DYNAMICS OF GROWTH IN A FINITE WORLD

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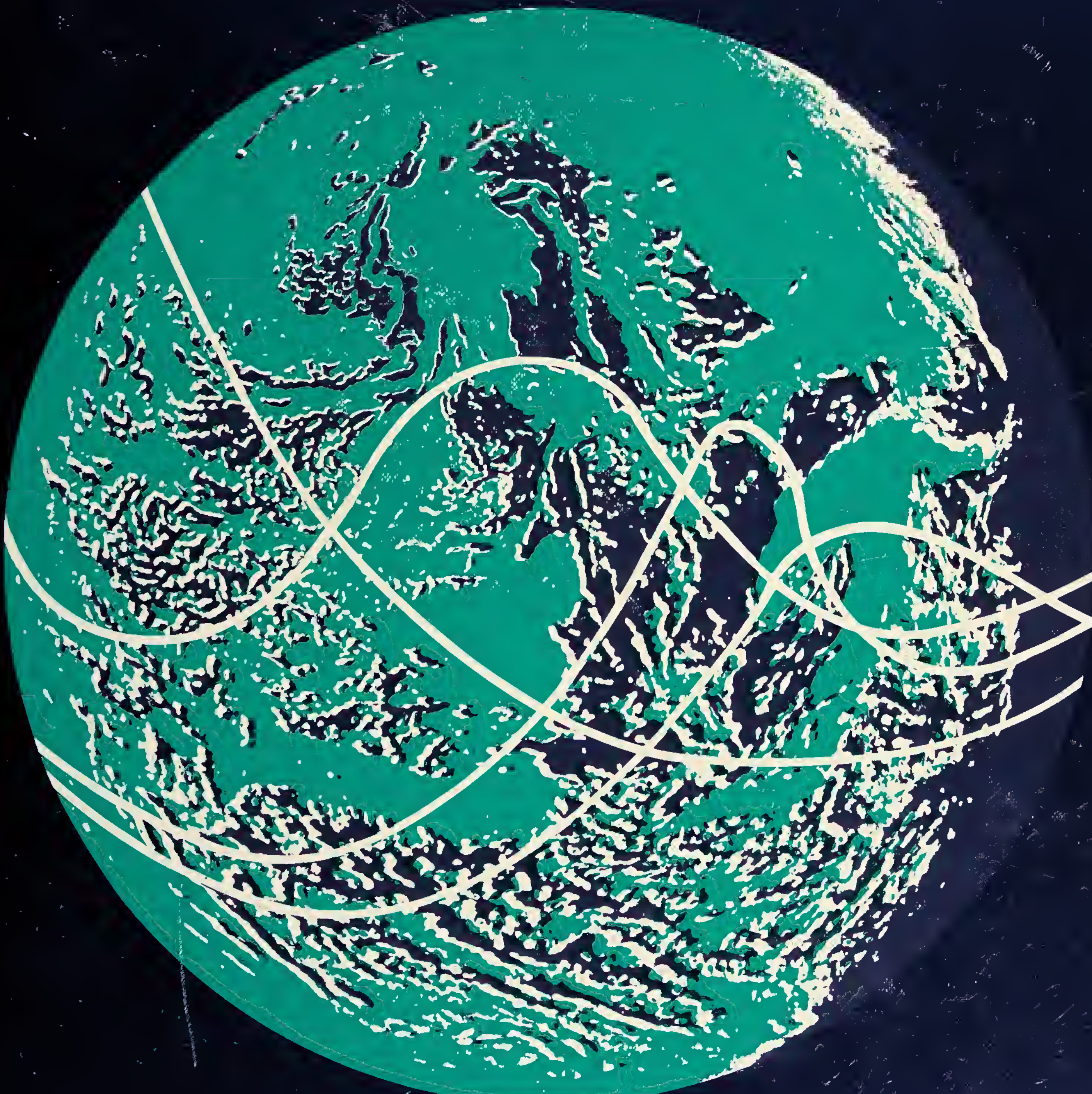

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We dedicate this report, with our deepest admiration and appreciation, to

Dr. Jay W. Forrester,

whose fundamental contributions to the field of dynamic modeling and whose perceptive prototype model laid the foundation for our efforts,

and

Dr. Eduard Pestel,

who provided the moral and material support necessary to initiate the research program described here.

Preface

Most people acknowledge that the earth is finite. Yet the belief that continued material growth is possible and desirable remains an important influence on the majority of public and private decisions. Policy makers generally assume that growth will provide them tomorrow with the resources required to deal with today's problems. Promises that the poor will receive a share of the additional goods and services created by growth are widely substituted for any real effort to change social values or redistribute current income. Deficit spending, high interest rates, and the squandering of materials are all prevalent, and all are justified in part by the claim that more income, greater productivity, and increased resource reserves will inevitably be available in the future.

Recently, however, concern about the consequences of population growth, increased environmental pollution, and the depletion of fossil fuels has cast doubt upon the belief that continuous growth is either possible or a panacea. Yet it is difficult for individuals or institutions to recognize or respond to limits to growth, for the causes and consequences of increased production and population extend over long time periods, are numerous, and lie interlinked within a system too complex to be encompassed easily by the human mind. Before current social objectives and institutional forms can be intelligently reevaluated, new theoretical bases are required to assist in understanding the dynamics of growth in a finite world.

In July 1970 the executive committee of The Club of Rome attended a seminar presented by members of the System Dynamics Group at the Massachusetts Institute of Technology. The committee had come to determine whether the system analysis techniques developed at M.I.T. by Professor Jay W. Forrester and his associates could provide new perspectives on the interlocking complex of costs and benefits inherent in continued physical growth on a finite planet. Professor Forrester brought to The Club of Rome meeting a preliminary computer simulation model, called World2, that specified important relationships among population, economic output, and environmental constraints.* At the meeting, plans were developed for a research program to test and extend Forrester's initial theories. I directed the group of scien-

*See Jay W. Forrester, *World Dynamics* (Cambridge, Mass.: Wright-Allen Press, 1971).

tists and students involved in that effort, and worked with my associates to prepare the material for three reports on our research.

Our first book, *The Limits to Growth,** presents the basic premises underlying our research program. It describes the dynamic characteristics of exponential growth, the physical limits to growth imposed by a finite planet, the relation of technological advance to physical constraints, and the various levels of population and material consumption that might be accommodated upon this earth. *The Limits to Growth* also summarizes the assumptions comprising our revised global model, World3, and illustrates the conclusions derived from it through the use of twelve computer simulation runs generated by the model.

Our second report, *Toward Global Equilibrium: Collected Papers,*† is an anthology of thirteen research papers prepared by Professor Forrester and the project staff. Seven of the papers provide technical descriptions of the submodels we constructed to study in detail specific sectors of the global models. The submodels illustrate the level of detail and the time horizon appropriate for future efforts to disaggregate the world models. In addition, they test the utility of important, simplifying assumptions in World2 and World3 and extend the perspectives derived from the global models to shorter-term issues more relevant to current decision makers.

The Dynamics of Growth in a Finite World, the third book in the series, presents a detailed description of World3, the computer model that was constructed to facilitate our understanding of growth in global population and material output. Although the model will certainly be improved through further work, it currently provides an easily understood, dynamic theory of the long-term, complex changes arising from physical growth in a finite environment. This text will serve analysts who wish to extend our analysis or to construct their own large-scale simulation models. It also provides a technical basis for multidisciplinary courses on population, the environment, and economic development. We assume throughout this text that the reader is throughly familiar with the material presented in *The Limits to Growth*.

The version of World3 presented here differs in several minor respects from the model employed in *The Limits to Growth*. After publication of the first book, several variable names were changed to clarify the meaning of an element or to make our terms more consistent with the nomenclature of the relevant fields. A few numerical parameters were also altered, and some dynamic phenomena were modeled in more detail to incorporate new data obtained since the completion of the first report. The changes in World3 affect neither the general behavior of the model nor the conclusions derived from it. In Chapter 7 of this book we present computer runs from the final version of World3 that are identical in all important respects to those presented in *The Limits to Growth*. To maintain consistency within the three reports, future printings of *The Limits to Growth* will employ a set of twelve computer runs generated by the

*D. H. Meadows et al., *The Limits to Growth* (New York: Universe Books, 1972).

†D. L. Meadows and D. H. Meadows, eds., *Toward Global Equilibrium: Collected Papers* (Cambridge, Mass.: Wright-Allen Press, 1973).

version of World3 described here. Appendix G to this report presents the rerun equations required to obtain those twelve runs.

Our team disbanded after completing The Club of Rome project, but all the former members are continuing their research on various aspects of the limits to population and material growth. Our current research at Dartmouth has now shifted to constructing simulation models that offer the time horizon and the detailed empirical validation necessary for managing the transition to material and demographic equilibrium at both the national and the regional level.

Acknowledging the contribution of everyone who has assisted our work is impossible, because modeling social systems is chiefly an exercise in synthesis. Not only our data but even most of our theories were drawn from the work of others. The task of assigning credit is further complicated by the fact that many of the concepts in World3 were employed in a context unfamiliar to and perhaps even unacceptable to their originators. Under the circumstances, I have chosen to let the references cited throughout this book testify to our indebtedness for the content of World3. Here I shall express our appreciation only to those who made a direct contribution to the conduct of the research project.

The Volkswagen Foundation and The Club of Rome accepted the risk of sponsoring a highly unorthodox project and provided continuing support throughout its evolution. Three members of the Club's executive committee played a special role: Aurelio Peccei constantly encouraged us to maintain a global and long-term perspective; Eduard Pestel provided assistance by securing the initial funding and by providing profuse and pertinent remarks on an early draft of this third report; and Carroll Wilson was a continuous source of wisdom, helping us to locate obscure but important information and recommending approaches to the administration of the project.

At M.I.T., Jay W. Forrester built the prototype model, World2, offered the use of his simulation laboratory facilities, and provided through his own research a set of intellectual standards that inspired each member of the team. Three long-suffering secretaries struggled through numerous drafts of this report. We are grateful to Judy Machen, Constance Fitzsimmon, and Donna Brown for their ready willingness to incorporate endless changes into the text of the manuscript. Jack Pugh, Thomas Todd, and Phil Koch provided the programming assistance required to initiate the work at M.I.T. and then transfer the model to Dartmouth College. Bill Shaffer spent long hours at the console creating the printouts for all model listings, runs, and documentation. Steve Flanders lent his special style to the artwork in the report, and Jean Clark patiently labored to convert our scribbled marginal insertions into a legible manuscript. We would also like to thank the publishers of this book, especially Holly Foster and Naren Patni, who managed to remain polite and helpful as deadline after deadline slipped by while we struggled to make explicit verbally the many concepts implicit in the equations of World3.

Finally, I want to express my appreciation to the entire team listed in *The Limits to Growth* for making the project a great pleasure, socially and intellectually. One member of the group merits special mention. Roger Naill took ultimate responsibility for converting the disparate chapters on the model sectors into a self-consistent

manuscript. Only through the many tedious hours he invested during this past year has the model become easily accessible to others.

The job of global modeling is certainly not finished. World3 should be criticized, revised, and extended. Understanding the interactions involved in other important problems, such as international conflict or the inequality of income distribution, will require new models quite different from World3. Further global simulation studies will benefit from the fresh perspectives of new groups working with new methods and in institutional and cultural contexts different from our own. We hope our three-volume report will facilitate their efforts and stimulate the extensive technological development, value shifts, and institutional changes that must occur as human society begins to evolve toward global equilibrium.

Dennis L. Meadows

Hanover, New Hampshire
November 30, 1973

Contents

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The Philosophy and Methodological Assumptions of World3

Beyond Ghor there was a city. All its inhabitants were blind. A king with his entourage arrived nearby; he brought his army and camped in the desert. He had a mighty elephant, which he used in attack and to increase the people's awe.

The populace became anxious to learn about the elephant, and some sightless from among this blind community ran like fools to find it. Since they did not know even the form or shape of the elephant, they groped sightlessly, gathering information by touching some part of it. Each thought that he knew something because he could feel a part.

When they returned to their fellow-citizens, eager groups clustered around them, anxious, misguidedly, to learn the truth from those who were themselves astray. They asked about the form, the shape, of the elephant, and they listened to all they were told.

The man whose hand had reached an ear said, "It is a large, rough thing, wide and broad, like a rug."

One who had felt the trunk said: "I have the real facts about it. It is like a straight and hollow pipe, awful and destructive."

One who had felt its feet and legs said: "It is mighty and firm, like a pillar."

Each had felt one part out of many. Each had perceived it wrongly.

Idries Shah, Tales of the Dervishes

1.1 ALTERNATIVE WORLD MODELS

In this book we describe the nature and implications of a particular world view, or world model, that we constructed to understand better the long-term causes and consequences of growth in the world's human population and material production. No single element of this world model is new to human thought. What is new is the synthesis of many isolated, incomplete perceptions into a more complete picture, an attempt to comprehend the whole system rather than just its single parts.

Many world models have been developed in the past. Every person carries in his head a mental model, an abstraction of all his perceptions and experiences in the world, which he uses to guide his decisions about future actions. Two mental models in particular have been shared by so many individuals that they have been the basis for social policy at various times throughout history. For simplicity we shall refer to these models here as the "ecological" and the "technological" images of man.

The ecological world view depicts mankind as an integral part of larger, natural systems, limited by physical laws and a finite earth:

> the vital essence in man is the same as that in a gnat, the same as that in an elephant. [Brhadaranyaka Upanishad 1. iii. 22]
>
> Elevated as man is above all other animals by his intellectual facilities, food is equally necessary to his support; and if his natural capacity of increase be greater than can be permanently supplied with food from a limited territory, his increase must be constantly retarded by the difficulty of procuring the means of subsistence.[Malthus 1830, p. 45]

> The economy of nature and ecology of man are inseparable, and attempts to separate them are more than misleading, they are dangerous. Man's destiny is tied to nature's destiny and the arrogance of the engineering mind does not change this. Man may be a very peculiar animal, but he is still a part of the system of nature. [Bates 1960]

Policies derived from this model are often tempered with caution about the possibilities for human expansion and with respect for the imperfectly understood, obviously powerful forces of nature.

The technological model pictures the earth's natural systems as created expressly for the use of man, who is a creature apart, endowed with an intelligence that lifts him above the constraints of nature:

> And God blessed them and said unto them, Be fruitful and multiply, and fill the earth, and subdue it; and have dominion over the fish of the sea, and the fowl of the air, and over every thing that moveth upon the earth. [Genesis 1:28]

> The scientific age differs in kind, and not only in degree, from the preceding mechanical age. Not only ingenuity but, increasingly, understanding; not luck but systematic investigation, are turning the tables on nature, making her subservient to man. [Barnett and Morse 1963]

> There are no substantial limits in sight either in raw materials or in energy that alterations in the price structure, product substitution, anticipated gains in technology and pollution control cannot be expected to solve. [Notestein 1970]

According to the technological view, no real constraints to man's possible accomplishments exist—only a danger that his freedom to overcome natural obstacles may be curtailed by political restrictions or that his courage to innovate may fail.

Modern adherents of either theory would probably agree about one aspect of man's relation with nature—it is subject to some degree of control; there is scope for action and improvement. Although physical laws may be immutable, man's condition within the natural system is defined to a certain extent by his own decisions and actions. As his understanding of natural and social systems increases, those decisions and actions may improve the welfare of the entire human race.

Unfortunately, neither the ecological nor the technological model provides an adequate basis for increasing human understanding of the world. Both theories are based on simple mental models, intuitive generalizations from observations of real-world events. Those observations are partially correct, just as each blind man accurately described his own impression concerning part of the elephant. However, since mental models can incorporate and process only a few observations at a time, they are necessarily incomplete. The blind men could not comprehend the whole elephant, and they would have been unable, on the basis of their partial models, to control it very well.

To manage complex social systems effectively, policy makers must bring together a variety of mental models, both ecological and technological; translate them into a common language; and determine simultaneously all their important implications. That process of synthesis requires formal models, that is, models whose assumptions are stated explicitly so that they can be widely examined and discussed. Formal models can be expressed in words, pictures, or other symbols, but they are probably best stated in mathematical equations, for two reasons: mathematics is a precise and a neutral language, understood by people from many cultures and academic fields; and assumptions expressed in mathematical notation can be processed by a computer so that a great amount of information can be stored and analyzed easily.

The model presented here, called World3, is an example of a formal, mathematical model of a complex social system. It combines elements of both the ecological and the technological world views, as well as theories derived from many traditional disciplines. Like all models, it simplifies the great complexity of the total socioeconomic system (if it were not simplified, it would be as incomprehensible as the real system itself). However, it is considerably more complex than any mental model; therefore, it is a step in the direction of greater comprehensiveness.

The method we used to select, translate, and analyze the wide variety of information contained in World3 is called system dynamics. It is based on a modeling paradigm quite different from the ones most commonly used in the physical and social sciences. Since some of our readers may be unfamiliar with this technique, in this introductory chapter we describe the basic principles of the modeling procedure.*

1.2 STEPS IN THE MODELING PROCESS

Making a formal systems model is a nonlinear process that involves many experiments, regressions, and reiterations.† Nevertheless, the process must cycle through a number of logical steps in sequence; each step is dependent on the successful completion of the one before. In constructing World3 we repeated this sequence many times, with corrections and revisions in the model being made during each iteration. In this book we shall use the sequence to structure our presentation of World3. The steps in the modeling process are:

1. General verbal description of the system within which the problem is observed.
2. Precise specification of the model's purpose in terms of the dynamic system behavior to be explained.
3. Definition of the model's time horizon.
4. Identification of the major elements necessary to represent the relevant aspects of the system.
5. Postulation of the model's structure; conceptualization of causal relationships and feedback loops.
6. Estimation of the model's parameters; quantification of causal assumptions.
7. Evaluation of the model's sensitivity and utility through computer simulation.
8. Experimentation, by means of further simulation, with possible alternative policies.
9. Communication of results.

*For more complete expositions of system dynamics, see Forrester 1961, Forrester 1968, Hamilton 1970.

†For a vivid description of the typical, cyclical process of model conceptualization, see Randers 1973.

The next part of this introductory chapter describes the guidelines we followed and the results we obtained in steps 1 through 4 in the construction of World3. Although these first steps appear to be simple and obvious, they are without question the most difficult and important stages of the modeling process. The essence of modeling is to simplify a system that is too complex to understand in full detail. This simplification requires the elimination of many real-world observations that are judged to be irrelevant to the problem being studied. It also calls for the aggregation, or grouping together, of elements that behave in a similar fashion. The decisions about which elements to include, which to omit, and which to aggregate are crucial to the eventual usefulness of the model, and they should be made only with reference to a carefully defined problem statement and time horizon.

The last part of this chapter describes only the guidelines employed in steps 5, 6, and 7, the specification and preliminary testing of the World3 model equations. The results of these steps are provided in Chapters 2 through 6, where the equations for each of the five major sectors in World3 are presented.

Step 8, experimentation with the model, is described in detail in Chapter 7 by means of numerous computer simulations. These simulations test the sensitivity of the model to changes in parameters and indicate the effects of alternative policies.

The final step, the communication of results, is carried out briefly in Chapter 8 and more extensively in the other two books of this series (Meadows et al. 1972, Meadows and Meadows 1973).

1.3 DESCRIPTION OF THE SYSTEM

In 1900 the human population numbered about 1.6 billion, and it was growing at about 0.6 percent per year (Carr-Saunders 1936). By 1970 the global population had more than doubled, and it was increasing at a rate of 2.0 percent per year, a rate of growth unprecedented in human history (PRB 1971). In the year 1900 about 9,000,000 people were added to the earth's population; in 1970 the net increase was 72,000,000. It is expected that the global population will rise to between 5.5 billion and 7 billion by the year 2000 (U.N. 1971).

To feed this growing population, agricultural output has also expanded. From 1951 to 1966 world food output rose by 34 percent. During the same period cultivated land was increased by 16 percent, grazing land by 35 percent, investment in tractors by 63 percent, and the annual use of nitrate fertilizers and pesticides by 146 percent and 300 percent, respectively (SCEP 1970, pp. 115, 118). Further increases in agricultural yield may be anticipated; for example, the new cereal grains of the Green Revolution promise to raise grain yields in selected regions by 300–400 percent.

The human use, displacement, and discard of resources are also increasing at record rates. The world consumption of minerals is currently growing by about 4 percent per year (NCMP 1972). Man-engendered release to the environment of at least thirteen major elements* exceeds natural rates of release by factors ranging from

*Iron, nitrogen, manganese, copper, zinc, nickel, lead, phosphorus, molybedenum, silver, mercury, tin, and antimony (SCEP 1970, p. 116).

3 to 100. World energy consumption has been increasing at 5–6 percent per year, which corresponds to a doubling time of 12–14 years. The growing use of materials and energy continues to be accompanied by increasing environmental pollution, as manifested by impure air and water supplies, diminished soil fertility, and the extinction of plant and animal species.

Although the world population has been growing rapidly, it has also, on the average, become richer and technologically more sophisticated. Global industrial output has grown even faster than population; it increased by 7 percent per year during the 1960s (U.N. 1970). The number of books published, the maximum speed of transportation, the capacity for computer data storage, and the productivity of an hour of labor have also grown exponentially (McHale 1972).

In summary, the complex system represented in World3 has historically exhibited increasing growth rates of population, industrial output, food production, and resource use. All this productive and reproductive activity is based on complex ecosystems that provide the maintenance functions necessary for human society. These ecosystems are governed by immutable physical laws and are vulnerable to degradation from misuse. The human social system is composed of political and economic institutions that respond to perceived shortages, primarily through the development of new technologies.

1.4 SPECIFICATION OF MODEL PURPOSE

To be useful to policy makers, a model must make some statement about the future, but information about the future may take several different forms. A model may provide, for example:

1. Absolute, precise predictions. (Exactly when and where will the next solar eclipse be visible?)
2. Conditional, precise predictions. (*If* the emergency core cooling system fails, what will be the maximum pressure on the nuclear reactor's containment vessel?)
3. Conditional, imprecise projections of dynamic behavior modes. (*If* corn prices are stabilized, will hog prices tend to fluctuate more or less strongly?)
4. Summary and communication of current trends, relationships, or constraints that may influence the future behavior of the system. (How do the paths of amino acid synthesis in a bacterial cell intersect? Where does the town zoning plan allow commercial construction?)
5. Philosophical explorations of the logical consequences of a set of assumptions, without any necessary regard for the real-world accuracy or usefulness of those assumptions. (On a curved surface, which theorems of Euclidean geometry still hold? How many angels can dance on the head of a pin?)

World3 was designed to provide information of the third sort. We had to limit ourselves to conditional and imprecise questions, rather than precise predictions, for two reasons. First, social systems are by their nature unpredictable in the absolute sense. Since any prediction made about the future of a social system becomes an influence on social policy, the prediction itself may change the system's behavior. Second, the incomplete and inaccurate world data base currently available does not permit precision, even for conditional long-term predictions of social systems. Thus purposes 1 and 2 do not appear to be feasible goals for a long-term social model.

Although precise long-term predictions for social systems do not seem to be attainable, a conditional, imprecise understanding of the global system's dynamic properties is possible. That level of knowledge is less satisfactory than a perfect, precise prediction would be, but it is still a significant advance over the level of understanding permitted by current mental models. It should provide a useful input to future policy decisions—about population control, energy consumption, and investments in new technologies, for example—that will have a significant impact on human society for many decades to come.

Figure 1-1 illustrates the four possible behavior modes that a growing population can exhibit over time. The mode actually observed in any specific case will depend on the characteristics of the carrying capacity—the level of population that could be sustained indefinitely by the prevailing physical, political, and biological systems—and on the nature of the growth process itself. One of these basic behavior modes must characterize any physically growing quantity, such as pollution, productive capital, or food output. *The purpose of World3 is to determine which of the behavior modes shown in Figure 1-1 is most characteristic of the globe's population and material outputs under different conditions and to identify the future policies that may lead to a stable rather than an unstable behavior mode.*

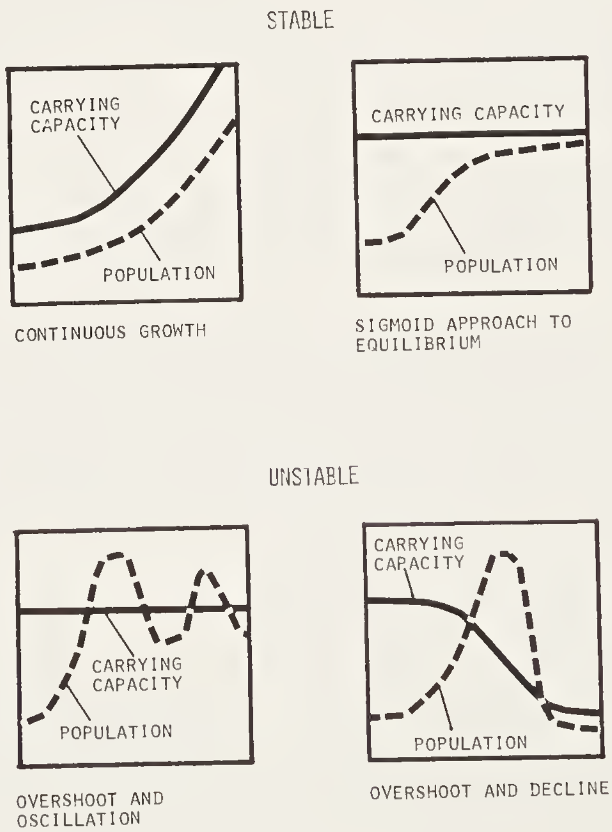

Figure 1-1 Four possible modes of population growth

1.5 DEFINITION OF MODEL TIME HORIZON

The time horizon of a model is the period over which the modeler is interested in the system's behavior. That period usually corresponds either to the time necessary for the system to manifest a behavior mode of interest or to the time required for the system to respond fully to some proposed new set of policies.

A human lifetime is about 70 years, persistent pollutants may circulate in the environment for 50 years, capital equipment may be used for 10 to 50 years, and new technologies may require 30 to 80 years to be developed and implemented globally. Thus the dynamics of human population and capital growth and their interaction with the environmental carrying capacity could extend over more than 100 years. We chose to simulate World3 for two centuries, beginning in 1900. The model's behavior over the 1900–1970 period can be compared with historical behavior for a rough test of model utility. The projection of the model's behavior to the year 2100, about two human lifetimes beyond the present, traces out the future implications of the assumptions we made about the system.

It was mechanically possible to continue the computer analysis past the year 2100. We did not do so because the validity of many important assumptions so far into the future is questionable and because information about developments that might occur beyond the year 2100 could have little impact on present-day decisions.

1.6 IDENTIFICATION OF MAJOR SYSTEM ELEMENTS

The choice of a 200-year time horizon automatically limited the dynamic phenomena we had to include explicitly in the model to events characterized by time constants ranging from 20 to 200 years. For example, the following dynamic phenomena occur over the relevant time period and could conceivably influence the behavior of the system:

Demographic transition
Soil erosion
Displacement of labor with capital
Passage of pollutants through food chains
Health care advances
Resource substitution

All these processes were included explicitly or implicitly as dynamic factors in the model. Events that take place over a very long period, compared with the model's time horizon (ice ages, genetic evolution), or a very short period (minor business cycles, seasonal weather variations) were treated in one of three ways: they were excluded from the model entirely, represented by a constant factor, or subsumed in the model's coefficients.

Even with the exclusion of very long-term and short-term factors, innumerable variables remained that could be incorporated into a world model. Since we were not trying to answer all possible questions about the system, nor to predict its exact future, extensive detail was unnecessary in World3. It was also undesirable because a model that is too complex cannot be easily communicated, criticized, or improved. We were looking for just those basic elements that are both necessary and sufficient to represent the mode of approach of the human population to the environmental carrying capacity. Elaborations and alternative formulations can always be inserted into the model, tested for their effects, and finally included if their effects are indeed significant. But World3 was constructed to be as simple as possible, without omitting the information required to fulfill its purpose.

Primary Model Sectors

We began the construction of World3 by representing in separate sectors the two quantities most responsible for material growth:

1. Population—incorporating the effects of all economic and environmental factors that influence human birth and death rates and thus population size.
2. Capital—including the manufactured means of producing industrial, service, and agricultural outputs.

As population and capital grow, they stimulate the development of new technologies that permit more efficient use of the earth's resources. At the same time, the increasing numbers of people and factories require more resources for their maintenance. Therefore, the model had to include representations of these resources and the dynamic processes that increase or decrease them. We included them in three sectors representing determinants of the environmental carrying capacity:

3. Agriculture—including all land and other factors influencing the effects of capital inputs on food production.
4. Nonrenewable resources—representing the fuel and mineral inputs required to make use of the capital stock for producing goods and services.
5. Pollution—standing for the persistent materials produced by industry and agriculture that may reduce human life expectancy, agricultural productivity, or the normal ability of ecosystems to absorb harmful substances.

Figure 1-2 illustrates schematically the five model sectors and the most important interactions among them. Many other sectors could be added to make the model more complete. For example, renewable resources besides food—fresh water, forest products, and fish—could be included. Like agricultural products, these resources depend on solar radiation and are produced continuously at a rate that may be enhanced by technology and reduced by pollution or misuse. We omitted them from World3, since their dynamic similarity to food indicated that their inclusion would not produce any behavior modes not already contained within the agriculture sector. Similarly, energy could be represented as a separate sector. However, the long-term behavior of fossil energy reserves is dynamically similar to that of other nonrenewable resources, so traditional energy sources were subsumed in the World3 nonrenewable resource sector. The impact of ultimate energy sources, such as fusion and solar energy, is discussed under social feedback mechanisms in section 1.7 and in the exponential technological changes section of Chapter 7.

Another aspect of the system that could be included as a separate sector is the set

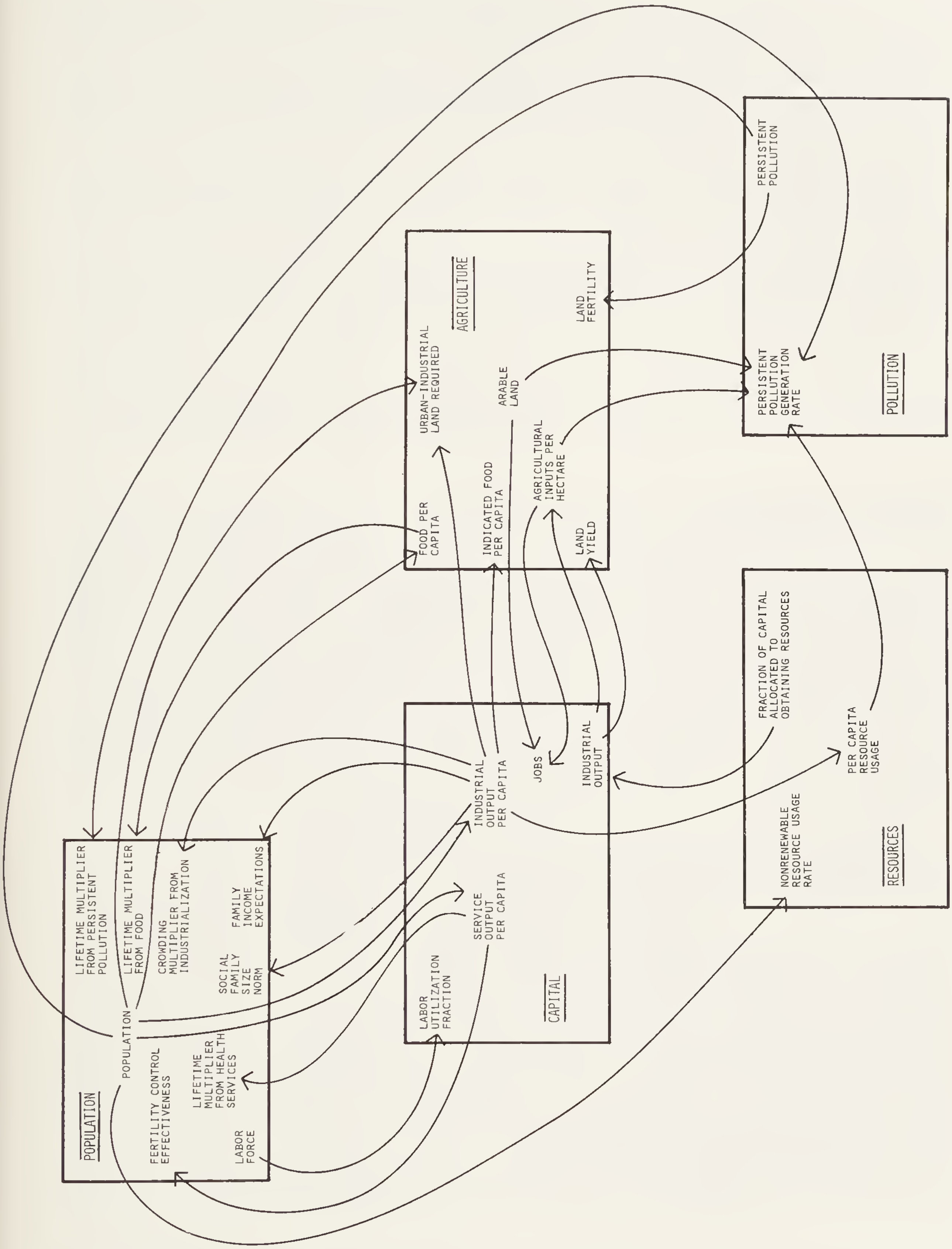

Figure 1-2 Interactions among the five basic sectors of World3

of human sociopolitical institutions that defines social goals and values and thus strongly influences the growth of population and capital and the use and allocation of resources. Rather than represent these institutions separately, we chose to interweave their effects implicitly throughout the five sectors of the model. The assumptions that led us to that choice are important enough to warrant further discussion, and we shall return to them in section 1.7.

It is sufficient here to mention only the most important simplifying assumption we made about the social system. Since we were primarily concerned with the approach of the human population to the carrying capacity defined by physical limits, we assumed that the social system would not produce any global, discontinuous misuse of resources on a scale greater than that prevailing today. In other words, we did not attempt to model political events like those that might trigger a nuclear war, a massive work stoppage, or a complete disruption of international trade. World3 incorporates only factors representing the gradual effects of the social system as it changes human values in response to new economic or environmental situations.*

Degree of Aggregation

Once we had defined the five model sectors, it was necessary to decide how much detail to include within each one. Should the population be subdivided by age or nationality? Should economic variables be grouped by continent, type of economy, developing and developed nations? Should every kind of resource and pollution be represented separately? These are questions of aggregation, the degree to which elements with common characteristics are grouped together. Choosing the appropriate level of aggregation in any model involves a difficult trade-off. A highly disaggregated model with much detail may be unwieldy and incomprehensible; an aggregated model with little detail may leave out important relationships that could alter the behavior of the model and the conclusions drawn from it.

World3 is a highly aggregated model because we made comprehensibility an important goal and asked an imprecise question whose answer does not require great detail. The following five chapters describe and justify the degree of aggregation chosen for each of the model sectors. In World3 the population is partly disaggregated by age, but not by nationality or income. Capital is effectively divided into four categories: industrial, service, agricultural, and that used for obtaining resources (for example, refineries, smelters, mining equipment, and oil tankers). Land is separated into potentially arable, arable, and urban-industrial categories. Neither the pollution nor the resource sector is disaggregated to represent different materials. Each of these sectors contains only one state variable, characterizing a typical persistent pollutant and nonrenewable resource, respectively.

We did not disaggregate World3 into two submodels representing the industrialized and nonindustrialized regions of the world, although that disaggregation is an

*Our assumption of smoothly functioning social institutions makes World3 an optimistic model that indicates only the maximum physical options for the total system. Severe, discontinuous social malfunctions could reduce the limits to growth levels well below those indicated by the model.

obvious one to make. It would have complicated the model by a factor of more than two. For our purposes, the added complication seemed to be unnecessary. The physical system connecting population with the environmental carrying capacity is structurally the same in any geographic subregion. The physical causes of instability and the policies that lead to material stability would also be expected to be the same (although the relative timing and emphasis of the steps toward stabilization in each region would differ). The systems that distribute and assimilate persistent pollutants and govern the technology and magnitude of resource use are essentially global. Thus we chose not to divide the model along economic or geographic lines. To investigate problems not addressed in this study, such as inequality in the distribution of wealth or income, we would construct a new model, designed for that purpose, rather than disaggregate and adapt World3.

1.7 POSTULATION OF MODEL STRUCTURE

Structural versus Parametric Assumptions

Having identified the relevant elements of the system, we next had to specify all the important relationships that interconnect those elements to form a system. We did this in two steps, in order of increasing precision. First, we postulated the general system structure; then we estimated the numerical values of the parameters that quantify that structure. The guidelines we used to carry out this process are discussed here. The resulting equations and parameters are treated in detail in Chapters 2–6.

Structural assumptions express the general causal links among model elements, indicating which elements are affected by changes in other elements. The following are examples of the structural assumptions included in World3:

1. An increase in food per capita will cause an increase in human life expectancy, if all other factors remain constant.
2. An increase in food per capita will cause a decline in the percentage of industrial output invested in the agriculture sector and an increase in investments made in the service and industrial sectors, all else being equal.
3. An increase in the area of cultivated land will cause an increase in food production and thus an increase in food per capita, all else being equal.

Since structural assumptions are not quantitative, they are not a sufficient basis for projecting the future behavior of the system. Each must be quantified by means of parametric assumptions. For example, a parametric assumption had to be added to World3 to indicate the exact number of years that would be added to average life expectancy if food per capita were increased from 1,800 to 2,500 calories per person per day. The general process of making and testing the parametric assumptions in World3 is discussed in section 1.8.

Representing System Structure

The structural assumptions that make up a system dynamics model are commonly expressed by a causal-loop diagram (see Figure 1-3). In a causal-loop dia-

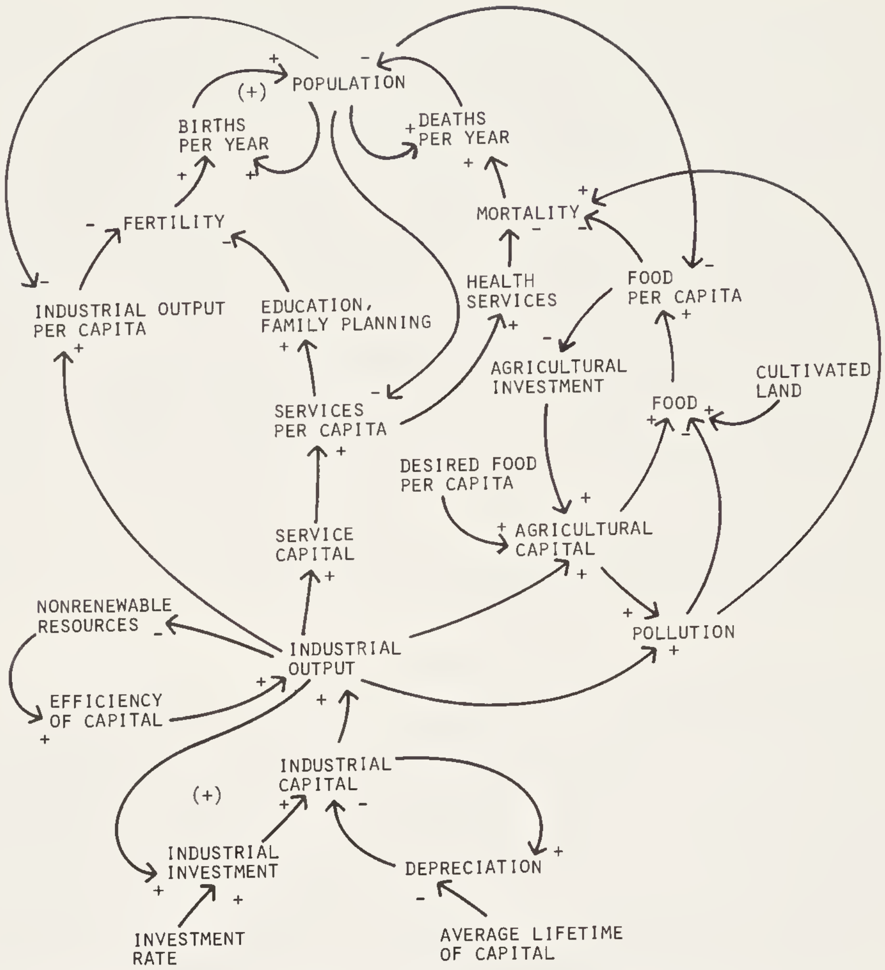

Figure 1-3 Causal-loop diagram of several important feedback loops in World3

gram, system interactions are shown by arrows leading from each element to all other variables that might be influenced by changes in that element. The polarity of each causal influence is indicated by a + or − sign near the head of the arrow. A positive polarity means that an increase in the first element will cause an increase in the second (and a decrease will cause a decrease). A negative polarity signifies that an increase in the first element will produce a decrease in the second (and a decrease will produce an increase). Causal-loop diagrams are rough sketches of the interacting feedback loops in the model. They do not contain enough information to permit a complete understanding of the possible modes of behavior or to analyze the model on the computer, but they do convey the general pattern of major system interactions.

A DYNAMO flow diagram contains considerably more information about the model structure than a causal-loop diagram. It provides information about the functional form used to represent each element in the DYNAMO equations of the model. DYNAMO, the computer language most often used to express system dynamics models, is not absolutely essential to the method—other flow diagram conventions and computer languages could be used. However, since DYNAMO was developed specifically to represent the continuous feedback interactions in system dynamics models, it was the easiest language for us to use in defining the elements of World3.

All the flow diagrams and equations in this book follow the DYNAMO format. The complete DYNAMO flow diagram for World3 is shown in Chapter 7 and is included in the pocket on the back cover of this book. The conventions used in DYNAMO flow diagrams, equations, and computer output are explained briefly in Appendixes C, D, and E.

The Structure of World3

Two important feedback loops in World3 produce the potential for exponential physical growth in the model system. The first governs human births; the second determines investment in industrial capital. In the first loop an increased number of human births increases the population, and the greater number of people then leads to still more births (after a 15–30 year delay required for newborns to mature and bear their own children). Similarly, an increased rate of capital investment adds to the stock of industrial capital, which makes possible a greater industrial output. Increased output, in turn, permits more investment, which raises the stock of capital still higher.

Growth in population and capital is exponential in form because of the nature of the processes that generate population and capital. People are needed to produce more people; machines and factories are needed to produce more machines and factories. Annual increases in population or capital thus depend in part upon the amount of population or capital already present. Whenever the rate of growth of any quantity varies directly with the amount of that quantity, a positive feedback loop is present, and growth, if it occurs at all, will be exponential.

The existence of a causal structure that provides a potential for exponential growth does not mean that the potential is always realized. In addition to the positive feedback loops that promote exponential growth, World3 contains numerous environmental, economic, and social factors that may balance or even overbalance the forces inducing growth. These factors constitute negative feedback loops within the model system. Their relative effectiveness constantly changes as growth progresses, and the resulting balance between growth forces and stabilizing forces continually shifts. In the real world, and also in World3, variations in the set of inputs from the environment can produce negative, positive, or zero rates of growth of population and capital at different times. No simple constant exponential growth rate for either population or capital was built into the world model. However, when the positive forces are dominant (when they overbalance the negative ones), the model will generate exponential growth at a rate that may vary over time.

The negative feedbacks that can balance the growth potential of population and capital are contained primarily in the agriculture, resource, and pollution sectors of the model in the form of assumptions about the physical limits of the global system. The limits are represented as dynamic, not static. They may be raised or lowered, depending on events elsewhere in the system. World3 incorporates the following assumptions about these limits:

1. The amount of potentially arable land that can be developed into actually cultivated land through the investment of capital is finite. As the stock of potentially

arable land is diminished, the marginal cost of land development, measured in terms of capital and energy, increases.

2. There is a limit to the amount of food that can be produced from each hectare of arable land each year. This limit can be approached by investment in agricultural inputs such as fertilizers, pesticides, and tractors. Eventually, however, there are diminishing returns to these inputs. The land yield limit can be decreased by very high levels of pollution or overintensive cultivation, and it can be restored to its original value by investment in land maintenance.
3. The stock of nonrenewable resources in the earth is finite. The absolute limit of available resources is the entire mineral content of the earth's crust. However, long before that limit is reached, the marginal cost—in capital and energy—of extracting and processing each unit of resource will rise to prohibitive levels.
4. There is a limit to the rate at which environmental pollutants can be rendered harmless by natural assimilation processes. Pollution levels can be kept below that limit by reducing the toxicity or quantity of industrial and agricultural emissions. However, pollution control requires capital investment, which is subject to diminishing returns. Moreover, the rate of natural pollution absorption can be lowered by the pollutants themselves if they reach levels that interfere with the environment's assimilation mechanisms.

In World3, physical limits provide negative feedbacks to population and capital growth, primarily through the assumption of diminishing real returns to the utilization of any physical resource. They become strong enough to balance the positive feedback forces of physical growth only when that growth brings capital or population close to assumed absolute limits. Negative feedback is also provided by various social mechanisms: shifts in relative prices, advances in technology, and changes in social values may operate to adjust the rate of approach of the growing population to the ultimate carrying capacity of the environment. These social feedback mechanisms are incorporated into World3 implicitly; they are interspersed throughout all five model sectors rather than being incorporated in separate sectors of their own. Since their representation in the model is indirect, and since they may be important in the development of new policies, it is worthwhile to describe the assumptions we made about these mechanisms while designing World3.

Social Feedback Mechanisms

Detailed system dynamics models of price change, technological advance, and social value change have been constructed by others.* The purpose and time horizon of our project made it unnecessary to include elaborate representations of these three factors in World3. Here we shall describe how simple social feedback mechanisms were included in World3 and how more complete representations of these subsystems might be constructed by anyone wishing to disaggregate the model.

Economic price is a function of two socially determined variables: the current

*System dynamics models of price change have been presented by Naill (1973), Meadows (1970), and Weymar (1968), Roberts (1964) developed a detailed representation of new technological development programs, and McPherson (1965) and Randers (1973) have constructed models of social change.

marginal value society places on a specific good or service, and the apparent marginal cost of supplying that good or service. Economists postulate that the price system performs a long-term stabilizing function in economic systems by signaling resource scarcity. When a material becomes scarce, the cost of obtaining it increases, and all products containing it will increase in price. The price increase may trigger numerous social responses. For example, the search for natural deposits of that material may be intensified; the recycling of discarded products containing it may be increased; manufacturers may learn to use the material more efficiently or to substitute another material; or consumers may decide to get along with less of each product containing it.

World3 includes several causal relationships between the supply of some material (such as food, nonrenewable resources, or industrial capital) and the response of the economic system to that material's scarcity (develop more agricultural land, allocate more capital to resource production, or increase manufacturing efficiency). These relationships are most realistically represented with price as an intermediate variable:

decrease in supply → rise in price → social response.

World3 simplifies the model of social response by eliminating explicit reference to price, the intermediate variable. We shortened the representation of the causal chain to:

decrease in supply → social response.

The ultimate regulating effect of the price system is thus included, but price does not explicitly appear in the model.

We assumed that the price system conveys its signals of scarcity to decision makers accurately and with a delay that is insignificant on a 200-year time scale. Thus the price mechanism was eclipsed to increase the model's simplicity and comprehensibility. If actual prices are biased or do not immediately reflect declining resource supplies in the real world, the global economic system will be less stable than its facsimile in World3. If price information is transmitted to institutions that adjust their production or consumption patterns only after a long delay, the economic system will be less able to adjust itself to any limit, and the tendency for the system to overshoot its limit will be increased. Our representation of the price system in World3 thus tends to overestimate the stability of the real-world system.

Technological advance, like price, is a social phenomenon; it results from applying man's general knowledge about the world to the solution of specific, perceived human problems. If we were to make a complete dynamic model of the development of a given technology, we would include the following:

1. A level of accumulating general knowledge, with the rate of accumulation dependent on the resources devoted to basic research.
2. A widespread perception of some human problem.
3. An allocation of physical resources, human effort, and time to search for a technical solution to the problem. If the level of basic knowledge is great enough, the solution will be found after some delay.

4. Another delay, to allow for testing, social acceptance, and implementation of the new technology. The length of this delay will depend on the magnitude of the required departure from the present way of doing things.
5. A larger impact of the technology on the total system, including social, energy, and environmental costs in areas widely separated from the actual point of implementation.

Nearly every causal relationship in World3 could conceivably be changed by some sort of new technology. In the past, various technologies have directly or indirectly improved birth-control effectiveness, increased food production, and provided better techniques for abating pollutants. They have also increased life expectancy through medical advances, hastened the rate of land erosion, and developed more toxic pollutants. It is by no means certain that technologies will continue to do any of these things in the future, for the human values and economic institutions that govern technological development are always subject to change.

Since so many causal relationships can be altered by conceivable technological changes, we had to consider building technological change directly into each model relationship as we formulated it. We did that by assigning possible technologies to three categories: already feasible and institutionalized, feasible but not institutionalized, and not yet feasible.

Some causal relationships have historically been influenced by technology and continue to be so influenced today. They occur whenever social agreement is reached about the desirability of change and when resources and institutions to bring about that change are already integral parts of the system. Some examples are medical technology to improve health, industrial technology to raise production efficiency, agricultural technology to increase land yields, birth-control technology to control family size, and mining technology to discover and exploit lower-grade nonrenewable resources. A significant number of the world's people have adopted a value system that will continue to promote these technologies as long as their costs can be afforded. They are effectively built into the world's socioeconomic system. Therefore, they are also built into the relationships of World3, with the assumption that they will continue to develop and spread through the world, without delay, as long as economic support for them continues.

Other technologies have not been so widely accepted that they can be considered functioning parts of the world system. It is not clear that all the nations of the world will be willing to institutionalize and pay for such technologies as pollution control, resource recycling, the capture of solar energy, supersonic transports, fast-breeder reactors, or increased durability of manufactured goods. All these technologies are feasible, but it is not possible to state with confidence when or whether any of them will be adopted on a worldwide scale. Therefore, we incorporated many of them as optional functions that anyone analyzing World3 can activate at any specified time in the model run. The model can thus be used to test the possible impact of any or all of these technologies and the relative advantages or disadvantages of adopting them.

One set of technologies was omitted from the model—discoveries that we cannot possibly envision from our perspective in time. No model, mental or formal, can incorporate unimaginable future technologies as they may actually occur. That is one reason why no model can accurately predict the future. Any long-term model that is being used to aid the policy-making process must be updated constantly to incorporate surprising new discoveries as they are made and to assess how they may change the options of human society.

It would have been possible to include in World3 the assumption that some unimaginable discovery will come along in time to solve every human problem. Many mental and formal models seem to be based on that assumption,* and its effect on the model's behavior is illustrated in Chapter 7 (section 7.5). But our own bias as modelers and as managers has been to search for policies based on the realistic constraints and potentials of the system as they appear at the moment, rather than to rely on developments that may or may not occur in the future.

We have already mentioned that both technology and price are dynamic elements that depend directly on the values of human society. Values also influence many other dynamic elements of interest in a model of physical and demographic growth. Therefore, although World3 was not designed to depict the dynamics of social value change, the model had to contain some assumptions about human goals as they influence and are influenced by the processes of physical growth.

In the difficult task of modeling human values we tried to include only the most basic values that can be regarded as globally ubiquitous. They begin with requirements for survival—food, water, shelter—and go on to include a hierarchy of other desires—longevity, children, material goods, and social services such as education. Some of these values (for example, desired family size and preferences among food, material goods, and services) are represented explicitly in the model as variables that have an important influence on economic decisions. Others are included implicitly, as in the allocation of service output to health services or in the quantity of nonrenewable resources used per capita.

All the values included in World3 are assumed to be responsive to the actual physical and economic condition of the system; thus they are all involved in feedback loops. The patterns of dynamic value change included in the model, however, were limited to the patterns of change historically observed over the last hundred years or so. During that time, the major global force behind value change has been the process of industrialization, a process that is still under way in most nations of the world. Therefore, the values that both shape and respond to the development of the model system follow the historical patterns observed during industrialization. As industrialization increases in the model—measured by the level of industrial output per capita—the aggregate social demand shifts in emphasis from food to material goods and finally to services. Changes also occur in the emphasis placed on obtaining children, education, and health care and in the distribution of various goods and services throughout the industrializing economy.

We did not build into World3 any global shifts in values other than those that might be expected to take place as the world becomes more industrialized. It is possible that new value systems will evolve, but the pace of value change is always slow and the precise nature of new social attitudes is currently more a matter for

*For examples, see Boyd 1972, Oerlemans et al. 1972, and Cole et al. 1973.

speculation than for logical projection on the basis of any generally accepted body of theory. We chose to represent unprecedented value changes by a set of switches throughout the equations of the model, which the operator can use to express his own hypotheses about future social development.

Ecological and Technological Assumptions

Proponents of either the ecological or the technological world view may argue that the structural assumptions of World3 are biased against their position because World3 includes the basic assumptions of the other side. Physical limits to material growth are indeed represented in the model: depletable resources are brought into the production function, and diminishing returns to physical inputs are considered inevitable. When viewed from the perspectives afforded by the technological model of man, these assumptions appear to be heretically Malthusian. Those subscribing to the technological mental model may fear that assumptions like those in World3 will engender a pessimism that will block mankind from pursuing feasible solutions to the problems caused by growth.

On the other hand, we assumed in World3 that cultivatable land, agricultural yields, and resource reserves are greatly expandable by technological improvements yet to come. We also assumed that perfectly effective birth control and the production of energy from nondepletable sources are achievable, that demographic transition will always accompany industrialization, and that human material desires are satiable. This set of assumptions may be totally unacceptable to those who accept the ecological image of the world. They may believe that important physical limits have already been exceeded and that the model irresponsibly exaggerates the options available to global society and will further postpone corrective actions that are long overdue. They may also believe that the physical limits to growth will in practice be much lower than those suggested by World3 since social factors that produce drastic misuse of resources, such as international conflict, erosion of mental health, greed, or the inability to manage increasingly complex systems, are not included in the model.

The debate between ecologists and technologists on the nature of the world appears to be similar to that on the nature of elephants by the blind men, each of whom perceived only a part of the whole. In World3 we tried to provide a set of structural assumptions that would be general enough to include both points of view, because we recognized partial validity in each extreme. The model structure represents both man's adaptability and the earth's physical limits. Various assumptions about their relative importance can be tested, not by changing the model's structural assumptions but by changing the parameters that express quantitatively the effectiveness of technologies, the position of limits, and the nature of social choice.

1.8 ESTIMATION OF MODEL PARAMETERS

The network of interlocking feedback loops defined by the structural assumptions constitutes the skeleton of the model, the framework upon which all further analysis depends. System dynamics places primary emphasis on determining this model structure, rather than on estimating numerical parameters, for three reasons. First, experience in modeling feedback systems rapidly demonstrates that even the most sophisticated numerical estimation techniques will not produce useful conclusions from a faulty or incomplete model structure. Second, system dynamics models are usually concerned with imprecise questions about the general behavioral tendencies of social systems. Third, a correct causal structure generally produces realistic model behavior, even with only approximate numerical parameters.

Since this primary focus on the formulation of causal structure rather than on the estimation of parameter values differs markedly from the relative emphasis in several other modeling techniques, we shall describe in some detail the role of quantitative data in system dynamics models in general and in World3 in particular.

The Spectrum of Available Information

The observations mankind has assembled about the world vary greatly in form, accuracy, and precision. Some numerical information that is both accurate and precise has been gathered by scientific measurements carried out on carefully controlled physical systems. Examples of this kind of information include graphs of the boiling point of water as a function of pressure, tables of tides and the motion of planets, and measurements of the speed of light. Such information forms the basis for most models in the natural and engineering sciences, but it constitutes only a small fraction of total human knowledge.

A second body of knowledge, inherently less accurate but more comprehensive in its coverage, takes the form of statistical data on complex, uncontrolled social systems. Examples include census reports, economic indicators, and the results of opinion polls. The precision of this information varies widely. Inexpensive data processing and storage procedures have permitted the acquisition of large quantities of statistical information, and growing data banks provide quantitative inputs to most models in the social sciences. However, all the social data banks combined contain only a small portion of the information that people have acquired through observations of the world around them.

The least precise but most comprehensive information available is that acquired through direct individual and group experience. It is typically expressed in the form of intuitive guess, expert opinion, or group consensus. Although this information also varies greatly in accuracy, is generally nonquantitative, and is seldom communicated clearly, it provides the basis for most mental models and nearly all human decisions. Some examples are a voter's personal opinion about the relative honesty of two politicians, an analyst's projection of the stock market's response to a prolonged energy shortage, or a board of directors' consensus about which new product will most enhance its company's profits.

System dynamics is primarily a technique for simulating social systems, and its users are working to understand the possible behavior patterns of a total system rather than to predict the precise future value of a specific variable. Therefore, the method emphasizes using the most comprehensive available information, however precise, in the belief that social systems are often guided by human perceptions, biases, goals, expectations, or dissatisfactions that cannot be measured exactly and are not included in any standard compilation of statistical data. Though they are important, these intangible variables are seldom measured, because their dimensions are difficult to define operationally. However, they have often been experienced, in a casual and imprecise way, and mental models contain numerous accurate impressions of their role in social systems. Estimates of such unmeasured, intuitive variables are generally included in system dynamics models on the assumption that their inclusion, even with some inaccuracy, produces a more useful and accurate representation of the total system than does their omission.

Sensitivity to Parameter Changes

World3 is a device for testing the implications of alternative assumptions, not a predictor of future events. Numerous simulations of the model system with different sets of parameter values indicate the range of behavior modes that the system can exhibit and the sensitivity of those behavior modes to parameter changes. Since many of the model's parameters may be inaccurate, it is especially important to understand how the conclusions drawn from the model may be influenced by errors in their values.

In keeping with the purpose of the model, we identify sensitive parameters by observing changes in the model's qualitative behavior, not its quantitative output. For example, a change that causes the population in World3 to level off at 6 billion instead of 7 billion would not be considered significant—the population still levels off, and its behavior mode is still stable. On the other hand, if a small change in one parameter causes the model to shift from an overshoot mode to a stable equilibrium, we would regard that parameter as sensitive and would put considerable effort into estimating it as accurately as possible.

Fortunately, given the inaccuracy of most social data, the behavior of complex feedback systems is generally not qualitatively sensitive to parameter values. In such systems numerous negative feedback loops, each acting to maintain a system variable within a certain range of values, tend to offset small numerical changes in any one loop by inducing opposing changes in other loops. Thus complex systems tend to exhibit the same behavior mode over a wide range of parameter values; their behavior is determined more by their structure than by the precise values of their numerical parameters. The behavioral stability of complex systems can be illustrated by many common examples: the ability of the human body to maintain a constant internal temperature when the external temperature fluctuates, the tendency of commodity prices to oscillate regularly in many different countries under a variety of political systems, and the energetic stability of a diverse tropical forest ecosystem (as contrasted with the instability of a monoculture, which is no longer a complex system).

There is one important exception to the general rule that complex systems are insensitive to parameter changes. Sensitive points may exist within the system structure, where a change in a certain combination of parameters becomes equivalent to a major structural change. These points are rare, and they generally occur at the intersection of several positive and negative feedback loops, where a small shift in numbers may change the relative dominance of loops and thus the tendency of the entire system to grow or decline. An important purpose in making a dynamic model is to locate these points because they indicate relationships on which more research may be necessary to understand the system fully. They also indicate decision points in the system where new policies may be effective in altering system behavior.

Physical Limits in World3

One group of parameter values in World3 is of particular importance, not because the model behavior is sensitive to their values but because their estimation reflects most directly the ecological or technological bias of the modeler. These are the values that express the ultimate physical limits in World3.

We found only subjective, imprecise, and inaccurate information to use in estimating the limits beyond which growth in land development, capital intensification of agriculture, resource acquisition, and pollution assimilation would produce socially unbearable costs. Although reasonable estimates of some limits, given present technologies, are available, there is no way of knowing how they may be affected, positively or negatively, by future technologies. Extreme assumptions about ultimate limits may render the model output either uninteresting (by setting the limits so high that they are ineffective before the model year 2100) or unhistorical (by setting them so low that they stop growth before the model year 1970). The model itself cannot determine which set of values is correct; it can only serve as a device within which any set can be tested and evaluated.

For the reference run of the World3 model (Figure 7-6), we attempted to assign values to the limit parameters that are consistent with present global resource estimates and currently foreseeable technologies. Other values, both higher and lower, were tested in subsequent model runs. The values assumed in the reference run are:

1. Potentially arable land—3.2 billion hectares, or about twice the area currently under cultivation.
2. Maximum yield per hectare—6,000 vegetable-equivalent kilograms per hectare-year, or three times the global average yield in 1970.
3. Nonrenewable resources (total exploitable stock)—250 times the amount consumed globally in 1970.
4. Persistent pollution assimilation rate (per year)—25 times the amount of pollution rendered harmless by natural ecosystems in 1970.

Our justification for these values and the tests of alternative values are presented in the relevant sector descriptions. We believe that the assigned values represent an intermediate position between the extreme ecological and technological views. They allow for considerable progress beyond the limits attainable with present technology, but they do not assume that technology will be able to push back the physical limits indefinitely.

1.9 EVALUATION OF MODEL UTILITY

After the feedback-loop structure has been established and quantified, the model can be analyzed on the computer to calculate from the entire set of structural and parametric assumptions the resultant behavior of all the variables over time. Numerous alternative assumptions can be made and tested. Throughout this process the modeler assesses the model's behavior, by comparing it with his knowledge of the real-world system's characteristics, to decide whether he has sufficient confidence in the model to use it as an input to policy decisions.

Confidence in a model can be established by many different tests or measures. Models constructed for precise prediction are often judged by their ability to reproduce past time-series data accurately, on the assumption that a close fit to past system behavior will increase the likelihood of an accurate prediction of future behavior.

Such a test is not appropriate for a model like World3, which was not constructed for quantitative accuracy. As noted earlier, many short-term factors that have influenced the real-world system historically were deliberately omitted from our model as irrelevant to the long-term development of the system. Furthermore, since World3 was designed to answer questions about aspects of system behavior that have not been manifested in the past, even a fair fit to historical data would not guarantee its utility in producing statements about the future. We certainly expected World3 to reproduce all qualitative behavior modes exhibited by the system in the past, but we did not consider that a sufficient test of the model's utility. Our test for World3 is related, instead, to the way it is supposed to assist decision makers.

Models of social systems can be used as policy tools in several different ways. An extremely complex model can be used only as a black box. The user gives it some information on current conditions or trends, and the model produces a description of an appropriate course of action. The user must take the underlying assumptions and logical processes of the model on faith, and his own understanding of the system's structure is not improved by working with the model.

A model can also be used as a learning tool by which the user can enlarge and clarify his own mental model of the system. His understanding of the system will increase when he is forced to state his own assumptions explicitly and precisely and when he can observe exactly how those assumptions fit together, interact, and result in a complex, long-term behavior pattern. As he observes how and why alternative assumptions change the system's behavior, he can begin to derive the general principles by which the system is guided. Used in this fashion, a computer model can lead its user to structure and analyze intuitively much more information than was previously accommodated in his mental model.

World3 was intended to be used in this second way, on the assumption that mental models, rather than black-box computer models, are and should continue to be the primary basis for social policy. Therefore, our criteria for judging the usefulness of the model were the following:

1. Each assumption in the model should be consistent with direct measurements or observations of the real-world system; no assumption or parameter without real-world meaning should be added merely to improve mathematical convenience or historical fit.
2. When the total model is used to simulate historical time periods, the behavior of each variable should resemble the historical behavior modes of corresponding

elements in the real world. When the system is simulated into the future, each variable should follow an understandable path within a reasonable range of values.

3. The model should be sufficiently simple so that the reasons for its behavior can be comprehended and abstracted as generally applicable principles for dealing with the real-world system. Ultimately, the model should no longer be needed because its basic constituent relationships should become part of the mental models of its users.

A model that meets these three criteria will not be a perfect representation of the real world. It will not be able to answer all possible questions about the world, nor will it be able to make accurate predictions. But no social decision maker has the luxury of delaying his actions until a perfect model of social systems has been constructed, if indeed one ever becomes available. From the range of current models, mental or formal, he must choose the one in which he has the most confidence, and use that model to make his decision.

World3 was developed through an exercise in assembling information from many sources, summarizing it explicitly, exploring its implications, and generalizing from the process a little understanding about the future of the complex human socioeconomic system. This type of exercise can be valuable, even though the information it yields is incomplete. For example, it may bring about a critical reexamination of the underlying assumptions of current mental models and a more open discussion of the bases of social decision making. It may stimulate further attempts to improve the process of model making and the theories of social systems upon which all models depend. It may provide an interim model, until better models are made, as an input to long-term policy formulation. World3 is not *the* world model; it is *a* world model, one made at a rather primitive stage in the development of systems understanding. It is both a demonstration of what can be done and a challenge to do better.

REFERENCES

Barnett and Morse 1963	Barnett, H. J., and C. Morse. *Scarcity and Growth.* Baltimore: Johns Hopkins University Press for Resources for the Future, 1963.
Bates 1960	Bates, M. *The Forest and the Sea.* New York: Random House, 1960.
Boyd 1972	Boyd, R. "World Dynamics: A Note." *Science* 177, no. 4048 (August 11, 1972), pp. 516–519.
Carr-Saunders 1936	Carr-Saunders, A. M. *World Population: Past Growth and Present Trends.* Oxford: Clarendon Press, 1936.
Cole et al. 1973	Cole, S., et al., eds. *Models of Doom: A Critique of Limits to Growth.* New York: Universe Books, 1973.
Forrester 1961	Forrester, Jay W. *Industrial Dynamics.* Cambridge, Mass.: The M.I.T. Press, 1961.
Forrester 1968	Forrester, Jay W. *Principles of Systems.* Cambridge, Mass.: Wright-Allen Press, 1968.

Hamilton 1969	Hamilton, H. R., et al. *Systems Simulation for Regional Analysis*. Cambridge, Mass.: The M.I.T. Press, 1969.
McHale 1972	McHale, J. *World Facts and Trends*. 2nd ed. New York: Macmillan, 1972.
McPherson 1965	McPherson, L. F. "Organizational Change—An Industrial Dynamics Approach." *Industrial Management Review* 6, no. 2 (Spring 1965), pp. 51–65.
Malthus 1830	Malthus, T. R. *A Summary View of the Principle of Population*. Reprinted in *Population Geography: A Reader*, ed. G. J. Demko et al., pp. 44–71. New York: McGraw-Hill, 1970.
Meadows 1970	Meadows, D. L. *Dynamics of Commodity Production Cycles*. Cambridge, Mass.: Wright-Allen Press, 1970.
Meadows et al. 1972	Meadows, D. H., et al. *The Limits to Growth*. New York: Universe Books, 1972.
Meadows and Meadows 1973	Meadows, D. L., and D. H. Meadows, eds. *Toward Global Equilibrium*. Cambridge, Mass.: Wright-Allen Press, 1973.
Naill 1973	Naill, R. F. "The Discovery Life Cycle of a Finite Resource: A Case Study of U.S. Natural Gas." In Meadows and Meadows 1973.
NCMP 1972	United States National Commission on Materials Policy. *Towards a National Materials Policy: Basic Data and Issues*. Interim Report. Washington, D.C.: Government Printing Office, April 1972.
Notestein 1970	Notestein, F. W. "Zero Population Growth: What Is It?" *Family Planning Perspectives* 2, no. 3 (June 1970), pp. 20–24.
Oerlemans et al. 1972	Oerlemans, T. W., et al. "World Dynamics: Social Feedback May Give Hope for the Future." *Nature* 238, no. 5362 (August 4, 1972).
PRB 1971	Population Reference Bureau, Inc. *World Population Data Sheet*. Washington, D.C., 1971.
Pugh 1973	Pugh, A. L. *DYNAMO II User's Manual*. Rev. ed. Cambridge, Mass.: The M.I.T. Press, 1973.
Randers 1973	Randers, J. "Conceptualizing Dynamic Models of Social Systems: *Lessons from a Study of Social Change*." Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, Mass., 1973.
Roberts 1964	Roberts, E. B. *Dynamics of Research and Development*. New York: Harper & Row, 1964.
SCEP 1970	*Man's Impact on the Global Environment: Report on the Study of Critical Environmental Problems*. Cambridge, Mass.: The M.I.T. Press, 1970.
Shah 1970	Shah, I. *Tales of the Dervishes*. New York: E. P. Dutton, 1970.
U.N. 1970	United Nations. Department of Economic and Social Affairs. *Statistical Yearbook, 1969*. New York, 1970.
U.N. 1971	United Nations. *The World Population Situation in 1970*. Population Studies, no. 48. New York, 1971.
Weymar 1968	Weymar, F. H. *Dynamics of the World Cocoa Market*. Cambridge, Mass.: The M.I.T. Press, 1968.

2
Population Sector

Donella H. Meadows

The vitality of our discipline is shown in its undiscourageable effort to gather data on the past, much of it aimed at all-but-impossible prediction of the future, whose byproduct has been models through which population can be understood. Now is no time to stop just because some new variables have to be put into the equations.

Nathan Keyfitz

2.1 INTRODUCTION

World3 is a model of the continuous dynamic interaction between the human population and the global resource base. This resource base may be defined as the environmental and the economic potential to fulfill human needs. The model population and its resources are linked together through numerous, simultaneous causal relationships, which represent changes in either the supply of or the demand for various goods and services.

If the supply of and the demand for any given resource become unbalanced, the model system can generate two types of responses, as shown in Figure 2-1. An economic or technological response can change the supply of the resource. For example, a food shortage may bring about investment in improved seed varieties, or an oversupply of mercury may force a mine to close. Alternatively, a demographic response may change the demand for the resource by altering the population size (a food shortage may increase the death rate; an economic boom may increase the birth rate).

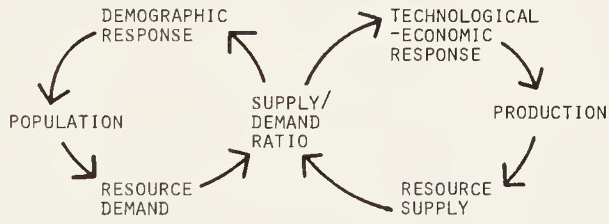

Figure 2-1 Population-resource feedback loops

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The world model contains numerous feedback loops representing demographic and technological-economic means of achieving a favorable balance between the population size and the supply of resources. These loops are intricately intermeshed, and they operate with different speeds and efficiencies. Since both the supply of and the demand for each resource are always varying and since societal responses of either type are usually delayed, a perfect population-resource balance is rarely actually attained. The system is usually in motion, compensating for a deficiency in one resource, depleting an oversupply of another, building up a greater demand for a third.

The function of the population sector in this total scheme is twofold:

1. It calculates the total population size, which is one determinant of resource demand.
2. It represents the demographic response of the population, through the birth rate and the death rate, to the changing resource supply.

The first function is a matter of straightforward arithmetic, although the dynamics of the population age structure can make the arithmetic rather complicated. Demographers have already developed the theory and the computerized models to carry out this sort of calculation (for a review, see Keyfitz 1971*a*).

The second function of the population sector—to represent endogenously the response of human birth and death rates to changing system conditions—is a far more difficult undertaking. It raises the most basic and perplexing questions about the behavior of human populations. What causes a population to grow, to stabilize, to decline? How do psychological and cultural factors interact with biological constraints to influence birth and death rates? How might the world population growth rate change as a result of technological or economic changes, such as increased industrialization, improved contraceptive techniques, or reduced infant mortality?

These questions are general and imprecise. They refer to the long-term dynamic patterns of population response to changing environmental conditions, not to specific, quantitative properties of the world population today. The model described here is an attempt to provide answers to these general questions. It is not intended to explain the precise history or predict the precise future of any given real population. It is a dynamic hypothesis about a generalized population. Thus it may be qualitatively applicable to all large populations, but it will be quantitatively accurate for none.

Most of the individual causal assumptions that make up the population sector are not proposed here for the first time. They have been taken from the works of many different scholars who have also sought to deduce general causal theories from their observations of various human populations. We have tried to organize these causal theories, translate them into a common format, choose a self-consistent set of theories, and examine the logical consequences of that set. The purpose of the exercise is not to produce a final, unimpeachable theory of population. Rather, it is to assemble the many separate pieces of the population puzzle that seem to be known now, and to understand the dynamic patterns they make when they are fitted together. The assembly process may of course reveal that some important pieces are missing or poorly defined. However, the broader view provided by the modeling attempt may at least indicate how to find or refine them.

Those who are interested in smaller population aggregates than the entire world population may find the basic causal structure postulated here a useful beginning for more precise short-term models. However, the model's parameters—the exact numerical forms assigned to the causal relationships—would certainly have to be altered to express differences in the cultures, technologies, and distributional inequalities of the various subpopulations of the world. Furthermore, migration, a most important type of human demographic response on the local level, is not an option on the global level and thus is not included in this model.

The dominant trends in the behavior of the world's population during this century, trends that a dynamic model must duplicate to pass a first test of confidence, are described in the following section of this chapter (2.2). The basic concepts and the general structure of the population sector are discussed next (sections 2.3 and 2.4). Each model equation is then presented in detail in section 2.5, along with the information that led to the form of the equation and to our choice of specific parameters. In the final section (2.6) computer runs of the population sector, driven by varying assumptions about external conditions, illustrate the possible behavior modes of the sector and its sensitivity to changes in parametric assumptions.

2.2 HISTORICAL BEHAVIOR MODES

Two basic dynamic characteristics are exhibited by all human populations: a tendency toward exponential growth, and a long delay in the population's adaptive response to changing external conditions. The actual rate of growth, the nature of the adaptive response, and the length of the delay vary, depending on many factors in the total system. Over the last hundred years the global population has been characterized by an increasing rate of exponential growth and by a response delay as long as one or two generations. In this section we present evidence for these historical trends in terms of changes in the mortality and fertility rates that have been observed in most subsectors of the world's population.

Exponential Growth

When any biological population grows, the pattern of growth over time tends to be exponential. The human population is no exception. Figure 2-2 shows the estimated growth of the world population, from 1650 to the present, and its projected growth until the year 2000. In the twentieth century, rapid exponential growth has been exhibited not only by the global human population but by nearly every national and regional population as well. For example, Figure 2-3 illustrates the population growth, both past and projected, of several nations and groups of nations from 1920 to 2000. The rates of growth are variable, but the overwhelmingly dominant behavior mode is exponential growth.

The tendency for the growth of any animal population to be exponential follows directly from the fact that the source of additions to the population is the population itself. The total increase in the population during any time period must be at least partially determined by the size of the population of reproductive age in that time

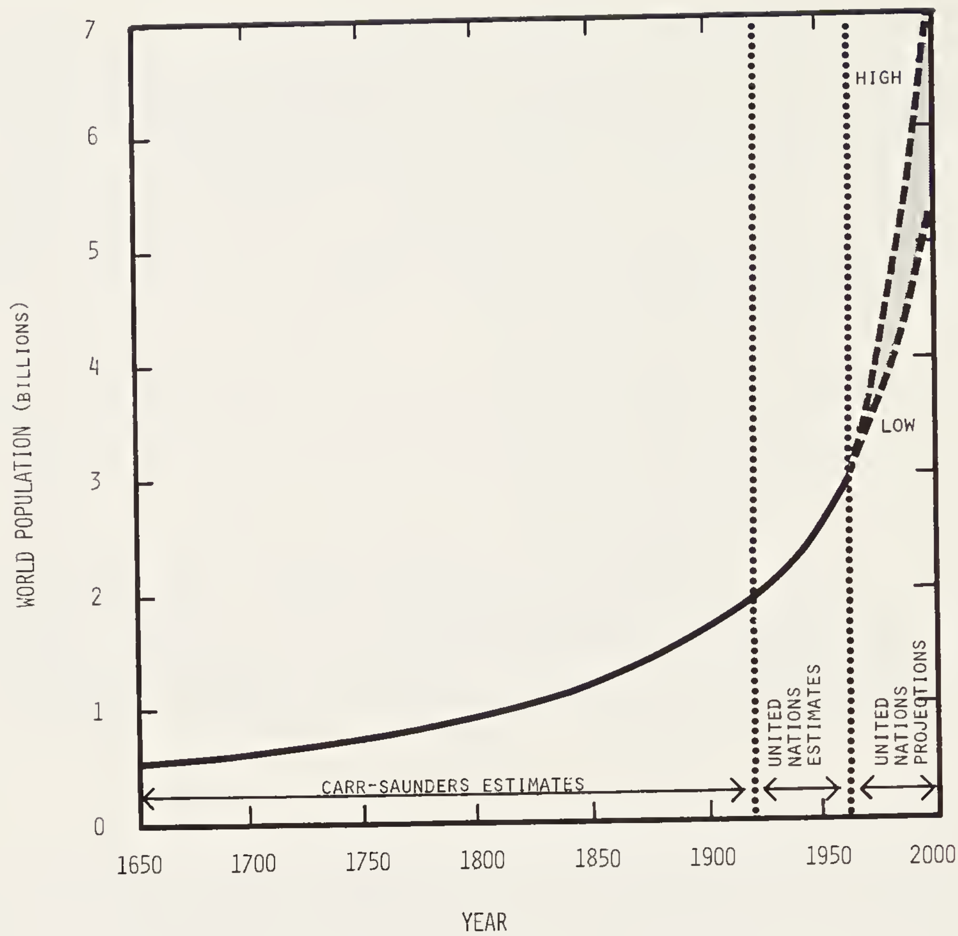


Figure 2-2 Global population growth, 1650–2000
Sources: Carr-Saunders 1936, U.N. 1966, U.N. 1972*a*.

period. Mathematically, the population increase can be expressed by the following differential equation:

$$\frac{dN}{dt} = rN$$

which states that the rate of change of the population, dN/dt, is proportional to the size of the population N. If the factor of proportionality r is constant, the solution to this equation is

$$N = N_0 e^{rt},$$

where N_0 is the initial population, N is the population at time t, r is the net population growth rate, and e is the base of the natural logarithm. The net growth rate r is usually not constant; it varies as a function of time, and the actual population growth is therefore not perfectly exponential in the strict mathematical sense of the word. However, human population growth is in theory, and in observed fact, a "positive feedback" exponential process. Past increases enhance the probability of further increases, unless strong forces from the rest of the system oppose the tendency toward growth.

For the global population, migration is not a factor. Thus the net growth rate r is

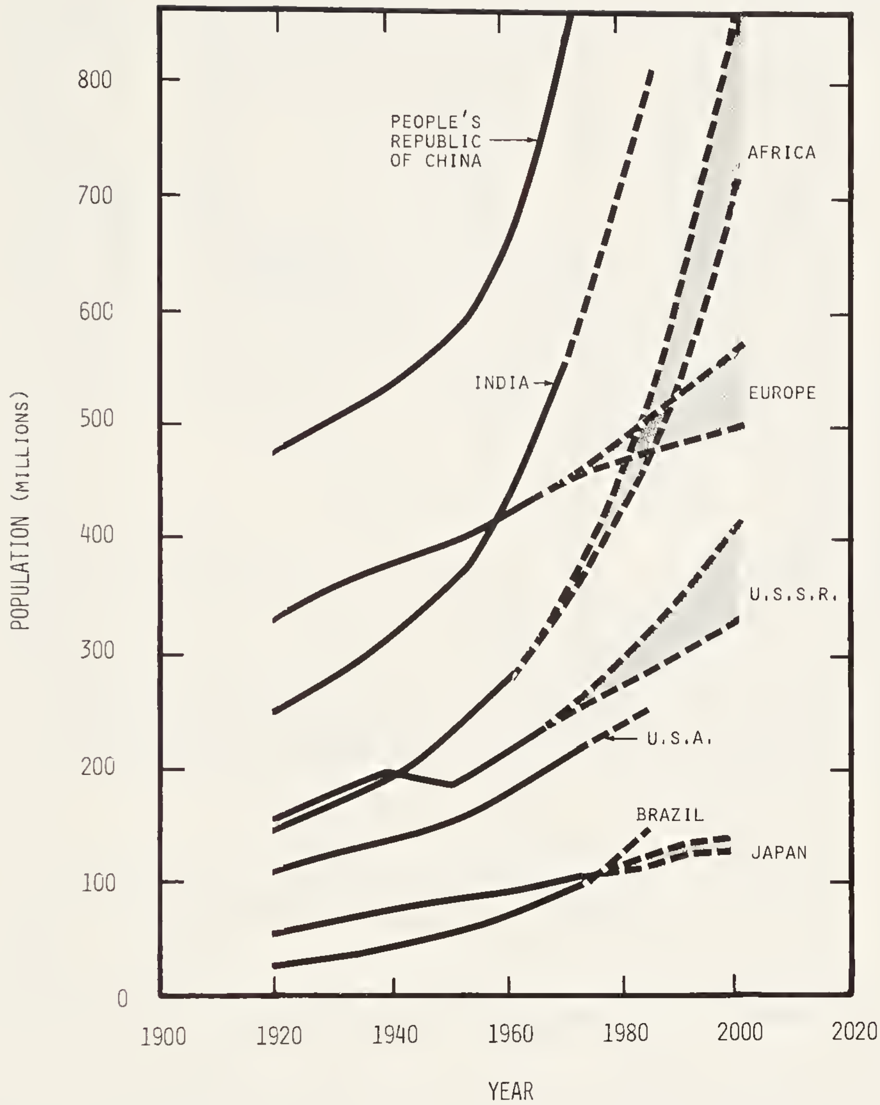


Figure 2-3 Regional population growth, 1920–2000
Source: U.N. 1966.

simply the difference between the birth rate B and the death rate D, both expressed as fractions of the total population:

$$r = B - D.$$

Demographers often refer to r, B, and D not as fractions of the population (for example, the birth rate was 0.02 of the population last year) but as percentages (2.0 percent of the population) or as ten times the percentages (20 per 1,000 persons in the population). The latter designation is called the "crude birth rate" (births per 1,000 persons per year) or the "crude death rate" (deaths per 1,000 persons per year).

The net growth rate could conceivably be positive (B>D, positive exponential growth), negative (B<D, exponential decay), or zero (B=D, constant population). Actual population growth rates have only rarely and temporarily been zero or negative, as Figure 2-4 indicates.

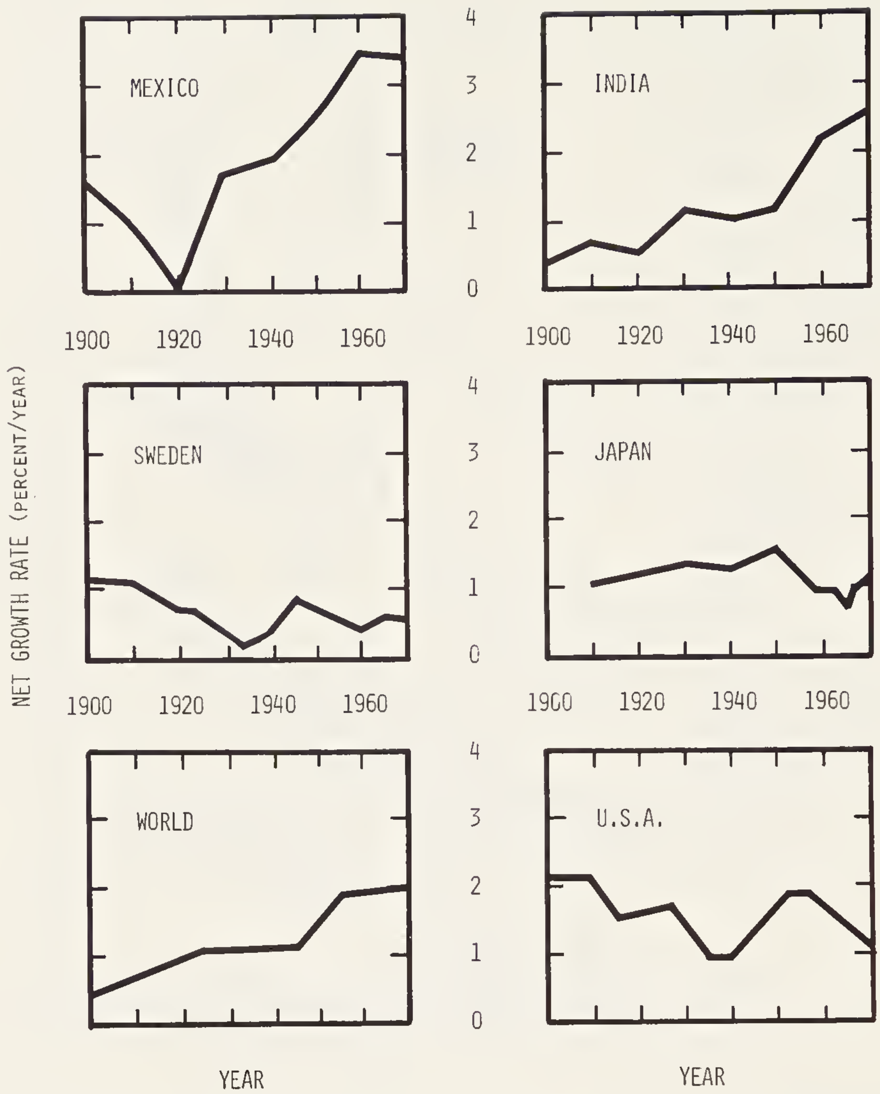


Figure 2-4 Regional and world rates of natural increase, 1900–1970
Sources: U.N. *DY,* Carr-Saunders 1936.

The total world population growth rate has been rising steadily since 1900, when it was about 0.6 percent per year (Carr-Saunders 1936). Its 1970 value was about 2.1 percent per year, or 21 per 1,000 persons per year (USAID 1971). If this rate of growth were to continue unchanged, the global population would double every 33 years.

To account for the increasing rate of growth of the world's population during this century, we must look for trends in worldwide birth and death rates that are sufficiently general to account for such a global change. We have identified three such general trends: falling mortality, intermediate fertility, and the correlation of fertility with industrialization.

Falling mortality Until very recently in human history, the death rate of human populations was high and erratic. Famines and epidemics, the results of seemingly uncontrollable environmental factors, randomly checked the population growth rate. As an example of prevailing mortality conditions before this century, in the Netherlands in 1840 one-fourth of all infants born died before the age of 2.5 years; one-half

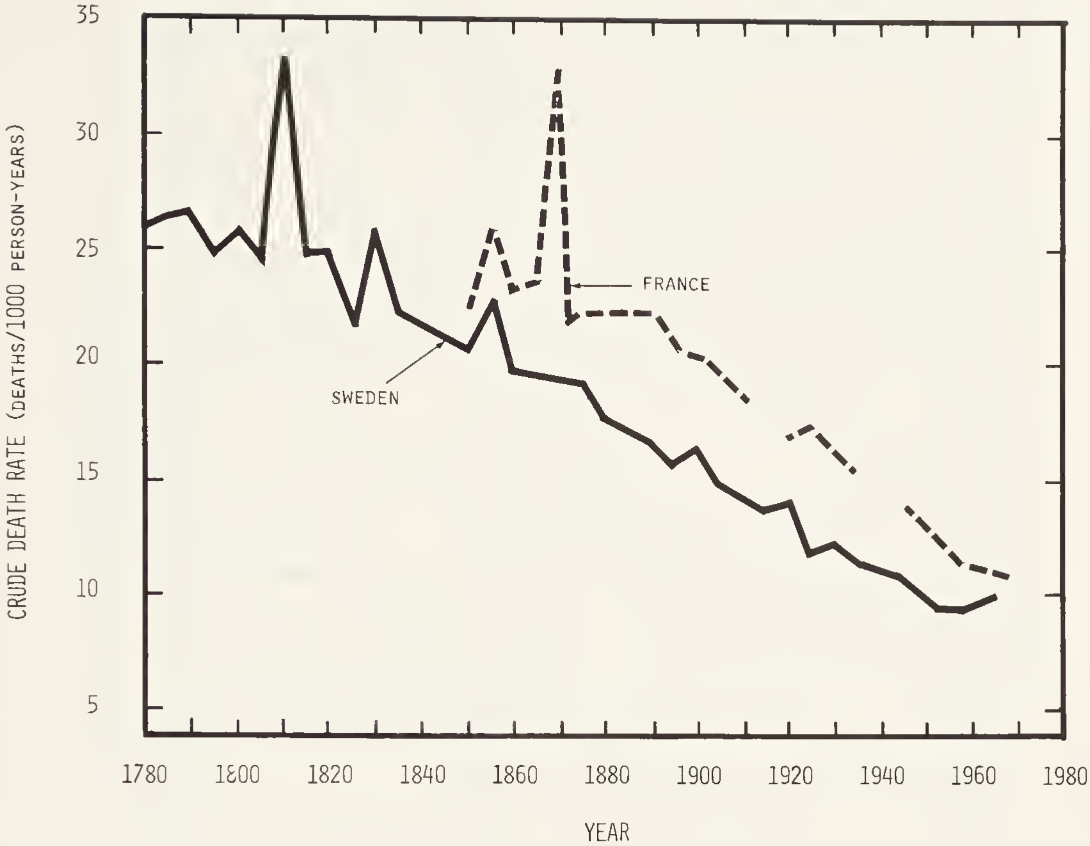


Figure 2-5 Crude death rates, Sweden and France, 1780–1965
Source: Keyfitz and Flieger 1971.

were dead by the age of 37.5 and three-fourths were dead by the age of 62.5 (Hauser 1969).

During the Industrial Revolution new technologies were gradually developed to control infectious diseases, improve nutrition, maintain a healthier environment and thus to reduce human mortality. The gradual impact of these technologies over time on the mortality rates of two Western nations is shown in Figure 2-5. The extent of this revolution in human mortality can be appreciated by comparing the statistics for the Netherlands given in the preceding paragraph with similar statistics for the same country 100 years later. In 1940, three-fourths of all infants born were expected to live to the age of 62.5 years, one-half to 72.5 and one-fourth to 82.5 (Hauser 1969).

In this century new methods of human death control have spread around the world, as indicated by the falling crude death rates and rising life expectancies illustrated in Figure 2-6.* Where social and economic conditions have permitted the introduction of improved agricultural and food distribution methods and modern medical advances, life expectancies have risen from a preindustrial average of about 30 years to an average of 70 years or more. In the nonindustrial countries this dramatic increase in life expectancy has occurred more recently and much more

*The life expectancy at birth e_0^o is a better measure of true health conditions in a population than the crude death rate, which is dependent both on health conditions and on the population's age structure. The crude death rate, on the other hand, is a direct input to the calculation of the immediate population growth rate. There is no simple relationship between life expectancy and the crude death rate, but they are generally inversely correlated.

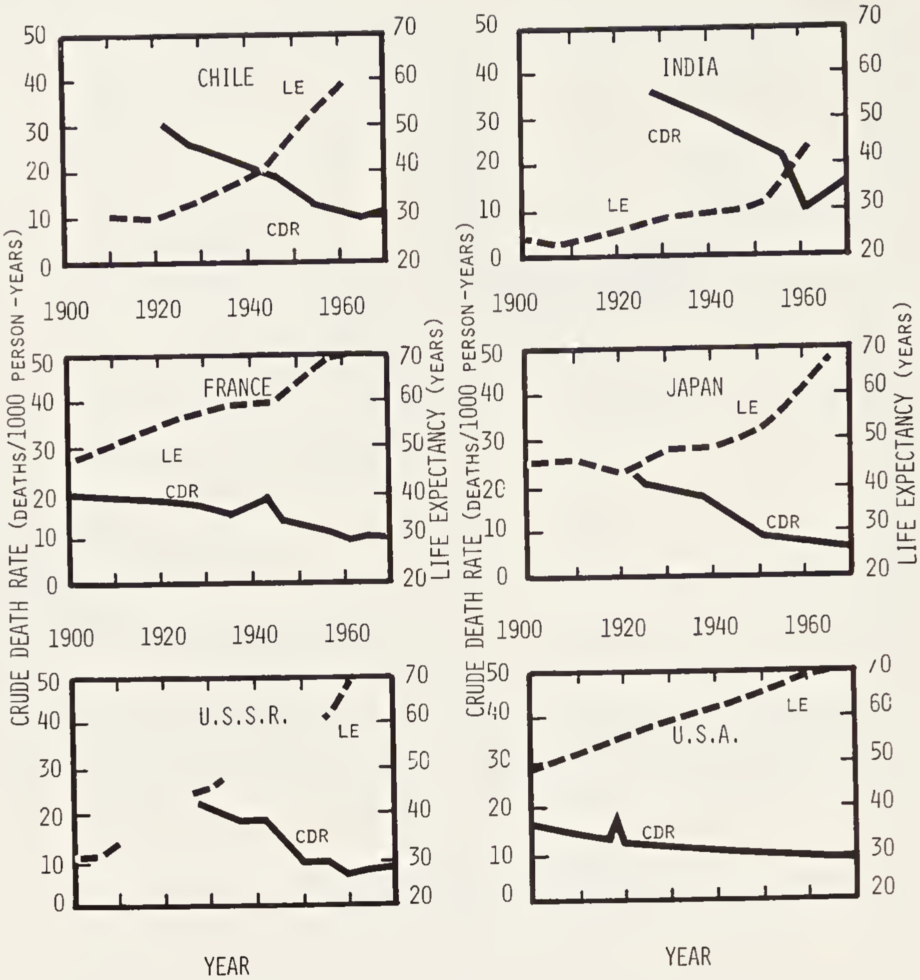


Figure 2-6 National crude death rates and life expectancies, 1900–1970
Sources: Bogue 1969; Keyfitz and Flieger 1971; Arriaga and Davis 1969, p. 223; U.N. *DY*.

suddenly than in the Western nations. The process is not yet complete; the world average life expectancy in 1968 was still only about 53 years (Population Reference Bureau 1968).

Intermediate Fertility Figure 2-7 shows the trends in crude birth rates for several countries. Although the birth rates in these countries vary considerably, several generalizations about aggregate fertilities can be postulated.

First, no country in the world exhibits a birth rate as high as the biological maximum. It has been estimated that the average maximum total fertility possible in a population is about 12 children per woman (see the discussion of maximum total fertility in section 2.5), which corresponds to a crude birth rate of approximately 88 births per 1,000 people per year.* All the birth rates shown in Figure 2-7 are

*Based on the assumption of an average 30 reproductive years per woman and an average fraction of reproductive women in the population of 0.22:

$$\frac{12 \text{ children}}{\text{woman}} \times \frac{1}{30 \text{ years}} \times \frac{0.22 \text{ woman}}{\text{person}} = \frac{0.088 \text{ children}}{\text{person-year}}$$

A more accurate table for converting total fertility to crude birth rates is given in Bogue (1969, p. 662). The highest total fertility shown there is 9.07 births per woman, corresponding to a crude birth rate of 65 per 1,000.

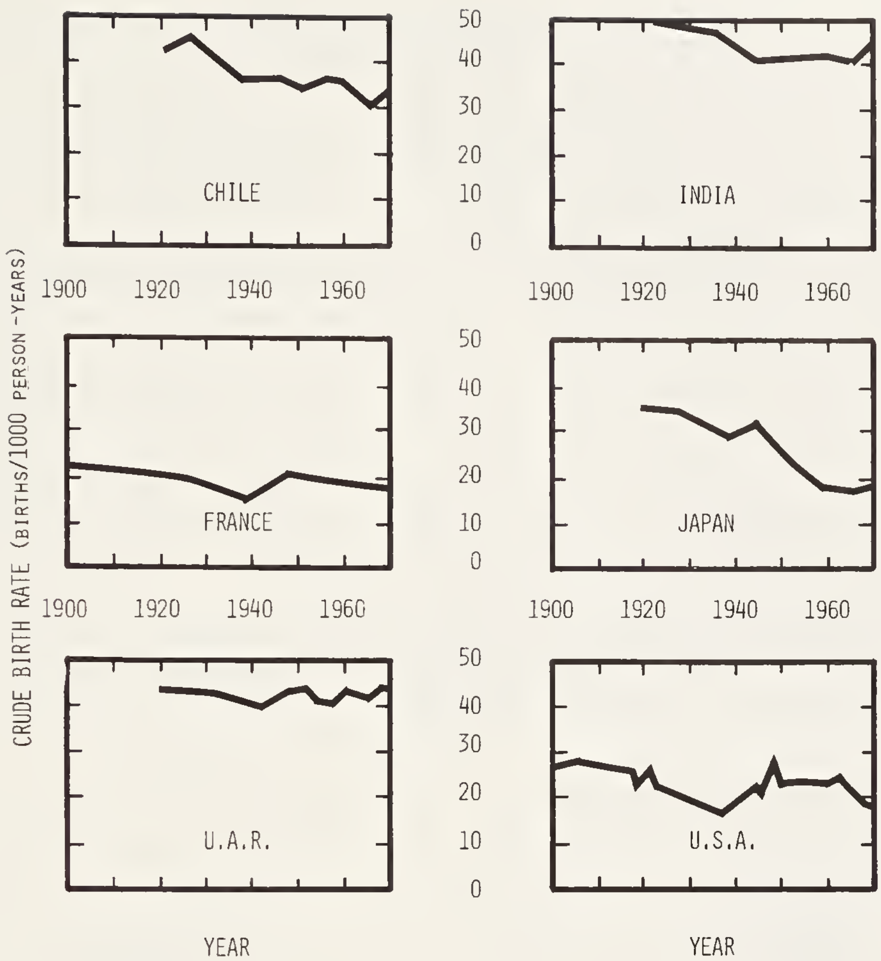


Figure 2-7 National crude birth rates, 1900–1970
Sources: Bogue 1969; Keyfitz and Flieger 1971; U.N. *DY;* Sen 1967, p. 410.

considerably below that number. In fact, it is rare for any population of significant size to sustain a crude birth rate as high as 60 per 1,000 per year. Some set of factors must be operating in every modern human population to keep the reproduction rate well below the biological maximum.

On the other hand, no large national population within recorded demographic history has sustained a fertility level low enough to stop positive population growth. In a population reproducing consistently and exactly at replacement level (an average family size of about two children under modern low-mortality conditions), the crude birth rate would be approximately 13 per 1,000. Although some European nations briefly approached replacement fertilities during the 1930s, and may be approaching them again in the 1970s, their fertility levels have not remained low enough long enough to produce a zero or negative population growth rate.

Thus historical trends indicate that biological or social factors in the present global population system operate to maintain birth rates at an intermediate level, with a minimum somewhat above the replacement level and a maximum well below the maximum level biologically possible. During this century the world's average crude birth rate has tended to decrease slightly, but it has probably never gone above or below the intermediate range of 30–40 births per 1,000 persons per year.

Correlation of Fertility with Industrialization Since the Industrial Revolution the fertility of populations and their average level of industrialization have been strongly and inversely correlated. The relationship between present crude birth rates and average values of GNP per capita for various nations of the world is illustrated in Figure 2-8.* Apparently, as nations industrialize, new forms of labor utilization, human settlement patterns, health care, and material comforts cause numerous social adjustments within the family. The net effect of these adjustments is to decrease the average birth rate. Although individual variations occur in the timing and extent of this effect, there have been no significant exceptions to the general pattern. The correlation was noted by observers of population changes in the eighteenth century, and it has been extensively documented for subpopulations within nations as well as across nations since 1900 (U.N. 1953, p. 86).

The empirical correlation between increasing GNP per capita and decreasing birth rate is obvious, but it does not imply anything about the direction of causation

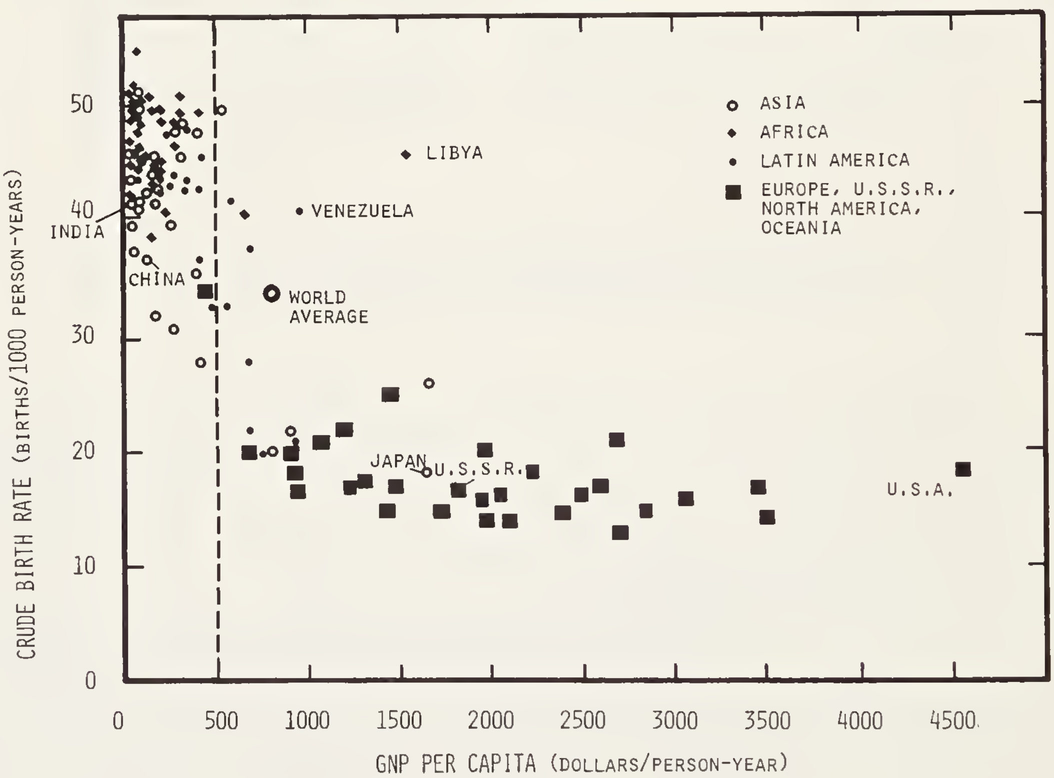


Figure 2-8 Crude birth rates versus GNP per capita, 1971
Source: USAID 1972.

*Data for plotting this and all other cross-sectional graphs in the population sector are summarized in Appendix D to this chapter. Although GNP per capita is not a very good measure of industrialization, it is generally the only measure available. For a discussion of the relationship between GNP per capita and industrial output per capita, see Chapter 3.

of this phenomenon. Plausible arguments have been advanced to demonstrate that higher incomes cause lower birth rates and that lower birth rates cause higher incomes. In fact, both arguments may be correct. As we shall discuss later, birth rate and industrialization are probably related through several different feedback loops. Thus fertility and industrialization may influence each other in many ways, and causal links may actually operate in both directions. A collection of data such as that plotted in Figure 2-8 only captures the state of this complex system at a particular time and can tell us little about the underlying causal structure.

Delayed Response

Demographic responses to new external conditions, through changed birth and death rates, are often significantly delayed. The two major sources of the delay are the age structure of the population and the inherent slowness of social change.

Population Age Structure It takes at least 15 years for a newborn child to mature and become a parent. There is a delay of more than 50 years before the child reaches the ages of highest probability of death. These obvious facts have profound implications for the dynamics of population growth. The long delays inherent in the biological processes of maturation and aging give every human population a strong momentum—a tendency to keep following the same dynamic behavior it has followed in the past. Because of that momentum, a population that has been growing rapidly will continue to grow for decades, even after fertility has fallen to the equivalent of two surviving children per married couple. Similarly, a population that has experienced fertility lower than the replacement level may continue to decrease for some time after fertility has again risen to the replacement level.

A population has momentum because it retains in its age structure a living ''memory'' of its past demographic history. A population's age structure is defined as the relative number of people in each age group. Population age structures can vary greatly, as illustrated by the different population pyramids in Figure 2-9. The shape of a population pyramid is determined by the past birth and death rates of the population, the very top of the pyramid reflecting the birth rate of 70 or more years ago as well as the cumulative death rate over the past 70 years. If the birth rate has been consistently high, the pyramid is a broad-based triangle, with many more young people than old people, as illustrated by the age structure of Peru in Figure 2-9. If the birth rate has been low, the number of people in each age group becomes more even, since each generation tends just to replace itself. An example is the population pyramid of the United Kingdom. If there have been wide swings in the birth rate or events such as wars that have had a great impact on the death rate of specific age groups, the age structure can be quite uneven, as the pyramids of the United States and West Germany demonstrate.

The age structure is both a result of the past birth and death rates of a population and a partial determinant of future birth and death rates. The number of births in any year is a function of two things: the average fertility of each woman of childbearing age (roughly 15 to 45 years), and the total number of women of childbearing age in the population. Peru's population pyramid indicates that every year for at least fifteen

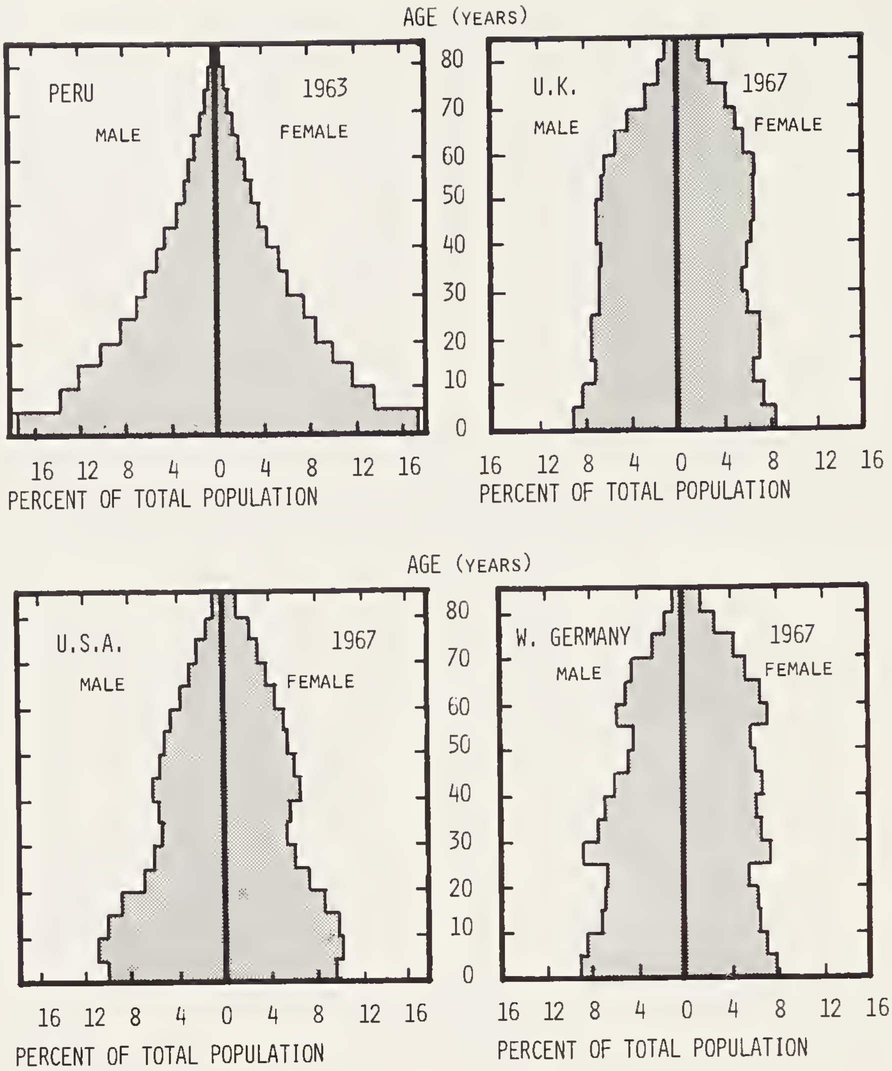


Figure 2-9 Population age structures
Source: Keyfitz and Flieger 1971.

years more women will reach the age of puberty than the age of menopause. Thus, even if the average fertility should fall tomorrow, it would be largely counterbalanced by the increasing number of women experiencing that lower fertility. The population would still continue to grow for many years, even if the average fertility of each woman were at the replacement level. Figure 2-10 illustrates the effects of population momentum on hypothetical future population trends in India and the United States under varying assumptions of declining fertility.* It is clear that a high rate of fertility in the past makes it more difficult to slow population growth through future declining fertility:

> Populations that are growing rapidly have by virtue of that growth, age distributions favorable to reproduction. Even if fertility falls to a stationary level, such regions continue to grow for at least 50 years before tapering off to their stationary

*Note that the time required for the population to reach equilibrium after replacement fertility has been attained is nearly constant. The percentage increase in the population during that time is greater for the population with a young age structure.

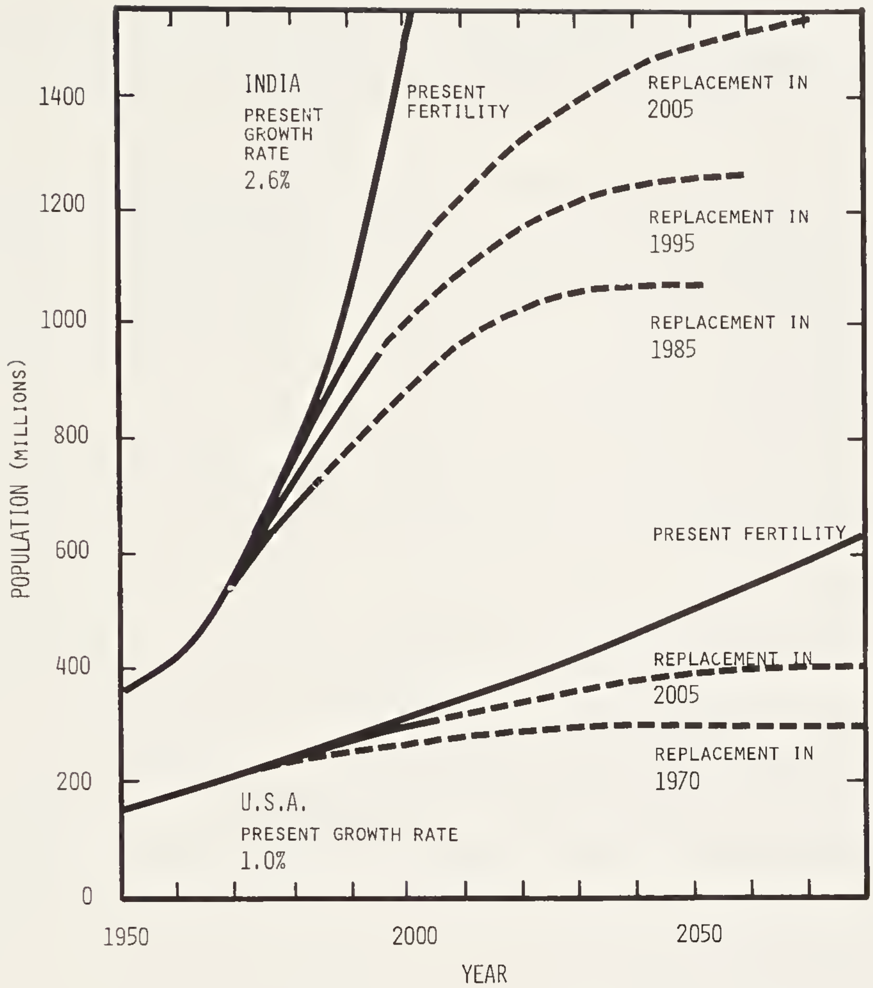


Figure 2-10 Population momentum, the United States and India, 1950–2050
Sources: Frejka 1968, Population Reference Bureau 1970.

> value at 60 percent or more above the present numbers. If the adoption of the stationary birth rates is postponed even as little as 15 years, the increase to stationarity would be not 60 percent but nearly 150 percent. [Keyfitz 1971*b*]

The age structure of the population affects the future death rate as well as the birth rate. The number of deaths depends both on the average mortality risk at each age and on the number of people of that age. The probability of death as a function of increasing age is highly nonlinear in all populations. Except for the first few years of life, the mortality risk increases significantly only at very high ages. A population with a relatively large fraction of older people, as in Great Britain, will have a relatively high crude death rate even though its general health conditions are excellent. Many nonindustrialized populations have poorer health conditions and lower life expectancies than industrialized populations, but their crude death rates are lower because the proportion of young people in their populations is extremely high. Thus a country with a history of high fertility and a young population will have a double impetus toward high population growth rates in the future. First, its crude birth rate will tend to be high because of increasing numbers of fertile people; second, its crude death rate will be low because of a low proportion of older people. In the short run, such a country will have to make a proportionately greater reduction in individual fertility to reduce its population growth rate than would a country with an older population age structure.

Social Change Another important delay in population systems is the slow adjustment of social institutions, including the family, to changing external conditions. The primary evidence for this slow adjustment comes from data on the demographic transitions of various countries, to be discussed later. However, several observers have also reported such a delay on the basis of personal experience with the changing social norms of specific populations.

> Taiwan had a history of slowly but steadily declining mortality under Japanese rule, followed by very rapid mortality decline after the war. Average life expectancy is now more than 60 years. The probability has been high for some time that almost all children will survive to adulthood. . . . Under present mortality conditions in Taiwan a single son is very likely to survive to adulthood, so having additional sons as "insurance" is probably an anachronism, but the traditional preference for several sons persists. The family size and sex composition being sought are approximately what a traditional Chinese family might have achieved with luck under high mortality and high fertility. . . . [Freedman 1963]

> Karimpur's village companions have achieved marked success with their farming demonstrations, but have been able to accomplish much less where their suggestions for change touched domestic routine and relations among people. The slower response in matters of social organization is not unusual in the history of mankind—social patterns are generally less amenable to change than technological patterns. [D. G. Mandlebaum in Wiser and Wiser 1963]

> The supposed resistance of factors of high fertility to social and economic changes is also borne out by the observation that the levels of fertility, in most high-fertility areas, do not appear to have changed very much during recent decades, in spite of considerable progress in health and education, and of accelerating urbanization. [U.N. 1965, p. 6]

Slow social adjustment to changing conditions is certainly not limited to matters of reproduction. It probably occurs whenever an alteration in an accepted mode of behavior diffuses throughout a society. The apparent period of delay between the stimulating change and the ultimate response is actually a time of great dynamic activity within the society, when all the steps leading to a final observable behavioral change are carried out. These steps may include (1) perception of the new environmental conditions, (2) diagnosis of a problem, (3) identification of a suitable response, (4) confrontation with interest groups defending the status quo, and (5) integration of the response into reinforced social patterns. Donald Bogue has described the probable sequence of changes required before a population can adjust its birth rate to a new, lower death rate:

> If death rates fall, the population must sense the fact by realizing that average family size is increasing. Merely attaining this awareness would require a period of several years. . . . Next, the implications of this change for individual and group welfare must be appreciated, and defined as undesirable. Finally, some socially acceptable solution (mode of fertility control) must be devised, diffused throughout

> the population, and adopted as socially acceptable behavior. Even under the most favorable circumstances substantial time would be required for a population to go through these steps. If there are strong forces resisting the regulation of fertility, the process is slowed even more. [Bogue 1969, p. 52]

In the case of changes in the birth rate the social adjustment delay may be particularly long, for at least three reasons:

1. A change in reproductive habits must be practiced consciously by a majority of the population before an observable aggregate response can be generated. Universal acceptance is not so necessary for many death-control changes, such as purifying public water supplies or spraying for disease vectors, for these changes require the participation of only a small administrative and professional corps.
2. In many cultures, reproductive matters are not considered an acceptable topic for public discussion. Therefore, the message promoting change and any new techniques (such as contraception) facilitating change must be spread through individual rather than mass communication channels.
3. Strong forces that tend to resist change in reproductive patterns are already built into every social system in the form of the family itself.

> Individuals who are socialized in families will be likely to want families themselves, to enforce norms and sanctions regarding families, and to take pleasure in acting out familial roles. This means that the family complex is itself a goal—the utilities represented by children are not merely economic or affectional, but socially structured in a powerful manner. [Blake 1965]

Although the existence of a relatively long delay in the reproductive response to changing environmental conditions does not imply that social norms regarding reproduction are totally rigid, it does suggest that they change only slowly, probably over several generations. This slow response is usually a source of system stability, ensuring a fairly steady renewal of the population regardless of sudden, random environmental fluctuations. Conditions under which the long response delay may cause instability are discussed in section 2.6 and in Chapter 7.

The Demographic Transition

The "demographic transition" (Notestein 1945) is the change over time of birth and death rates as a population undergoes the process of industrialization. The pattern of this transition has so far been roughly similar for all nations that have become industrialized. Examples are shown in Figure 2-11 as a function of time and in Figure 2-12 as a function of rising GNP per capita. The demographic transition tends to follow four successive stages as per capita income increases (Heer 1968, p. 10):

1. High, irregular death rate, high birth rate, very slow rate of population growth.
2. Rapidly declining death rate, slowly declining birth rate, increasing rate of population growth.
3. Slowly declining death rate, rapidly declining birth rate, decreasing rate of population growth.
4. Very low, stable death rate, low but fluctuating birth rate, slow to moderate rate of population growth.

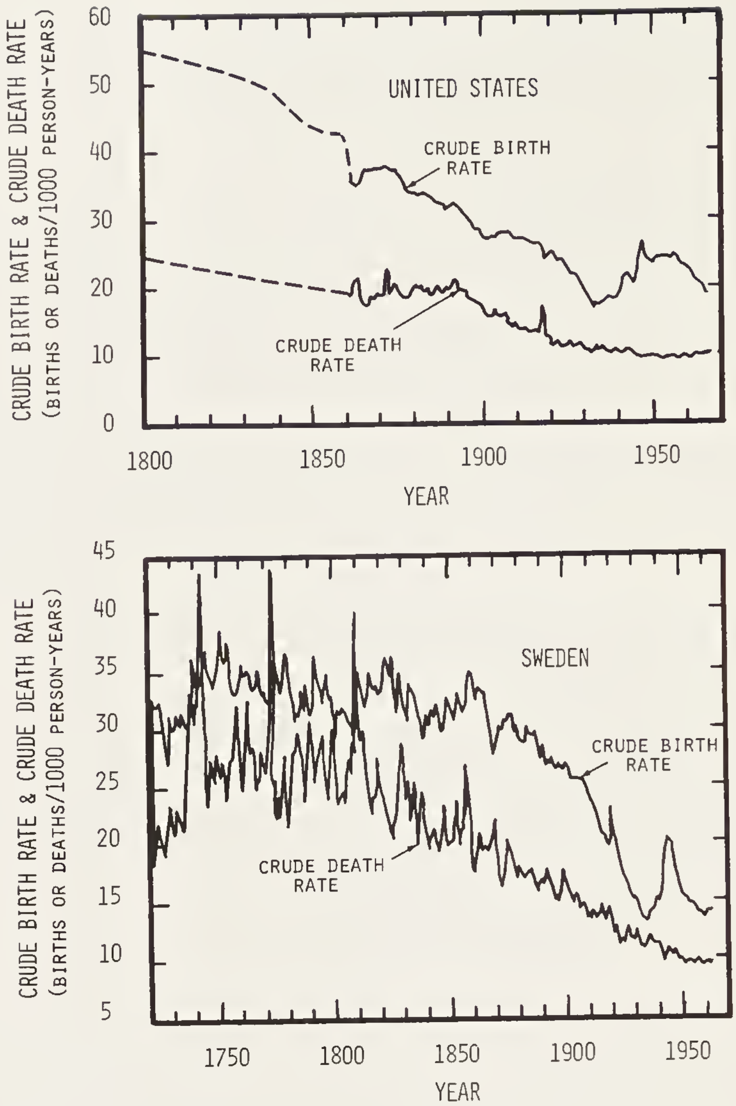


Figure 2-11 Demographic transition versus time, Sweden and the United States
Source: Bogue 1969.

The demographic transition is a complex manifestation of several dynamic population characteristics discussed here—decreasing mortality and fertility as industrialization proceeds, and significant delays in the adjustment of fertility rates to changing mortality rates and economic conditions. Although the pattern has been consistent in the countries that have already industrialized, several other patterns are theoretically possible. One, in particular, may be occurring now in some parts of the world. As shown in Figure 2-13, exportation of death-control techniques from the industrialized countries to some nonindustrialized ones has brought about a major decrease in death rates at a much earlier stage in the industrialization process than that which prevailed at the onset of the demographic transition in Western countries. There now appears to be little correlation between economic development and death rates, expecially in countries with per capita GNP values below 500 dollars. This deviation from the historical pattern could conceivably either hasten or postpone the declining birth rates that would complete the demographic transition in these countries.

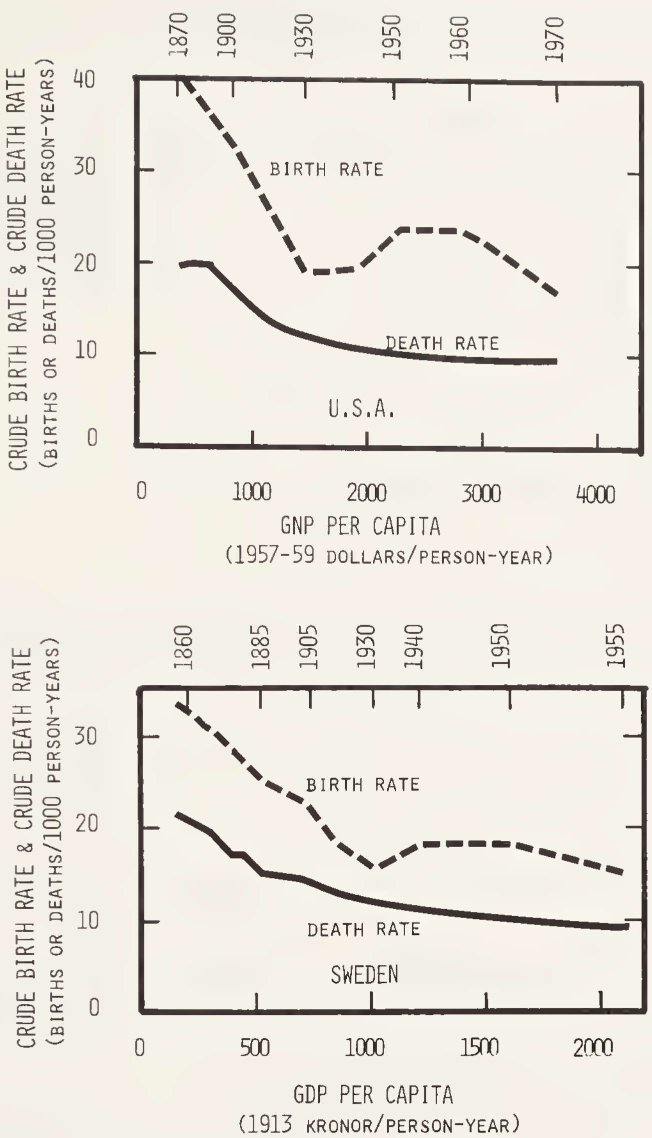


Figure 2-12 Demographic transition versus GNP per capita, Sweden and the United States
Sources: U.S. 1960, Johansson 1960, U.N. *DY*.

Although the historical relationship between industrialization and the death rate now appears to have changed, it is still possible to classify different populations of the world in terms of the various stages of demographic transition. The results of such a classification, shown in Figure 2-14, indicate that most of the world's populations have moved to the stage at which death rates have fallen but birth rates are still at or near their traditional high levels.

2.3 BASIC CONCEPTS

The determinants of human birth and death rates are as numerous and diverse as the cultural, economic, and environmental systems that form human experience. Therefore, any population model that tries to include each separate determinant soon

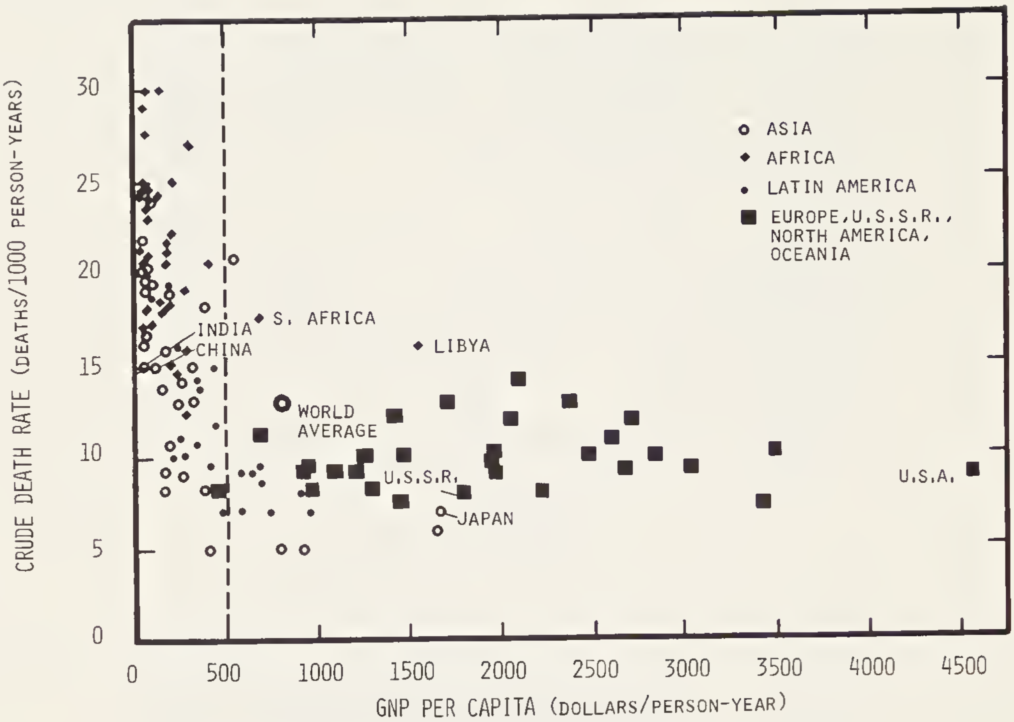


Figure 2-13 Crude death rates versus GNP per capita, 1971
Source: USAID 1972.

BIRTH RATE	DEATH RATE: LOW 5-20 PER THOUSAND	DEATH RATE: HIGH 20-40 PER THOUSAND
LOW 13-25 PER THOUSAND	28% OF WORLD POPULATION 0.7% ANNUAL AVERAGE NET GROWTH RATE (EUROPE, NORTH AMERICA, U.S.S.R., OCEANIA, JAPAN)	0%
HIGH 30-60 PER THOUSAND	57% OF WORLD POPULATION 3.0% ANNUAL AVERAGE NET GROWTH RATE (ASIA, LATIN AMERICA)	15% OF WORLD POPULATION 2.0% ANNUAL AVERAGE NET GROWTH RATE (TROPICAL AFRICA, PARTS OF ASIA)

Figure 2-14 Percentage of world population at various stages of the demographic transition
Source: Keyfitz 1971*b*.

becomes hopelessly confusing. By definition, a model is a simplification. This population model simplifies the population system by grouping all the factors that might possibly influence birth and death rates into logical, comprehensible categories of functional significance. The organizational scheme used in the World3 population sector is described generally in this section. The next two sections (2.4 and 2.5) show how this scheme was incorporated into the world model, initially as a structure of interlocking feedback loops, then as precise mathematical equations.

First, we distinguish between the demographic and the external determinants of birth and death rates (Figure 2-15). The demographic determinants arise from the

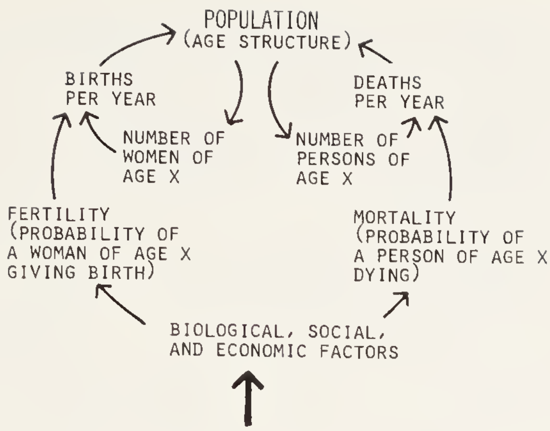


Figure 2-15 Demographic and external determinants of birth and death rates

population age structure, and thus they are themselves determined by past birth and death rates. The demographic determinant of the total number of births in any given year is the total number of women of each age in the population. The demographic determinant of the number of deaths each year is simply the number of persons of each age in the population.

Each demographic determinant is multiplied by an external determinant, the fertility or mortality, that reflects all the socioeconomic influences on the vital rates. The fertility is the probability that each woman of childbearing age will actually give birth. The mortality is the probability that a person of any given age will die.

What logical categories can be perceived in the many external determinants —biological, social, and economic—that affect fertility and mortality? It may be useful to distinguish between the voluntary factors that result from human intentions, desires, and goals and the involuntary factors that result from biological or physical constraints. For example, the fact that female fertility is essentially zero below age 15 and above age 50 is an involuntary, biological restraint on fertility. The fact that the Indian government disseminates literature and signs promoting the two-child family is a social input to the voluntary component of fertility. This simple voluntary-involuntary dichotomy is incomplete, however, because it gives no indication of the actual balance between the voluntary and the involuntary factors. Thus it is necessary to include a third category—the factors of control that a population can use to attain its fertility and mortality goals. Functionally, the control factors mediate between the voluntary and involuntary factors and determine how effectively a population can achieve its desired fertility and mortality rather than those imposed by nature. The factors of control are primarily technologies such as contraceptive techniques, public health services, and medical procedures.

The general classification scheme used in World3, shown in Figure 2-16, is based primarily on the voluntary-involuntary distinction just described, but with some significant modifications.

The three inputs to fertility in Figure 2-16 are the desired fertility (voluntary component), the maximum fertility (involuntary component), and the fertility control effectiveness (control factors). The desired fertility is that which would be observed if

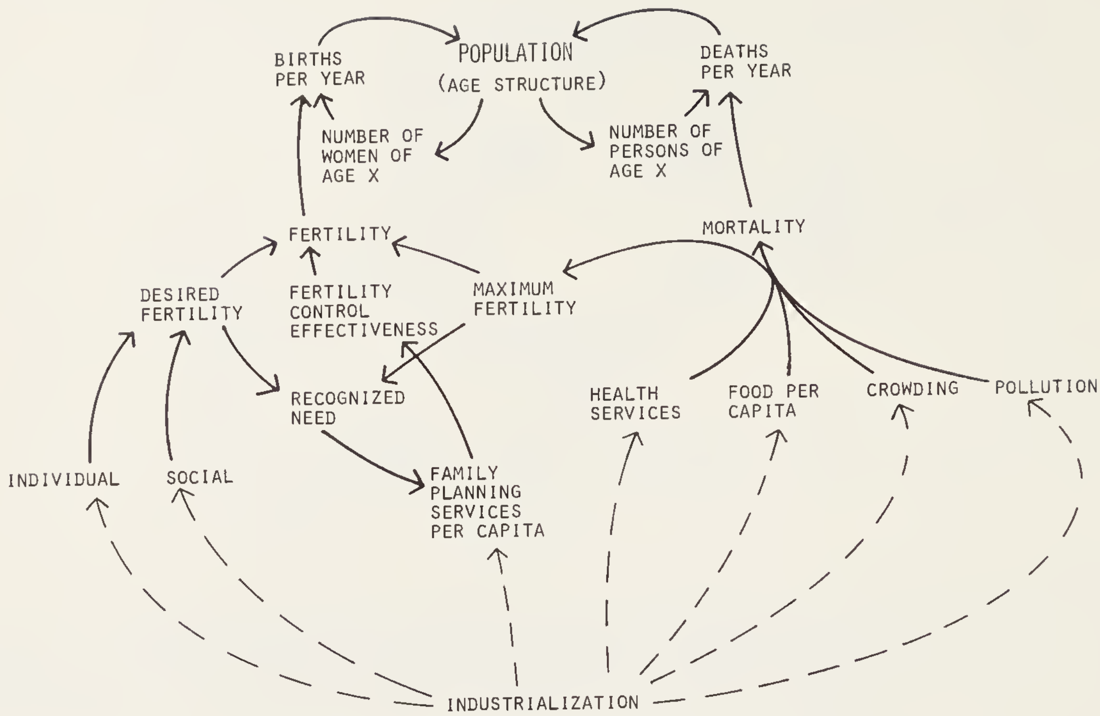


Figure 2-16 External determinants of birth and death rates

the population had perfect control over the reproductive process and produced children only when and always when desired. The maximum fertility is the fertility that would be observed if the population took no measures of any kind to reduce or restrict the fertility of any woman from menarche to menopause; it is the biological upper limit. Fertility control effectiveness indicates the extent to which a population can achieve its desired fertility rather than its maximum fertility, by any means, including late marriage, contraception, and abortion.

Each of these three inputs to fertility is itself responsive to many factors in the social and economic environment. For example, the desired fertility might be considered a function of two further categories of influence: the social norm with regard to fertility, and the average individual response to this social norm. Each category is described in more detail in the section on model equations (2.5). Because maximum fertility is related to the average state of health, it is influenced by all the factors that influence the mortality side of the model. Fertility control effectiveness is assumed to arise from two necessary elements: a socially recognized need for birth-control technology, and an investment in the research, manufacturing, and educational capabilities to develop that technology. Thus fertility control effectiveness, like all technological factors, has a voluntary component. It will not be developed if there is no need for it.

The determinants of mortality might also be segregated into voluntary, involuntary, and control categories. Involuntary or maximum mortality would be the mortality expected if no technologies of control were available beyond those practiced by a primitive hunting-gathering society. Desired mortality would express the social mortality goal. Mortality control techniques, like those of fertility control, may be assumed to arise from two factors: a perceived gap between desired mortality and maximum mortality, and an allocation of resources to mortality control technology.

In World3, desired mortality and the social need for mortality control are not represented explicitly. Instead, we assumed that desired mortality is constant and sufficiently low (perhaps zero) so that the social impetus for developing mortality control techniques is always present. Thus the only dynamic influence on the development of mortality control is the necessary investment in research and health service capital, represented in the model by health services per capita. Two other factors, pollution and crowding, represent the possible effects of the environment on the biological, involuntary aspects of mortality. The fourth input to mortality, food per capita, can be influenced by man's technology for the purpose of reducing mortality, but if it reaches very low values, it can have a major effect on involuntary mortality.

As indicated in Figure 2-16, the process of industrialization affects in some way all the mortality-fertility determinants we have mentioned. Industrialization has been a dominant agent in changing the human environment and the population growth rate in the recent past, as the demographic transitions of the industrialized countries have illustrated. It will continue to be a strong dynamic force in the future, for those transitions are far from complete throughout the world. The growth of industrial capital is generated by the other sectors of the world model, so for the purposes of this sector we assume that it is exogenously determined. When we simulate the behavior of the population sector we drive it with assumptions about the development of industrialization as a function of time.

Many influences on fertility and mortality have been suggested, in addition to the ones shown in Figure 2-16 (see, for example, Adelman and Morris 1966, Davis and Blake 1965, Friedlander and Silver 1967, and Mason et al. 1971). Several factors were omitted from the model because they fell into one of the following categories:

1. Factors that will remain relatively constant over the time span of the simulation (genetic variation, climate).
2. Factors that are strongly covariant with a factor already included (education).
3. Factors that result from primarily discontinuous and partially random processes (wars).
4. Factors that do not appear to have a statistically significant effect on population dynamics on a worldwide scale (religion, sexual mores).

2.4 CAUSAL STRUCTURE

In summary, the global population trends we are trying to capture with a dynamic model are:

1. All populations tend to grow exponentially, although the exponential growth rate is variable.
2. Mortality rates have fallen dramatically in this century.

3. Aggregate human fertility rates have historically been lower than the maximum possible rate and higher than the replacement rate.
4. Fertility tends to be inversely correlated with the level of industrialization.
5. Populations alter their reproductive behavior only very slowly in response to changing external conditions.

Some of the basic causal assumptions upon which the population sector is based are simple demographic definitions. Others are widely accepted general statements about human motivations. Still others are postulates, suggested by observers of population behavior; these postulates seem to be consistent with available data but cannot be directly proved or disproved at this time. Each assumption is discussed in more detail when the equation expressing it is presented in the next section (2.5). The basic assumptions may be summarized as follows:

1. The number of births each year is a function of the number of women of reproductive age in the population and the average probability of each woman giving birth that year (the average fertility).
2. The number of deaths each year is a function of the total number of people in the population and the probability of each person dying that year (the average mortality).
3. Average fertility depends on involuntary factors (maximum total fertility, or fecundity), voluntary factors (desire for a given average number of children), and the means available for achieving the voluntary goal (fertility control effectiveness).
4. Maximum total fertility (fecundity) is limited by the same factors that limit the general health of a population, especially the availability of health services and food.
5. Average desired family size is determined in part by the prevailing social norms with regard to families and in part by the average individual's response to those norms.
6. Any society's family size norm depends upon a complex of cultural and environmental factors that influence the perceived social and economic advantages and disadvantages of childbearing. Since any change in this norm must be endorsed by the society as a whole, the social norm shifts gradually, rather than quickly, as the environment changes.
7. Individuals and families do conform to the norm expected of them by society, but only to the extent permitted by their own perceptions and expectations of their personal resources for bringing up children. These expectations may shift relatively quickly.
8. Under conditions of a high perceived child mortality, families will produce extra children beyond the number ultimately desired to compensate for the risk of losing children.
9. Effective, low-cost methods of fertility control will be developed by a society if there is a perceived need for such methods and if sufficient economic resources are available to invest in developing them. In every society—even the most primitive—effective, but high-cost, fertility control methods are already available.

10. The average mortality of a population is also a function of involuntary factors, voluntary goals, and the means to attain those goals.
11. A goal of every human society is to keep its own mortality as low as possible. Therefore, there is always a recognized need for mortality control.
12. The primary mortality control methods are public health and medical technologies and improved means of food production and distribution. All these methods also require the investment of scarce resources from the economic system.
13. Possible factors influencing involuntary mortality are pollution, crowding, and lack of food.

The complex of feedback loops that joins all these assumptions is shown in Figure 2-17. This figure is derived from the classification scheme of Figure 2-16, but it includes, in addition to environmental influences on the population, the return influences of the population on the environment. Each single arrow in the diagram stands for one causal relationship, the direction of the arrow indicating the direction of causation. The arrows imply nothing about the quantitative nature of the relationship; they only indicate that some causal influence is acting there. The influence may be strong or weak, delayed or immediate, linear or nonlinear. The small + or − sign at the arrowhead indicates whether we believe the influence is positive or negative. The heavy arrows indicate inputs from other sectors of the world model. They are explained fully in the following chapters.

The two interlocking feedback loops, one positive and one negative, at the center of the population sector express the demographic relationships common to all population systems. They are shown separately in Figure 2-18. (In this and the

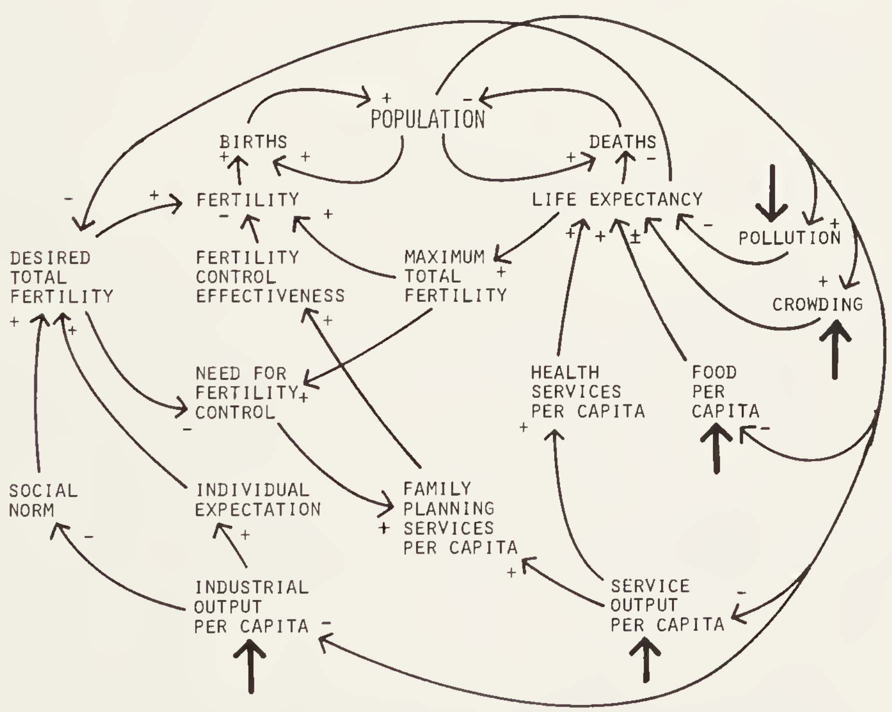


Figure 2-17 Population sector feedback loops

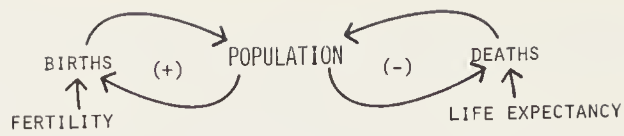


Figure 2-18 Demographic feedback loops

following figures the (+) and (−) signs in parentheses indicate the polarity of entire loops rather than of single relationships.) The positive loop on the left in Figure 2-18 expresses the tendency of every population to grow exponentially: the more births in the population each year, the larger the population; the larger the population, the more fertile people there will be; the more fertile people at any given level of average fertility, the more births there will be. Thus this loop, acting at any fertility level above replacement, generates an increasingly larger population as a function of time.

The negative loop on the right side of Figure 2-18 tends to counteract the exponential growth generated by the positive loop. At any given average life expectancy, the more people in the population, the more deaths there will be each year. The more deaths there are, the fewer people there will be the following year.

The relative strengths of the two loops depend on the average fertility, the life expectancy (which is a compendium of the average mortality at each age), and relative delays within each loop. The delays, caused by the population age structure, can be significant (15–70 years). If the strengths of the two loops are exactly equal, the population level will be constant; the size of the population will not change as time progresses. If the positive loop is stronger than the negative one, the population will increase exponentially. If the negative loop is dominant, the population will decrease exponentially.

Figure 2-19 shows the causal relationships that influence life expectancy in the world model. Life expectancy is a function of four factors: health services, food per capita, pollution, and crowding. Each factor affects the size of the population through a negative feedback loop; that is, each tends to act as a regulator to stabilize population by counteracting either an increase or a decrease in the population.

For example, let us trace through the operation of the feedback loop involving food per capita. If the population increases suddenly and no other change occurs in the system, the amount of food available per person will decrease. That decrease in available food in turn tends to decrease the average life expectancy somewhat, thus increasing the number of deaths in the population. With more deaths, the population level will tend to decrease, and the initial rise in population will be opposed. The loop also works in the opposite direction: a population decrease will result in more food per capita and an increase in life expectancy, thus tending to oppose the initial population decrease. The effectiveness of this population-regulating loop is highly variable. It has an important effect when average food per capita is close to the subsistence level, and it has virtually no effect when there is a large food surplus.

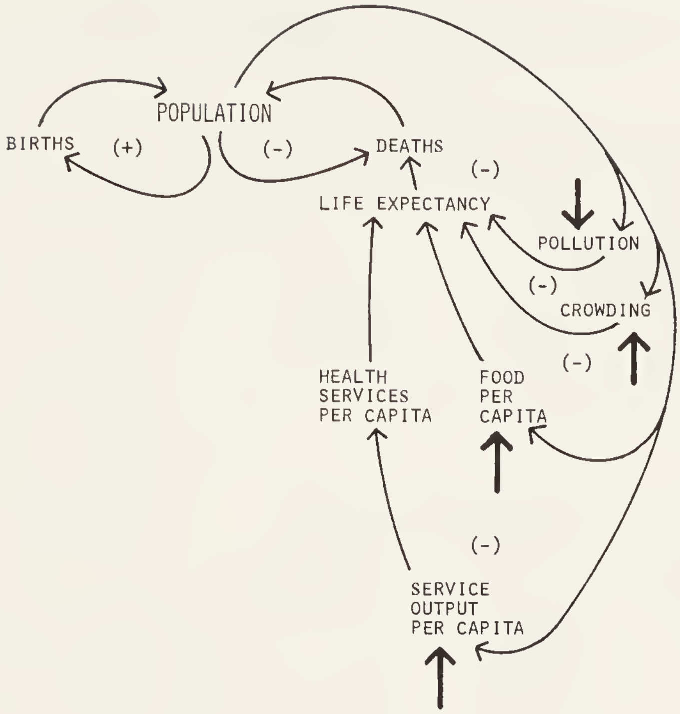


Figure 2-19 Feedback loops through life expectancy

Furthermore, the action of this loop is mediated by all the other interlocking loops in the system. For example, a larger population could also provide more labor to produce more food, leading to an influx of food (through the heavy arrow from the agriculture sector) sufficient to counteract this negative loop.

The negative feedback loops through health services per capita, pollution, and crowding* act on population in a similar way. Thus the human population is stabilized through the death rate by five negative feedback loops. One loop stems from the population age structure itself: the other four act through the external conditions of crowding, food supply, health services, and pollution. All these loops act, with varying efficiency, to keep the level of human population from rising indefinitely or from falling to zero. As conditions in the rest of the system change, the relative importance of each loop can change greatly.

The second half of the population sector, the feedback-loop structure controlling fertility, is shown in Figure 2-20. For simplicity, the five negative feedback loops on the death rate side in this diagram are represented by only a single loop proceeding from population through life expectancy and deaths back to population.

The maximum total fertility is a measure of the number of children a population could produce if it consistently tried to produce as many as possible. It is influenced in some way by each of the factors influencing life expectancy. As an approximation we made it a function of life expectancy itself, using the latter not as a direct causal factor but as an indicator of general health. Thus the four external factors that

*Under certain circumstances the crowding loop can also act as a positive feedback loop. See the discussion of this factor in section 2.5.

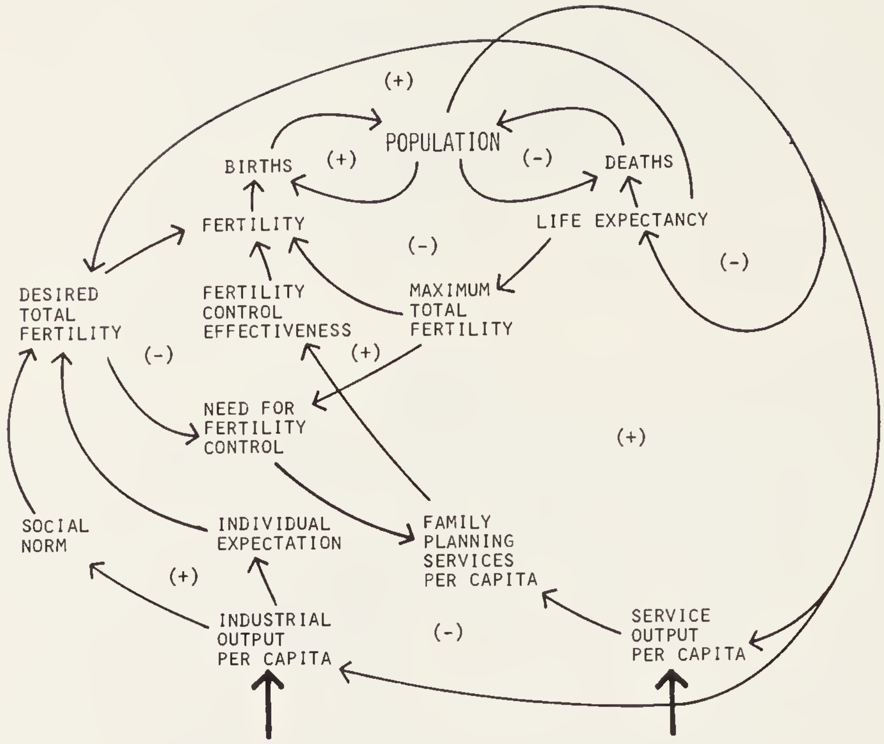


Figure 2-20 Feedback loops through fertility

influence the death rate through negative feedback loops also affect the birth rate through another (generally weaker) negative feedback loop.

The desired total fertility is involved in three feedback loops, two of them positive and one negative. The negative loop operates through the individual's assessment of the resources available for child-rearing. A population increase has a negative effect on industrial output per capita (all else being equal): as the growth rate of industrial output per capita decreases, the individual expectation of future family resources decreases, and desired total fertility decreases; a lower desired fertility leads to lower fertility, lower birth rate, and thus a lower rate of population increase.

This negative loop is counteracted by a positive loop that expresses the response of the social fertility norm to changing industrialization. A population increase causes a decrease in industrial output per capita, which after a long delay leads to a higher social norm with regard to family size. The higher norm then feeds back to increase the birth rate and the rate of population growth. The time delays in the two loops through industrial output per capita are quite different, and the relative strengths of the two loops are also very different at different levels of industrialization. Thus the model does not generate any simple response of desired family size to industrialization. The response can be positive, negative, or zero, depending on the growth pattern of the economic sectors.

Another positive feedback loop involving desired total fertility operates through life expectancy. This relationship expresses the hypothesis that families compensate for high mortality rates by purposely bearing more children than they actually desire. A population that perceives a high mortality rate among its children may desire to increase its fertility through this loop, but at the same time the poor health conditions that led to that high mortality may limit the possible fertility rate through the maximum total fertility loop.

The final causal loops in the population sector regulate fertility control effectiveness. This factor is increased by family planning services per capita in a positive feedback loop. A population increase leads to lower service output per capita, lower family planning services per capita, lower fertility control effectiveness, higher fertility, and thus a further population increase. All the loops, both positive and negative, influencing maximum and desired total fertility also affect fertility control effectiveness through the need for fertility control. (The need for fertility control is defined as the difference between maximum and desired fertility.)

There are several direct links between mortality and fertility in this model, and both respond independently to the economic and social factors generated in other sectors of the model. Thus many different mortality-fertility combinations may be generated, depending on the development of these outside factors. The model assumptions are not limited to the Malthusian hypothesis that population will automatically increase to its ultimate limit, at which point the death rate will rise to equal the birth rate. Neither do they automatically reflect the modern optimistic hypothesis that economic development will bring about a global demographic transition so that the birth rate will fall to equal the death rate. As we shall demonstrate in section 2.6, under appropriate external conditions the model system can exhibit either of these behavior modes, as well as other modes intermediate between the two extremes. A better expression of the basic philosophy incorporated in the feedback loops of the population sector is the "theory of demographic regulation" as described by Donald Bogue:

> Every society tends to keep its vital processes in a state of balance such that population will replenish losses from death and grow to an extent deemed desirable by collective norms. . . . These norms are not explicit opinions about desired population size or the optimum rate of growth. Instead, they are opinions concerning what constitutes the ideal size of completed family, or the number of surviving children a couple ought to have when it reaches the end of the reproductive period . . . . These norms are flexible and readjust . . . to changes in the ability of the economy to support population. [Bogue 1969, pp. 51–52]

2.5 DESCRIPTION OF EQUATIONS

A simplified DYNAMO flow diagram of the World3 population sector is shown in Figure 2-21. It represents a one-level population model with no disaggregation by age. For purposes of clarity, our discussion of the quantitative assumptions in the population sector begins with this simplest population model, which emphasizes the external rather than the demographic determinants of birth and death rates. At the end of this section we show how the single population level can be replaced by a four-level or a fifteen-level age-disaggregated representation, which more accurately expresses the demographic determinants of population dynamics.

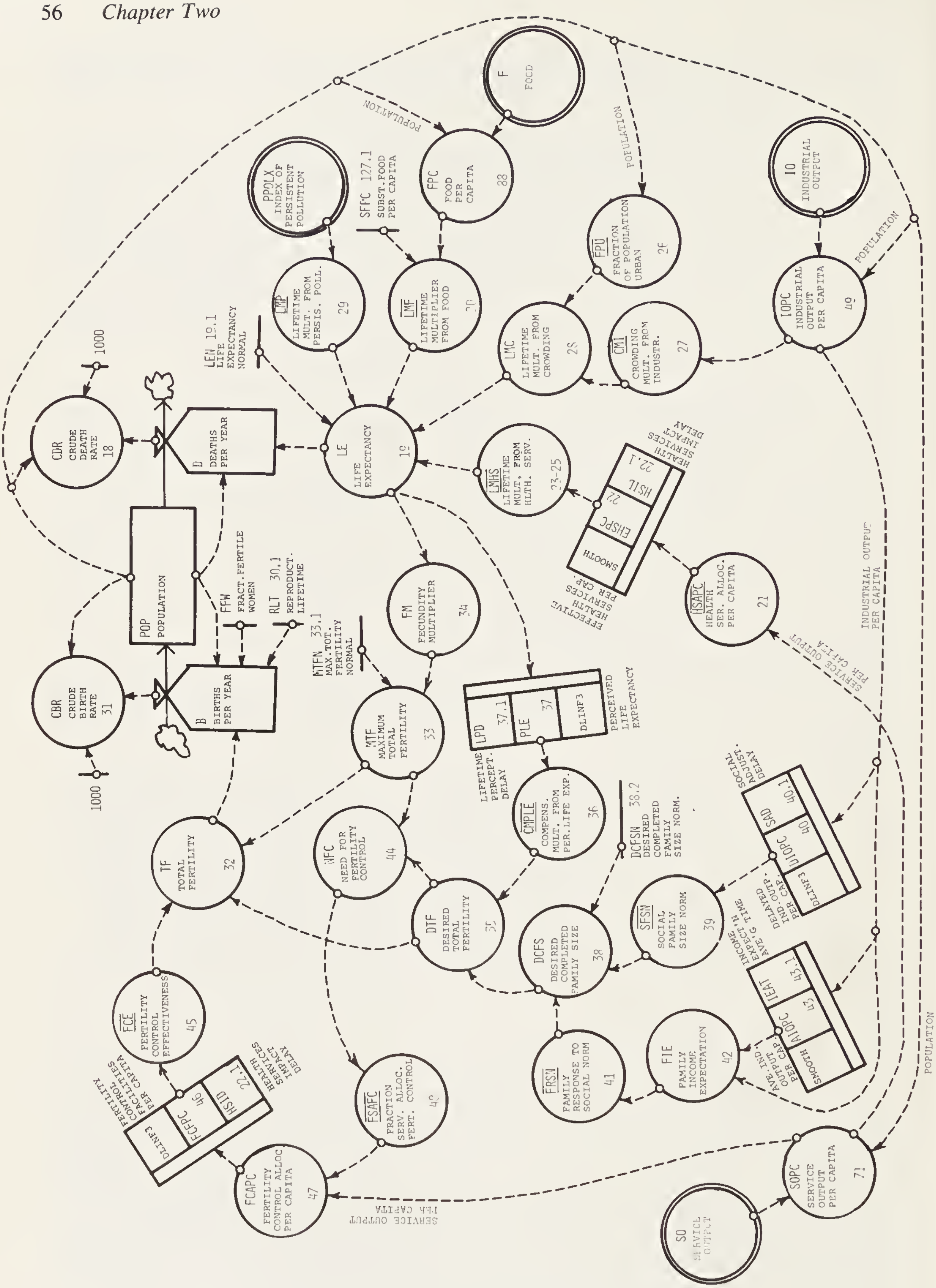


Figure 2-21 DYNAMO flow diagram—one age level

Year	Population (billions)	Source
1900	1.61	Carr-Saunders 1936, p. 42
1920	1.86	U.N. 1966, p. 133
1930	2.07	
1940	2.30	
1950	2.52	
1960	3.00	
1971	3.73	USAID 1971, p. 210
1970	3.59	U.N. 1966, p. 134 (“medium variant” projections)
1980	4.33	
1990	5.19	
2000	6.13	

Figure 2-22 World population estimates and forecasts

```
POP.K=POP.J+(DT)(B.JK-D.JK)
POP=POPI
POPI=1.61E9
    POP     - POPULATION (PERSONS)
    DT      - TIME INTERVAL BETWEEN CONSECUTIVE
                CALCULATIONS (YEARS)
    B       - BIRTHS PER YEAR (PERSONS/YEAR)
    D       - DEATHS PER YEAR (PERSONS/YEAR)
    POPI    - POPULATION, INITIAL (PERSONS)
```

The population POP at any time period equals the population in the previous time period plus the number of births B that have taken place and minus the number of deaths D.

The initial value of the population level is set at 1.61 billion, the estimated number of people in the world in 1900 (Carr-Saunders 1936, p. 42). Some world population estimates and forecasts for the years from 1900 to 2000 are shown in Figure 2-22.

It is important to remember that all global population statistics are highly uncertain, because poor or no census data have ever been collected for large areas of the world. In 1855, only about 17 percent of the world's population had been contacted in a census. By 1900, about 55 percent of the population lived in areas covered by a reliable census. In 1960 the total was 67 percent. There has been a drop from the high of 78 percent in 1950 because of the absence of more recent data on Mainland China (U.N. 1962, p. 3). Only 30 percent of the world's population is now covered by census and vital statistics records adequate for detailed demographic analysis (Keyfitz 1971*b*).

Mortality Equations

Death Rate D

```
D.KL=POP.K/LE.K
    D       - DEATHS PER YEAR (PERSONS/YEAR)
    POP     - POPULATION (PERSONS)
    LE      - LIFE EXPECTANCY (YEARS)
```

In the one-level population model the number of deaths per year D is expressed as the total number of persons in the population POP divided by the average life expectancy LE. Life expectancy in this simple nondemographic model is equivalent to the time constant of the exponential decline in population that would occur if there were no births. The lower the life expectancy, the larger the fraction of the population dying each year. If the average life expectancy is 50 years, one-fiftieth of the model's population dies each year. Thus in the one-level model the variable LE is simply a rough measure of the general health of the population.* In the age-disaggregated versions of the model, LE takes on its proper demographic meaning as a summary variable calculated from the total age-specific death rate table.

```
CDR.K=1000*D.JK/POP.K                                    18, S
     CDR     - CRUDE DEATH RATE (DEATHS/1000 PERSON-YEARS)
     D       - DEATHS PER YEAR (PERSONS/YEAR)
     POP     - POPULATION (PERSONS)
```

The crude death rate CDR is computed for graphic display, since it is the measure of mortality most often cited in compilations of world population data and the one from which the net population growth rate can be most readily calculated. It does not feed back to any other variable in the model. As we have already mentioned, the crude death rate is determined both by the probability of mortality at each age and by the population's age structure. In the simple one-level model, the age-structure contribution is not taken into account, and the mortality probability is expressed by a single number 1/LE. Since the world population in this century has contained a relatively large proportion of young people with low mortality risk, actual historical crude death rates tend to be somewhat lower than those generated by the one-level population model.

The world average crude death rate in 1970 was about 13 deaths per 1,000 people, or 1.3 percent. In the same year, reported crude death rates for individual nations varied from 29–30 in Angola and Upper Volta to 5–6 in Israel, Taiwan, Hong Kong, and Singapore (USAID 1971, pp. 210–214). The very low rates in the latter countries are due in large part to their young age structures. There is also a strong possibility of bias toward low values in national and global death rate statistics for two reasons: areas that do not record vital statistics tend to be those with the highest death rates, and in some areas that do gather vital statistics infant deaths are imperfectly registered.

Life Expectancy LE   Many different factors interact in the world to influence a population's average level of health, or life expectancy. The relative contributions of these factors have never been quantitatively assessed, in part because their interactions are extremely complex, as the U.N. Population Division has stated:

> It is by no means easy to assess the roles played by the various factors which have been at work in the reduction of mortality. It is not possible on the basis of existing

*The equation (deaths per year = population/life expectancy) is only demographically correct for a theoretical stationary population (Keyfitz 1971b, pp. 658–659).

> data to measure separately the effects of such diverse causes as the improvements in nutrition, housing, environmental sanitation, personal hygiene, and medical knowledge and services or the increasing health consciousness of people and their desire for a longer life. . . . Indeed, there is reason to believe that the analytical tools available at present for studying this problem are as yet deficient; the application of different methods to the same data results in different estimates of the relative importance of the factors. The problem is further complicated by the absence of reliable data. [U.N. 1953, p. 60]

When one variable of interest (life expectancy) seems to depend on a number of other variables (nutrition, housing, income, sanitation, education, medical services), statistical inference techniques are usually employed to sort out the relative importance of each contributing factor. Few statistical analyses have been carried out on the determinants of human life expectancy (for an example, see Kusukawa 1967), and, as the preceding quotation indicates, the results that have been obtained are generally contradictory and unsatisfactory. We believe the basic reasons are (1) that, as the United Nations suggests, the data base is not yet sufficient for rigorous quantitative analysis, and (2) that the causal relationships behind the data may not meet the basic requirements for statistical analysis. They may be highly nonlinear and mutually interdependent (that is, involved in feedback loops, so that no variable can be considered exogenous to the system or clearly independent of any other variable).

As an illustration of these statements, let us consider the three factors most commonly cited as important determinants of mortality: income or general standard of living, health care, and nutrition. A good case can be made both logically and empirically that the life expectancy of a population will increase as any of these three factors improves.

A preliminary analysis would suggest that income is highly correlated with and probably drives the other two—health care and nutrition. Income per se probably cannot raise life expectancy unless it can be spent on food, doctors, medicine, and housing. Thus rising income may affect life expectancy only through the ability of an industrializing society to provide better food, develop medical and sanitation technologies, and offer more health care facilities. The empirical relationship between income and food per capita is shown in Chapter 4; that between income and health service expenditures is shown in Figure 2-30.* Both relationships are quite regular and show little variation among the nations for which data are available. The mechanisms by which food and services are generated by a growing economy are contained in the agriculture and capital sectors of World3.

The empirical relationships between food per capita, health services, and life expectancy are shown in Figures 2-23 and 2-24 in the form of cross-sectional data from more than seventy nations for the period 1966–1968.* We shall discuss each of these relationships in detail later. It is important here to note just two simple points. First, the curves are nonlinear. As one would expect, when food or health care is

*See Appendix D to this chapter for original data.

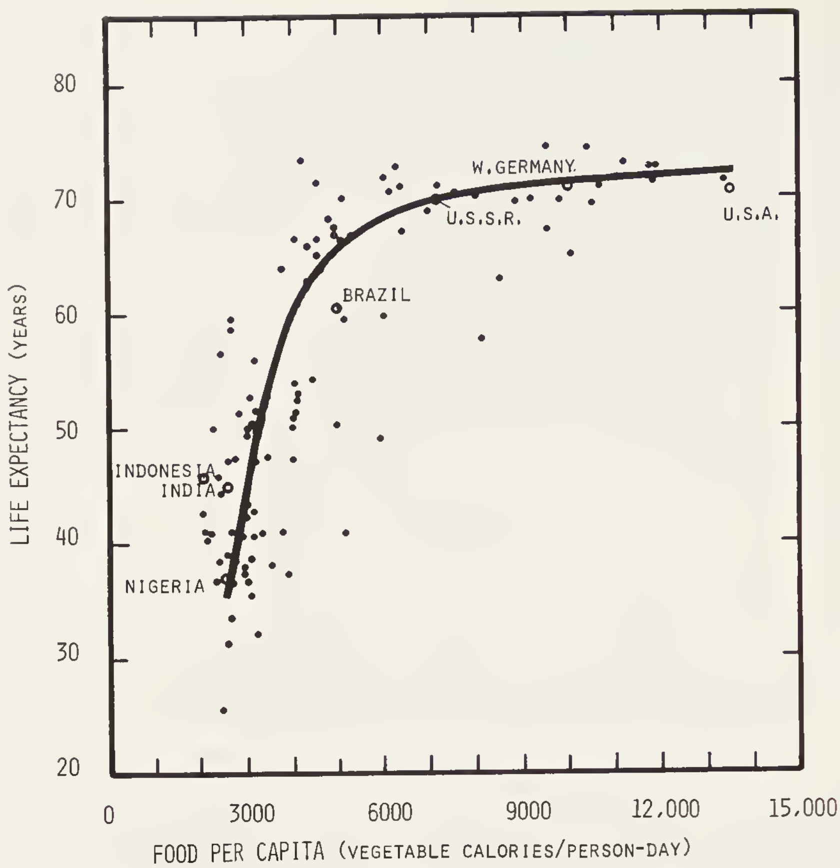


Figure 2-23 Food per capita versus life expectancy
Sources: U.N. 1972*a*, Keyfitz and Flieger 1971.

scarce, a small increase in either one results in a large increase in life expectancy. When food is plentiful and health care is readily available, however, a further increase of either has only a small effect on lifetime. Second, the variables plotted on each axis are mutually dependent. The denominator on both horizontal axes is population, and population depends on past values of life expectancy, among other things. This circular interdependence may strongly influence the empirical measurements that can be made. There are no points in Figure 2-23 below 2,000 calories per person per day, because a population with so little food would decrease rapidly, causing the available food per person to rise again above subsistence level.

Another problem in a statistical analysis of the data shown in Figures 2-23 and 2-24 is that food and doctors per person are correlated not only with life expectancy but also with each other. The empirical relationship between the two variables is shown in Figure 2-25. Food per capita and doctors per capita are roughly colinear, but with a good deal of variation in the relationship. The variation is especially noticeable at high values of both variables, where the marginal return of each (in terms of increased life expectancy) is nearly zero, so that the choice of more food or more health care is governed by secondary cultural differences rather than by the goal of minimizing mortality.

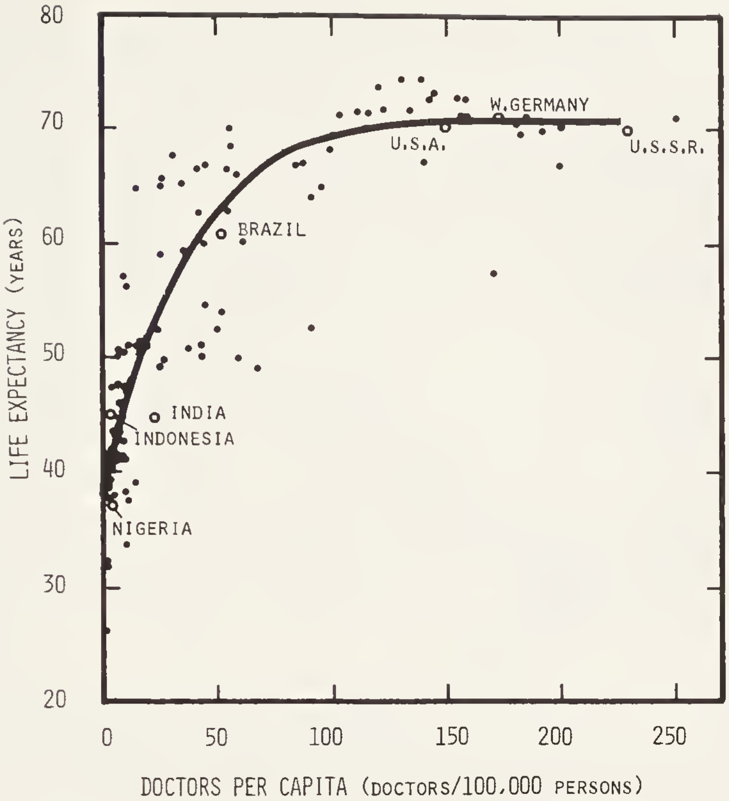


Figure 2-24 Doctors per capita versus life expectancy
Sources: U.N. 1972*a*, Keyfitz and Flieger 1971.

Given these multiple, complex interrelationships among the determinants of human health and the fact that the data base is and probably will continue to be unreliable, we did not attempt to investigate the determinants of life expectancy by statistical inference techniques. Instead, we tried to quantify approximately the causal relationships from what we know of the physical, biological, and economic facts underlying them. A detailed description of that process follows:

```
LE.K=LEN*LMF.K*LMHS.K*LMP.K*LMC.K                    19, A
LEN=28                                               19.1, C
    LE      - LIFE EXPECTANCY (YEARS)
    LEN     - LIFE EXPECTANCY NORMAL (YEARS)
    LMF     - LIFETIME MULTIPLIER FROM FOOD
                (DIMENSIONLESS)
    LMHS    - LIFETIME MULTIPLIER FROM HEALTH SERVICES
                (DIMENSIONLESS)
    LMP     - LIFETIME MULTIPLIER FROM PERSISTENT
                POLLUTION (DIMENSIONLESS)
    LMC     - LIFETIME MULTIPLIER FROM CROWDING
                (DIMENSIONLESS)
```

Four factors—food, health services, crowding, and pollution—are incorporated in the equation for life expectancy as modifiers, or multipliers, of a ''normal'' life expectancy LEN. The normal life expectancy LEN can be set at any arbitrary value as long as the four multipliers are all defined properly with respect to that value. We set the normal life expectancy at 28 years, the approximate value for a primitive

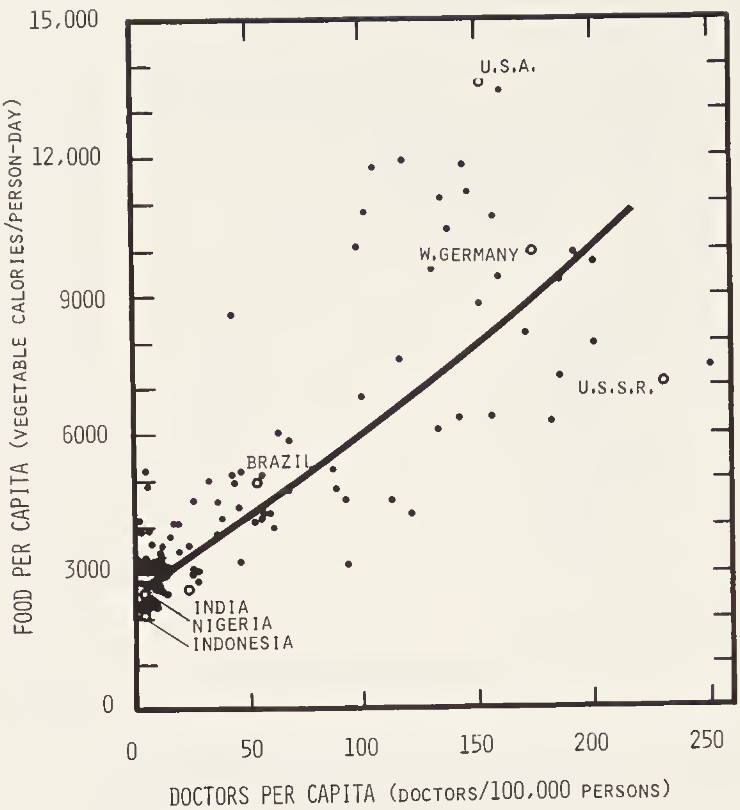


Figure 2-25 Doctors per capita versus food per capita
Source: U.N. 1972*a*.

Population	Average Age At Death (years)	Source
Neanderthal	29.4	
Upper Paleolithic	32.4	
Mesolithic	31.5	Deevey 1960
Bronze Age, Austria	38	
Classical Greece	35	
Classical Rome	32	
Geneva, 1561–1600	21	
Geneva, 1601–1700	28	
England, 1426–1450	33	U.N. 1953, pp. 50–51
Breslau, 1687–1691	33.5	
India, 1921–1931	27	
Primitive South American tribes, 1962–1970	35	Neel 1970
Latin America, 1860	25.9	Arriaga and Davis 1969
Portuguese Guinea, 1955	24.3	Keyfitz 1971*b*

Figure 2-26 Life expectancies of preindustrial populations

population with no medical advances and with a food supply near the subsistence level.

Age estimates from ancient skeletons (estimates that are probably too high because the bones of juveniles were seldom preserved) and other records suggest low average values for life expectancies in ancient societies and in preindustrial modern ones, as shown in Figure 2-26. Bogue has estimated that "throughout the long span of history prior to about 1650 the average expectation of life was 25 years or less" (1969, p. 566). Inscriptions associated with Egyptian mummies from about 100 B.C. indicate an average age of 22.5 years at death.

Thus the "normal" or reference mortality state for the model is defined as that of a preindustrial society, and the "normal" life expectancy is set at 28 years. Then each of the four lifetime multipliers expresses the effects of variations in one factor (such as food per capita) on the life expectancy of the preindustrial population, assuming that the other three factors (health services, crowding, and pollution) remain constant. For our reference population, the values of all four multipliers are defined as 1.0.

The life expectancy equation is written in multiplicative form, rather than additive or some other arithmetic form, to express a slight synergy among the influencing factors. For example, if at a given time the level of food available to a population is enough to raise its life expectancy above the reference by 30 percent, and no other factor is changed from its preindustrial value, LE would be calculated as follows:

$$\mathrm{LE} = \mathrm{LEN} \times \mathrm{LMF} \times \mathrm{LMHS} \times \mathrm{LMC} \times \mathrm{LMP}$$
$$36.4 = 28 \times 1.3 \times 1.0 \times 1.0 \times 1.0$$

If, in addition to the food increase, an increase in health services occurs that would also be sufficient to raise life expectancy 30 percent, all else being equal, the calculation would be:

$$\mathrm{LE} = \mathrm{LEN} \times \mathrm{LMF} \times \mathrm{LMHS} \times \mathrm{LMC} \times \mathrm{LMP}$$
$$47.3 = 28 \times 1.3 \times 1.3 \times 1.0 \times 1.0$$

The increase in life expectancy from 28 to 47.3 years is somewhat larger than it would be if the two 30 percent increases had been added rather than multiplied ($28 \times 1.6 = 44.8$). The multiplicative equation also allows us to capture more easily the shifting dominance of the four interacting factors. We can, for example, easily construct the lifetime multiplier from food LMF function so that zero food gives zero lifetime, regardless of the values of the other three multipliers.

Lifetime Multiplier from Food LMF The relationship between the average amount of food available to a person and that person's life expectancy is easy enough to postulate qualitatively. It is difficult to quantify exactly, especially since it is influenced by each person's age, genetic background, environment, food and exercise habits, and many other factors. Here we present data to establish the range and the general nonlinear shape of the food-mortality relationship aggregated over a large number of people, races, cultures, and climates. We also estimate the relative weight of the lifetime multiplier from food LMF with respect to other influences on life expectancy LE.

The nutritional level of a population can be expressed in several different units, none of which is entirely satisfactory, since human diets and metabolic needs are complex and vary greatly. In the agriculture sector of World3, world food output is generated in units of total kilograms of vegetable crops per year. Thus food per capita in the population sector is most easily calculated in kilograms of vegetable crops per person-year. The meat and animal products generated by the food production system are counted in terms of their vegetable equivalent—the number of kilograms of vegetable crops (grains, grasses) necessary to produce a kilogram of animal matter. On the average, about 7 kilograms of vegetable fodder are required to produce 1 kilogram of food of animal origin (Cépède, Houtart, and Grond 1964, p. 253). Thus in the world model:

$$\frac{\text{kilograms vegetable-equivalent food}}{\text{person-year}} = \frac{\text{kilograms vegetable food}}{\text{person-year}} + \frac{7 \times \text{kilograms animal food}}{\text{person-year}}$$

The measurement of food per capita in terms of vegetable equivalents accounts at least in part for both the quantity and the quality of the diet. Food of animal origin, which is higher in protein and usually more expensive, is counted seven times more heavily than food of vegetable origin. The index of vegetable-equivalent food intake is probably the best single measure of dietary sufficiency available at present.

> A population's health standards (over-all mortality, diseases and deaths from special causes, expectation of life at birth) are, indeed, much more closely tied in with the nutritional level when the latter is figured in vegetable calories than when it is figured in "final" calories. . . . P. V. Sukhatme, who heads the statistical branch of FAO, made a study of the different units of measurement proposed for calculating levels of nutrition, and concluded that the vegetable (primary or original) calorie gives the best simple scale, in terms both of food production and of human needs. [Cépède, Houtart, and Grond 1964, pp. 257–258]

The conversion between food expressed in kilograms per year and food expressed in kilocalories* per day can be calculated from the average energy content of vegetable matter—about 4.5 kilocalories per dry gram (Kormondy 1969, pp. 18–20), or 3.5 kilocalories per (wet) gram of harvested crops (see Chapter 4). To make the interface with the agriculture sector as simple as possible, we shall use the wet crop value:

1 kilogram vegetable food = 3,500 kilocalories.

The average minimum amount of food necessary for human subsistence (called subsistence food per capita SFPC in the model) is approximately 2,200 vegetable-equivalent kilocalories per day (FAO 1970, vol. 2, p. 491), which is equivalent to:

$$\frac{2200 \text{ kilocalories}}{\text{person-day}} \times \frac{1 \text{ kilogram}}{3500 \text{ kilocalories}} \times \frac{365 \text{ days}}{\text{year}} = \frac{230 \text{ kilograms}}{\text{person-year}}$$

1 kilogram per person-year = 10.4 kilocalories per person-day.

*One kilocalorie is often referred to as a Calorie in discussions of nutrition, and occasionally the capital C is omitted. Usually, a calorie or Calorie in the literature on nutrition is equivalent to 1,000 calories or a kilocalorie in terms of the physical measure of energy.

All the numbers used in discussing vegetable equivalents are rough averages and somewhat arbitrary. Given different conditions, kinds of animals, and animal products, the conversion factor from vegetable feed to animal product can vary from 9.2 (Cépède, Houtart, and Grond 1964, p. 259) to 2 (PSAC 1967, p. 250)—the lower figure applies only when the feed and the animal stock are very highly selected. The energy content of vegetable matter normally ranges from 4.1 to 5.2 kilocalories per dry gram (Kormondy 1969, p. 20). The energy needs of persons vary with their age, activity, climate, and basal metabolism. For each of these numbers we tried to choose an intermediate value that is commonly used by authorities in the field. Given the imprecise purpose of our model, such approximations are justified, especially since many of the differences between animals, crops, and people average out on a global scale.

The empirical relationship between food per capita FPC and life expectancy LE has already been shown in Figure 2-23. We cannot conclude of course, as Figure 2-23 implies, that a simple increase in food per capita is in itself sufficient to raise human life expectancy from 40 years to 70 years. The data have not been corrected for the impact of other variables on life expectancy, in particular for the fact that medical and public health services are also increasing in Figure 2-23 as food per capita increases. Since a statistical unraveling of these interconnected factors seems to be unattainable, we constructed the lifetime multiplier from food LMF relationship according to the following chain of reasoning.

The normal life expectancy, 28 years, was defined as that which prevails when the food supply is at subsistence level. Thus we have one point (indicated by X in Figure 2-27) in the desired relationship—the lifetime multiplier from food LMF must be 1.0 when the food per capita FPC equals the subsistence level of 230 vegetable-equivalent kilograms per person-year.

If food per capita falls below the subsistence level (FPC/SFPC < 1.0), the life expectancy would certainly decrease very quickly, since on the average there is not enough food per person to sustain life. The actual sharpness of the decline depends

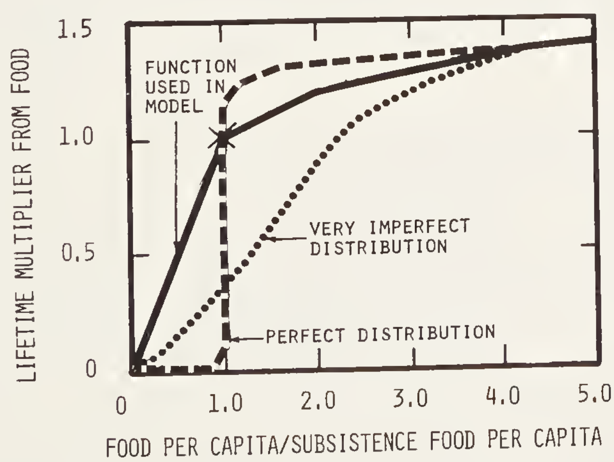


Figure 2-27 The effects of food distribution on the lifetime multiplier from food

on the equality of distribution of the food supply. If food were always evenly distributed among the populations of the world, the life expectancy would drop to zero almost immediately as food per capita falls below subsistence, since no one would have enough food to stay alive. In that case the slope of the curve would reflect only individual physiological differences in food requirements; it would look roughly like the dashed line in Figure 2-27. Food is of course far from evenly distributed in the real world. Therefore, we made the assumption that at any level of food production above zero some fraction of the population will acquire sufficient food for survival. In the absence of any information about how unequal food distribution might actually become under circumstances of scarcity, we made the relationship linear from FPC/SFPC = 0 to FPC/SPFC = 1. This linearity implies that the fraction of the population that does obtain food will consume only enough food per capita to survive and no more. If the few people with food actually consume a luxury diet, and if the extremely unequal food distribution persists as food supplies rise, a curve such as the dotted line in Figure 2-27 would express the relationship.

As the available food per capita rises above 230 kilograms per person-year, how much can life expectancy be expected to rise, given that all other factors remain the same? The answer to this question is complicated by the fact that no distinction is usually made between deaths from nonnutritional causes and deaths that are technically caused by infectious disease but that would not have occurred if the victim had not been weakened by malnutrition. Wyon and Gordon (1971, p. 194) have attempted to make this distinction in their studies of villages in northern India. They indicate that among 0–2-year-olds as many as 100 deaths per 1,000 live births could have been prevented by proper nutrition alone. Therefore, raising food per capita in these villages could have increased the average life expectancy by as much as twelve years.*

We assumed in the world model that increasing food above the subsistence level, with no other inputs, can raise the life expectancy of a preindustrial population by 40 percent—from 28 years to 39 years. This estimate agrees with the maximum life expectancy of 35–40 years observed in anthropological studies of primitive societies in favorable environments (Howell-Lee 1971). Most of this improvement in life expectancy would probably come from decreased infant and child mortality (Gordon, Wyon, and Ascoli 1967). The complete relationship we assumed between food per capita and life expectancy is shown in Figure 2-28 and is represented by the following equations:

```
LMF.K=TABHL(LMFT,FPC.K/SFPC,0,5,1)                        20, A
LMFT=0/1/1.2/1.3/1.35/1.4                                 20.1, T
    LMF    - LIFETIME MULTIPLIER FROM FOOD
               (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LMFT   - LMF TABLE
    FPC    - FOOD PER CAPITA (VEGETABLE-EQUIVALENT
               KILOGRAMS/PERSON-YEAR)
    SFPC   - SUBSISTENCE FOOD PER CAPITA (VEGETABLE-
               EQUIVALENT KILOGRAMS/PERSON-YEAR)
```

*Calculated from the formula (Keyfitz 1971*b*, p. 658)

$$\Delta e_0^o = -5\,\frac{l_x}{l_0}\,(e_x^o - 2.5)\Delta_5 M_x,$$

where l_x/l_0 is the probability of surviving to age x (= 1.0 here), e_x^o is the life expectancy at age x (28.0 here), and $\Delta_5 M_x$ is the change in the death rate over the 5-year period including x (−0.1 here).

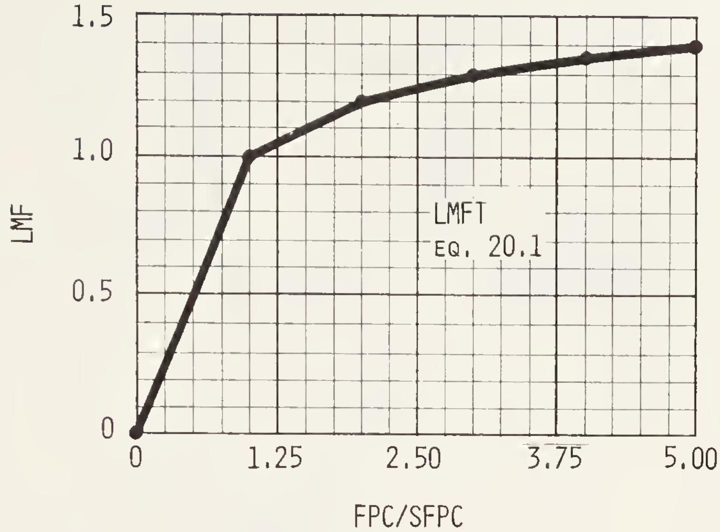


Figure 2-28 Lifetime multiplier from food table

Figure 2-28 reflects our estimate of the present apparent distribution of food among the world's people and among age groups within populations. Life expectancies might well be raised by 40 percent with much less food than is indicated by this figure if populations could be better educated about nutrition, if food were more equitably distributed, and if prevailing food habits could be changed. As Gordon mentions in his description of a Guatemalan village:

> In a region where everything grows . . . the choice of basic foods was culturally restricted to corn and beans morning, noon, and night. Fruits and garden vegetables were cash crops. An animal census of the villages showed few sources of animal protein and especially of milk for toddlers and young children. Cows existed but were scarce. As features of the social environment, tradition, custom, and taboos strongly influenced the choice of foods in a land of potential plenty. [Gordon 1969]

Social customs can conceivably be changed as a matter of deliberate policy. We would represent such a policy in World3 by altering the lifetime multiplier from food relationship to allow a steeper rise in life expectancy as food per capita increases. A model run under this policy is shown in section 2.6.

Is the causal relationship represented by the lifetime multiplier from food LMF instantaneous or delayed? It is true that human adults can exist for long periods on greatly reduced nourishment—as documented by numerous examples from famines and concentration camps (Keys et al. 1950). When human populations are viewed as a whole, however, the aggregate death rate rises very quickly under conditions of food shortage. Figure 2-29 shows the historical match between famines and death rates in medieval France. Although previously well-fed adults can survive food shortages, often for years, the weaker members of the human population, especially the very young, the old, and those already ill or malnourished, succumb very quickly, causing the average life expectancy to fall with little delay. In populations deprived of adequate food during World War II, peaks in clinical symptoms and death rates

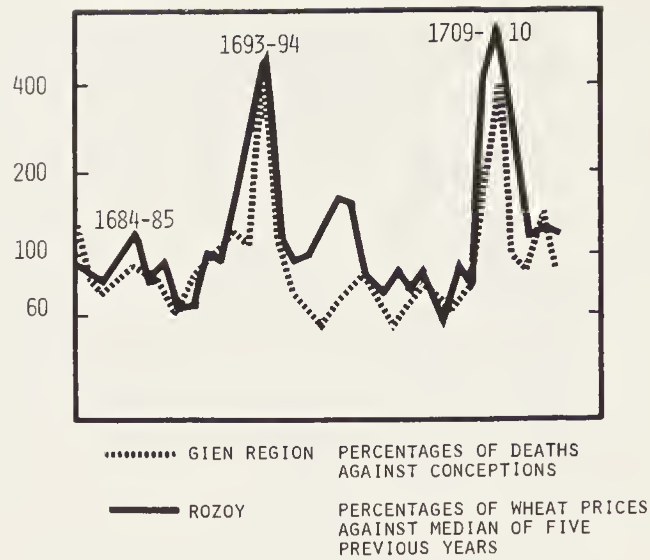


Figure 2-29 Famines and mortality in medieval France
Source: Adapted from Figure 10 of the *General Theory of Population*, by Alfred Sauvy, translated from the French by Christophe Campos, © 1969 by George Weidenfeld and Nicolson Ltd., and © 1966 by Presses Universitaires de France, Basic Books Inc., Publishers, New York.

lagged behind maximum times of food shortage by only a few months (Keys et al. 1950, pp. 19–29). In the reverse direction, an increase of food in a population that has been suffering from malnutrition can have a measurable effect on the death rate within a year—a period of time negligible in the 200-year perspective of our model runs. Thus we did not include an explicit delay between food per capita FPC and life expectancy LE in World3.

Lifetime Multiplier from Health Services LMHS   Although the correlation between available health services and life expectancy is generally recognized, there is surprisingly little concrete evidence with which to quantify it. The history of rising life expectancies around the globe, especially during the past forty years, is impressive (see Figure 2-6). Concurrent with this unprecedented improvement in human health has been a worldwide increase in medical knowledge and in public health efforts by local, regional, national, and international organizations. To link these two phenomena quantitatively, we must be able to answer the following questions:

1. Given a certain level of resources (capital, manpower, and manufactured goods) allocated to services in the economy, what fraction of these resources is likely to be devoted to health services?
2. Given a certain expenditure on health services per capita, what actual life expectancy would be experienced by a typical population, all other factors held constant?
3. Is the response of life expectancy to health service expenditures immediate or delayed?

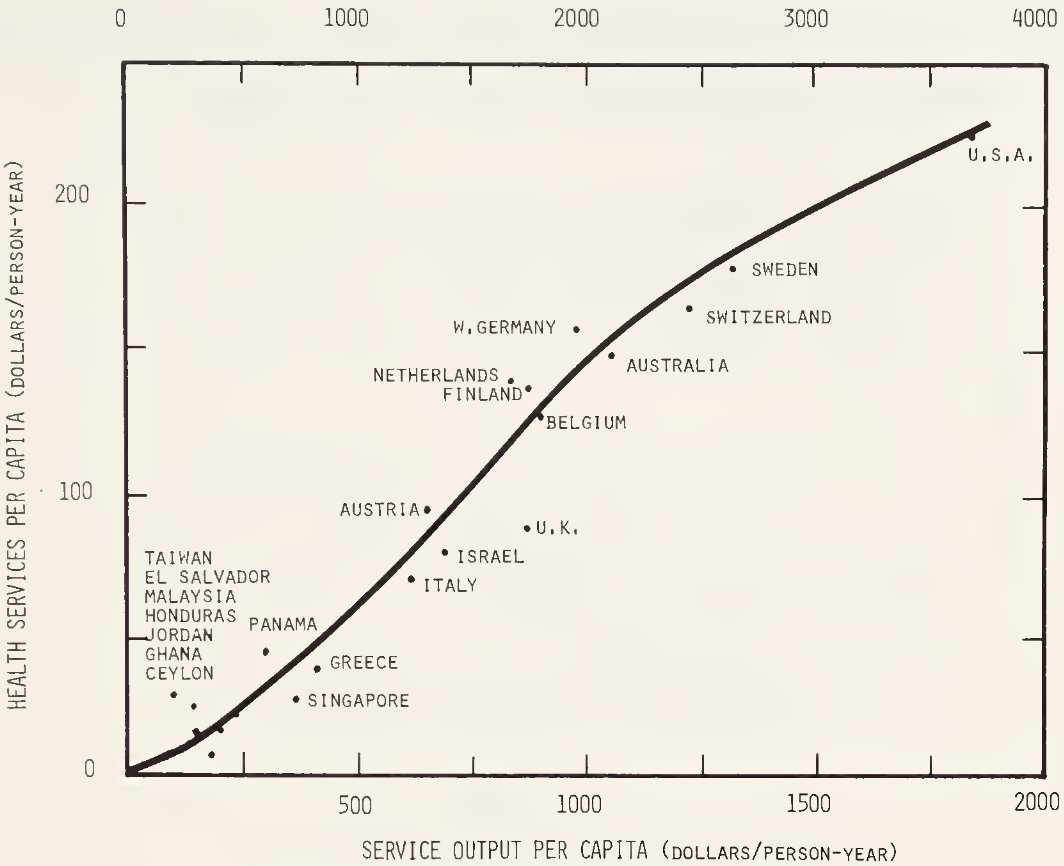


Figure 2-30 Health expenditures per capita versus service output per capita
Source: WHO 1971.

Information on total per capita health expenditures for the nations of the world has only recently been requested by the World Health Organization, and few countries have so far released any pertinent statistical data. In its 1971 summary of the world health situation, WHO published both private and public health expenditures for twenty-five countries. These are the most complete figures we were able to find for national health expenditures, and WHO qualifies them heavily. In some cases, only central government figures were recorded, but most of the nations do include central, state, and local expenditures in their estimates. Difficulties arise in comparing values of local currencies and in evaluating the quality and distribution of the services bought. Better statistics will probably be available in the future, since WHO realizes the importance of these data: "Despite the complexity, . . . this line of research is of growing importance in national health planning, and more knowledge is needed on the subject of health costs" (WHO 1971, p. 53).

In Figure 2-30, total health expenditures per capita (public and private) for these twenty-five nations are plotted as a function of total service output per capita. The relationship is slightly S-shaped and quite regular. The solid curve in Figure 2-30, which approximates the general trend, is included in the model to represent the increase in health services allocations per capita HSAPC as a function of total service output per capita SOPC. Thus in the world model, health services allocations per capita are assumed to vary between 10 and 15 percent of total service output per capita, or between 5 and 8 percent of the total GNP per capita. The relationship is plotted in Figure 2-31 and expressed by the following equations:

```
HSAPC.K=TABHL(HSAPCT,SOPC.K,0,2000,250)              21, A
HSAPCT=0/20/50/95/140/175/200/220/230                21.1, T
    HSAPC  - HEALTH SERVICES ALLOCATIONS PER CAPITA
                (DOLLARS/PERSON-YEAR)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    HSAPCT - HSAPC TABLE
    SOPC   - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
                YEAR)
```

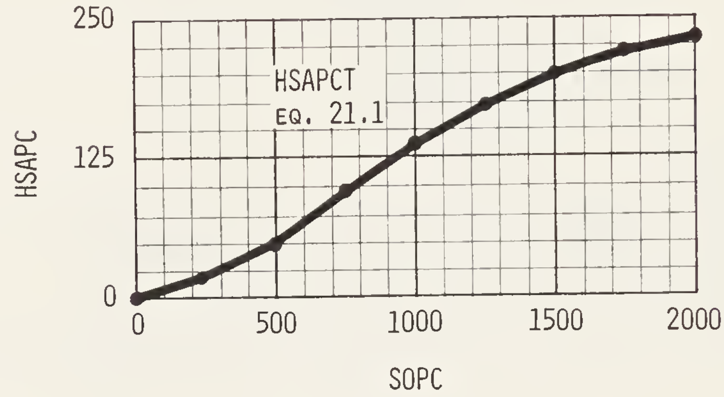


Figure 2-31 Health services allocations per capita table

As health services allocations increase in a given area, is the effect on average life expectancy immediate or delayed? Observations after the introduction of public health campaigns in some nonindustrialized areas indicate that the effect of such campaigns on life expectancy can be very sudden indeed. The classic example is Ceylon, where life expectancy rose from 45.8 years to 59.8 years in the eight-year period from 1946 to 1954 (U.N. 1962, p. 40). Yet it is also true that allocations for health services may not be instantly transformed into functioning doctors, hospitals, or research units and that new health facilities, even when operating efficiently, cannot immediately remove the effects of previous bad health in the population. A population may preserve for a time a "memory" of poor health care in the form of weakened bodies, remaining pockets of unexterminated disease vectors, or suspicious persons who do not make use of new services. In the reverse direction, a collapse of health services allocations would certainly result in some immediate increase in the death rate, but if the previous level of health care had been high, the population would probably possess for a long time enough medical knowledge, vaccinated persons, safe water supplies, and individual habits of sanitation to keep the life expectancy above the level otherwise indicated. We represented this relationship by inserting a first-order delay* between health services allocations per capita HSAPC and the

*For an explanation of first-order and higher-order delays, see Appendix F to this book and Forrester 1961.

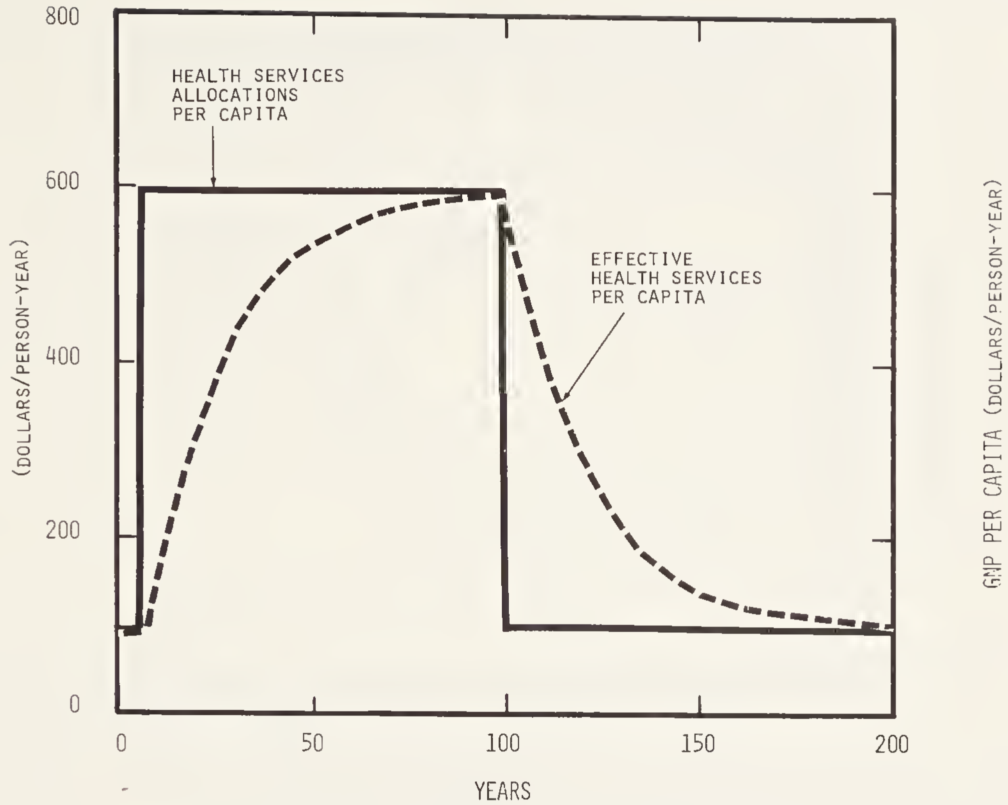


Figure 2-32 Health services impact delay

```
EHSPC.K=SMOOTH(HSAPC.K,HSID)                         22, A
HSID=20                                              22.1, C
    EHSPC   - EFFECTIVE HEALTH SERVICES PER CAPITA
                (DOLLARS/PERSON-YEAR)
    SMOOTH  - FIRST-ORDER EXPONENTIAL INFORMATION DELAY
    HSAPC   - HEALTH SERVICES ALLOCATIONS PER CAPITA
                (DOLLARS/PERSON-YEAR)
    HSID    - HEALTH SERVICES IMPACT DELAY (YEARS)
```

actual measure of health care, which we call effective health services per capita EHSPC. The time constant of the delayed response, called the health services impact delay HSID, has been set at 20 years. That value was chosen arbitrarily, and it can be easily varied in the model runs.

The delayed response of EHSPC to a sudden increase or a sudden decrease in HSAPC is shown in Figure 2-32. Here EHSPC rises immediately after the increase in HSAPC, but the full effect of the increased allocations is not realized until decades later. Similarly, a sudden decrease in HSAPC causes a quick erosion in EHSPC (and thus life expectancy LE), but it takes more than 50 years for the effective services to fall back to their earlier level.

Now we need to establish the third link in the causal chain—the relationship between effective health services per capita and actual life expectancy. This relationship must clearly be technology-dependent. An investment in health services in 1970 produced a far greater effect on life expectancy than the same investment in 1870 could have produced. In 1900 the average life expectancy, even in the most affluent nations of the world, was probably not more than 56 years (U.N. 1962, pp. 22–23).

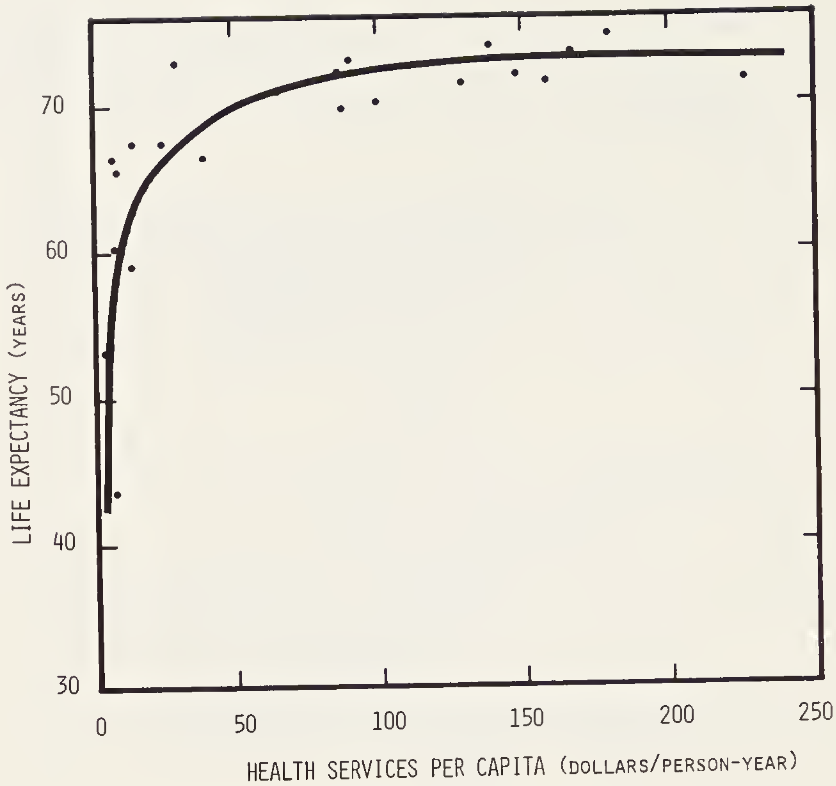


Figure 2-33 Health services per capita versus life expectancy
Sources: WHO 1971; Keyfitz and Flieger 1971.

Since 1900 a steady and spectacular advance in medical knowledge has extended the maximum life expectancy at birth in the most advanced nations to about 74 years. At the same time, advances in public health technology (for example, manufacture and shipment of vaccines, water and sewage treatment facilities, and insecticide sprays) have greatly decreased the cost of administering basic medical and preventive techniques to the general public. For example, Figure 2-33 shows the relationship in various nations between total health service expenditures and life expectancy. Apparently, an expenditure of as little as 20 dollars per capita per year with present technology is sufficient to raise life expectancy dramatically. Thus a graph of the lifetime multiplier from health services LMHS as a function of effective health services per capita EHSPC today would be quite different from one in 1900, and in 1990 the graph may be different from the relevant one today. Examples of hypothetical graphs for these three dates are shown in Figure 2-34.

The occurrence of a relationship that appears to be time-dependent, like the one in Figure 2-34, indicates that an important underlying dynamic function has been omitted from the model. In this case both the effectiveness and the cost of medical care are dependent upon a slow accumulation of medical and technical knowledge. The dynamics of this technological progress might be introduced into the model by including explicit representation of the past investment in medical research and development and of the time delays involved in testing and implementing new medical discoveries. We chose a simpler approach here by making two assumptions about the historical path of health technology:

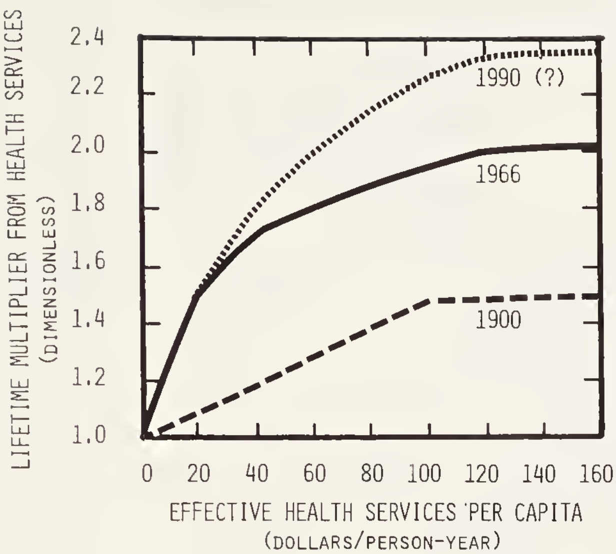


Figure 2-34 Lifetime multiplier from health services, 1900, 1966, 1990

1. Past medical progress, although it accumulated gradually, was first widely available on a global scale in the 1930s and 1940s.
2. Present medical technologies in the industrialized countries have reached a plateau as far as raising life expectancies are concerned and are not likely to increase life expectancies much beyond the present 70–75 year average, even with increased research investment.

The transition from the health technology of 1900 to that of 1966, as shown in Figure 2-34, certainly did not take place suddenly. Nevertheless, there is some evidence that the major developments responsible for the application of new medical knowledge (the reduction of costs) occurred quite rapidly during the period between 1925 and 1945. For example, Figure 2-35 shows the slow and gradual increase in life expectancy over 200 years in Sweden and the sudden spurts in life expectancy in several developing countries after 1920. Figure 2-36 shows a similar comparison for the countries of Latin America. Arriaga and Davis (1969) conclude from these figures that some major change in the relationship between the economic level of a population and its life expectancy began to occur about 1930.

> In general, the view is often taken . . . that the health of a population is a function of the economic level. Since economic development involves the entire society, it is a process that tends to be ponderous, relatively slow and somewhat regular over the long pull. Anything that depends on this process could be expected to share the same traits. Furthermore, . . . the life expectancy in a population [might be expected to be] an index of its economic stage.
>
> . . . up to about 1920 or 1930 these deductions appear to be true. . . . After 1930, however, . . . the rate of mortality change was extremely rapid, no matter whether the economy was booming or not. . . .
>
> At the present, regardless of the state of development of a country, certain public health and medical techniques can be applied—principally those measures whose applications are not expensive. . . . As a consequence, a backward country can succeed in combatting a particular infectious-communicable disease without having to develop or maintain a major medical establishment of its own. [Arriaga and Davis 1969]

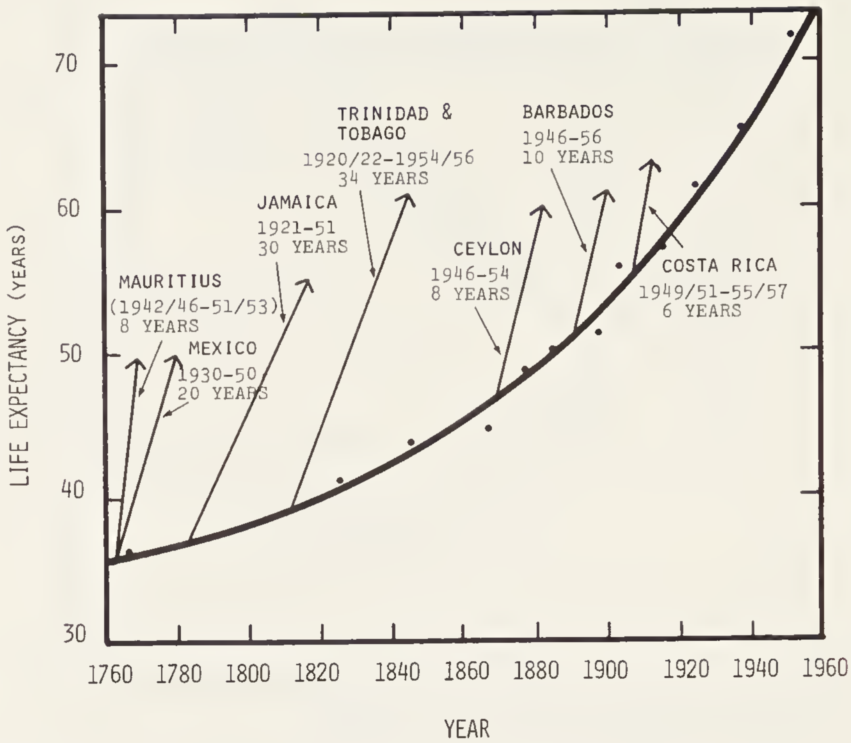


Figure 2-35 Mortality trends in Sweden and various nonindustrialized countries
Source: U.N. 1953.

In modeling the historical development of health technology, we have included a simple shift from the postulated 1900 table function to the 1966 one, the shift occurring at model time 1940. This shift (expressed by a CLIP function) is an approximation to an increase in technology that actually took place more gradually, but there probably was an unusually large advance, especially in decreasing costs, during the period 1930–1950. The changeover from one table to the other takes place at an effective health services per capita level of about 15 dollars in 1940. Thus the effect of health services on life expectancy can be represented by a composite table as shown by the heavy line in Figure 2-37. The CLIP function also introduces a hysteresis in our assumption of medical technological development. A decrease in expenditures for health services after 1940 would result in a movement back along the curve of present technology, not a retreat to past technology.

At high food levels, the curve shown in Figure 2-37 generates a maximum life expectancy of 78.4 years. We reserved the assumption of even higher life expectancies in the future for each model operator to include at his own discretion, and we assumed eventual diminishing returns to health expenditures. Indeed, the record of longevity in the developed countries over the past twenty years indicates that rising health services (at present technology) in these areas no longer result in any increase in life expectancy. Per capita health expenditures in the United States have risen from 60 to 220 dollars (at constant prices) since 1949, yet the life expectancy for white males over that period has risen by only about two years (Forbes 1967):

> The main determinants of longevity are cultural, rather than medical, factors in the countries in which infectious diseases are no longer among the predominant causes

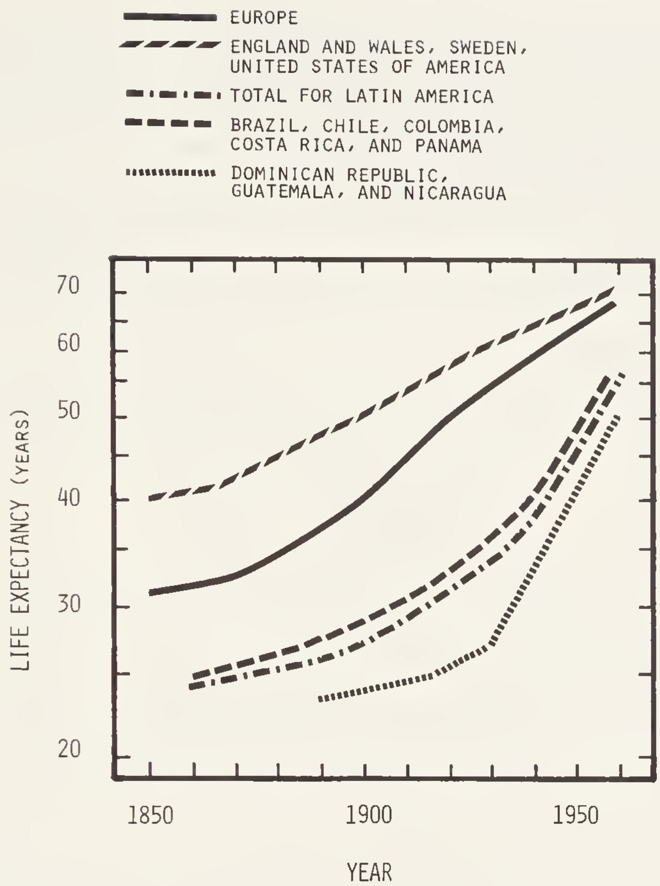


Figure 2-36 Mortality trends in Latin America
Source: Arriaga and Davis 1969.

of death. . . . It is probable that we could either halve or double the money now being spent on health without significantly affecting our longevity. [Forbes 1967]

What of possible future technological developments that would be equivalent in efficiency to the series of health advances that took place in the 1930s and 1940s? It is certainly not possible to predict the timing or extent of any future advances. It is possible, however, to test the impact of developments by postulating

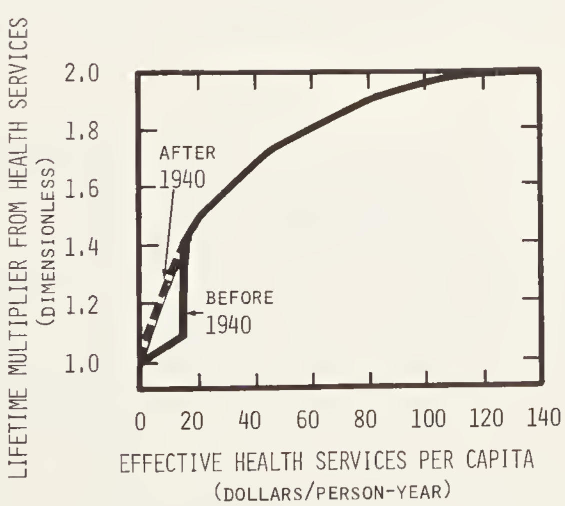


Figure 2-37 Hysteresis in lifetime multiplier from health

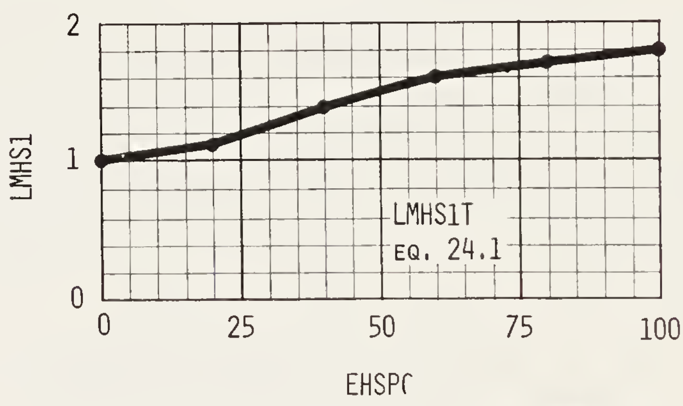
their magnitude and the time at which they may occur. For example, the effects of the curve for the year 1990, shown in Figure 2-34, which assumes a major breakthrough that leads to an increase in the maximum average human lifespan from 75 to 100 years, is tested in the model runs in section 2.6.

Unless otherwise indicated, in the model runs in this chapter and in Chapter 7, the relationship actually used in World3 for the lifetime multiplier from health services LMHS will be that shown by the solid line in Figure 2-38, which gives a maximum average life expectancy of 56 years at subsistence food levels and of 78.4 years at high food levels.

```
LMHS.K=CLIP(LMHS2.K,LMHS1.K,TIME.K,1940)              23, A
    LMHS    - LIFETIME MULTIPLIER FROM HEALTH SERVICES
                (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    LMHS2   - LMHS, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    LMHS1   - LMHS, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN

LMHS1.K=TABHL(LMHS1T,EHSPC.K,0,100,20)                  24, A
LMHS1T=1/1.1/1.4/1.6/1.7/1.8                            24.1, T
    LMHS1   - LMHS, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LMHS1T  - LMHS1 TABLE
    EHSPC   - EFFECTIVE HEALTH SERVICES PER CAPITA
                (DOLLARS/PERSON-YEAR)

LMHS2.K=TABHL(LMHS2T,EHSPC.K,0,100,20)                  25, A
LMHS2T=1/1.4/1.6/1.8/1.95/2.0                           25.1, T
    LMHS2   - LMHS, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LMHS2T  - LMHS2 TABLE
    EHSPC   - EFFECTIVE HEALTH SERVICES PER CAPITA
                (DOLLARS/PERSON-YEAR)
```



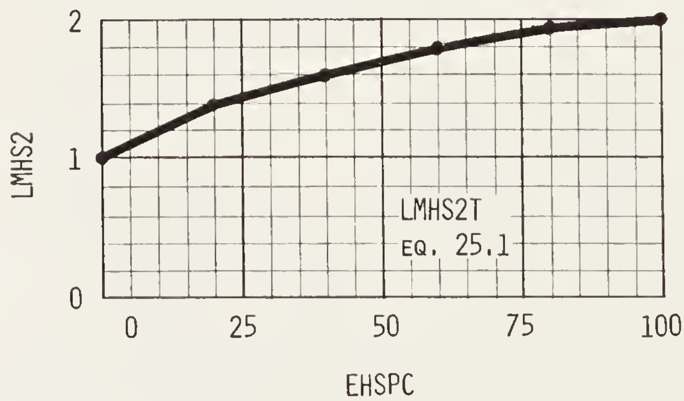


Figure 2-38 Lifetime multiplier from health services table

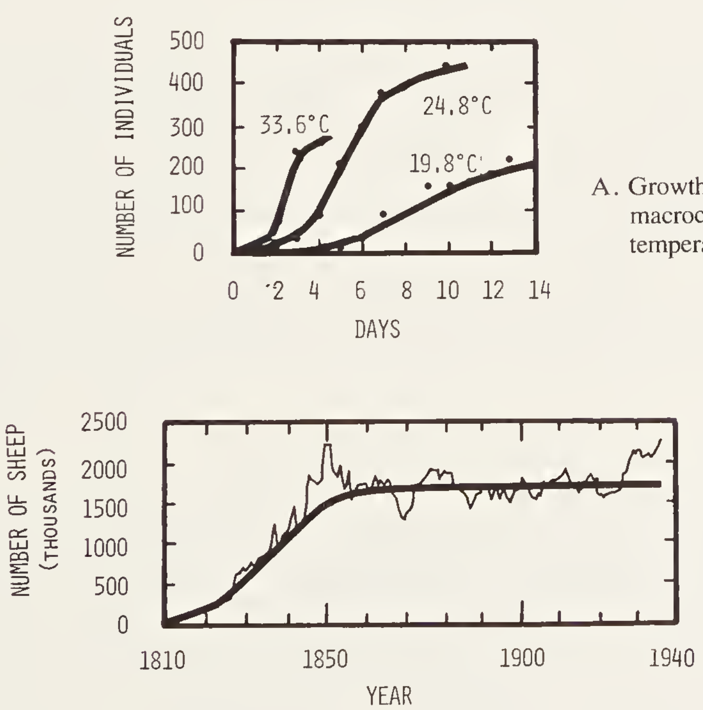
Lifetime Multiplier from Crowding LMC It is a common belief that the human population is self-regulating with regard to its own density. A self-regulating population is one that exhibits pure exponential growth only at low density and gradually decreases its growth rate as a function of its own increasing numbers. Finally, at high density a self-regulating population reaches a steady state with a zero net growth rate and no further population increase.

Many animal populations do indeed exhibit self-regulating behavior, gradually leveling off to some equilibrium population size. Such behavior results in a characteristic "sigmoid" or "logistic" growth curve (see Figure 2-39). In some cases these experimentally observed sigmoid growth curves can be fitted with the following modification of the exponential growth equation:

$$\frac{dN}{dt} = rN\left(\frac{K-N}{K}\right).$$

Here N is the total number of individuals in the population, K is the maximum supportable population in a given geographic area (sometimes called the carrying capacity), and r is the maximum rate of growth of the population under optimum conditions (in ecologists' terms, the biotic potential). The maximum possible growth rate is exhibited only when N is very small. As the size of the population increases, the intrinsic growth rate r is reduced by the factor (K−N/K), which finally equals zero when N = K.

This equation does not give a *causal* explanation of the factors reducing the growth rate at high population densities. It does not even specify whether the reduc-



A. Growth of the water flea (Moina macrocopa) at three different temperatures

B. Growth curve of sheep subsequent to their introduction in Tasmania

Figure 2-39 Sigmoid growth curves
Source: Kormondy 1969.

tion in growth rate occurs by means of a decrease in the birth rate or an increase in the death rate. In animal populations the principal mechanism appears to operate through the death rate:

> Populations are self-governing systems. They regulate their densities in relation to their own properties and those of their environments. This they do by depleting or impairing essential things to the threshold of favourability, or by maintaining reactive inimical factors, such as the attack of natural enemies, at the limit of tolerance. [A. J. Nicholson; quoted in Kormondy 1969, p. 105]

To what extent does the concept of a density-dependent growth rate apply to human populations? If it does apply, should it be represented as an influence that increases the death rate, decreases the birth rate, or both?

The first published world model World2 (Forrester 1971, p. 43) contained a density factor called the crowding ratio, a simple measure of population divided by land area. It was hypothesized that the crowding ratio influenced both the birth rate and the death rate, but through nonlinear multipliers rather than through the simple linear multiplier (K−N/K). These nonlinear multipliers were intended to represent the effect on the population growth rate of a number of possible biological and social responses to increasing density.

> Crowding is here assumed to include psychological effects, social stresses that cause crime and international conflict, the pressures that can lead to atomic war, epidemics, and any effects from too many people that are not more appropriately defined into the other influences that are represented in the model. [Forrester 1971, p. 43]

The World2 crowding ratio, as its author admits, is a simple, preliminary representation of an extremely complex set of phenomena about which very little is known. As Figure 2-40 indicates, even among groups of nations with some common cultural, climatic, or economic base, the relationship between population density and population growth rate is ambiguous, if indeed there is a discernible relationship at all. Furthermore, the statistics relating the density and the growth rates of specific subpopulations of the earth, which may effectively draw on resources outside their own boundaries, may have no relevance to the impact of the total population density on the entire global system, for the latter must be self-contained. On the other hand, although no clear influence on aggregate growth rates is apparent, some of the crowding effects cited by Forrester—stress, alienation, epidemics, social conflicts—are plausible mechanisms for population self-regulation, mechanisms that have been suggested by others, that have been observed in animal populations, and that deserve further study.

We assumed in World3, as Forrester did in World2, that there is a crowding modifier on the human death rate (the effect of crowding on the birth rate will be discussed later).* We included it because we believe there may be some important biological-sociological feedback from population size to population health beyond the

*In many animal populations, self-regulation under crowded conditions occurs through fetal and very early infant mortality. In field studies this effect may be interpreted as a lower birth rate; we would classify it as a higher death rate.

Country	Population Density (persons/km²)	Net Growth Rate (%/year)
Netherlands	319	1.0
Norway	12	0.7
United Kingdom	228	0.5
El Salvador	165	3.0
Brazil	11	2.8
Chile	13	1.9
Japan	280	1.2
United States	22	1.0
USSR	11	0.9
Rwanda	136	2.9
Tanzania	14	2.6
Zambia	6	2.9
Hong Kong	3829	2.4
Taiwan	390	2.3
Laos	13	2.5
Lebanon	248	2.5
Turkey	43	2.5
Jordan	24	3.3

Figure 2-40 Population densities and net population growth rates, 1970
Source: Appendix D to this chapter.

obvious feedbacks through food and health services. There seems to be little direct evidence that such a modifier does or does not exist. Because we know little about the possible magnitude of this factor, we assigned to it only a weak influence on the total behavior of the model. Several models of the mechanism behind the crowding factor might be imagined—most of them more complicated than a simple, immediate feedback from average population density. Some of the possible mechanisms will be discussed here to suggest alternatives to modelers who would like to explore this relationship further. The *last* mechanism described is the one actually included in World3.

1. Increased competition for a decreasing share of resources. One explanation for sigmoid growth curves in animal populations is that the growing population exerts an increasing pressure on some limited resource (food supply or nesting space, for example). As the average resource available per individual declines, the competition for the resource increases, resulting in a higher death rate for poor competitors through overt violence. In human populations, however, numerous economic and technological methods exist for resolving an increased competitive pressure on resources without necessarily causing a rising death rate. In fact, most of the rest of the world model is designed to represent these adaptive processes. If at some time the

economic-technological systems are not capable of handling the competitive demands of an increasing population, the result in the model is an input to the death rate through the lifetime multiplier from food LMF or through the lifetime multiplier from health services LMHS, or a change in the birth rate. Thus it is not necessary to include an explicit influence from crowding to express the effect of the conflict of individuals for decreasing resources.

It is also possible that population pressure on resources might result not in individual competition but in socially sanctioned war and thus in an increased death rate through international conflict. Studies of past international conflicts seem to indicate that, historically at least, there is little correlation between population density per se and participation in wars, although population density may be involved in a complicated interaction with many other factors (Bremer, Singer, and Luterbacher 1971; Choucri and North 1972). Since causal theories of social conflict and technology of international warfare are both evolving rapidly, we omitted this complex conflict factor from our representation of crowding in this preliminary model. It is a sociopolitical factor that may well stop growth below the physical limits we represent, and it may be directly dependent on pressures from those limits. It is an important subject for future research.

2. Increased exposure to infectious disease. The role of population density in the transmission of infectious diseases has been recognized by epidemiologists for decades (see, for example, Taylor and Knowelden 1957, p. 199). It has been vaguely sensed by the general populace for centuries. Until this century, cities were widely known as unhealthy places to live in because of crowding and pestilence. Life expectancy in London in 1841 was 35 years, in Liverpool and Manchester it was only 26 years, while for England as a whole it was 41 years (Glass 1964). In Stockholm in the eighteenth century, life expectancy was 16 years; for all of Sweden it was 35 years. In the United States in 1830 one-half of a cohort of age 5 would survive to age 65 in rural areas, to age 56 in small cities, and to age 41 in large cities (U. N. 1953, p. 52). The spread of the last plague epidemic in France was highly associated with the pattern of population concentrations (Biraben 1968).

These statistics pertained before medical control of infectious diseases eliminated those diseases as the major cause of human deaths. As public health techniques and medical knowledge improved, the rural-urban differential in life expectancies gradually decreased. In the United States in 1901, the average life expectancy for city dwellers was 10 years lower than that of the rural population; in 1910 it was 7.8 years lower; in 1939, 2.6 years lower (U. N. 1953, p. 62). There is some evidence that in several developing countries today urban life expectancy is actually higher than rural life expectancy because sanitary improvements and medical services are available only in cities (Arriaga 1967).

The relation between population density and the death rate from infectious diseases is clear; all else being equal, as the density increases, the death rate from infectious diseases would be expected to increase. The relation between density and overall life expectancy, however, must also take into account the relative contribution of infectious diseases to the total death rate. This contribution is high only in areas where effective health services per capita (defined previously) are low. Although crowding may have a significant effect on life expectancy in these areas, in most of the world today health services are more than adequate to control infectious disease.

A dynamic representation of the dependency of life expectancy on crowding as modified by the prevailing level of health care is shown in Figure 2-41. The influence of density on life expectancy is altered by the degree of control of infectious diseases, more control resulting in a smaller influence. "Living space" could be defined in terms of total land area or, more specifically, in terms of urban land area or actual housing space per person. Health service expenditures would be generated by the economy, as indicated in the discussion of the lifetime multiplier from health services in section 2.5.

3. Local pollution. Densely settled populations in industrialized areas create and consequently are exposed to local pollution. This pollution is dynamically different from the persistent global pollution modeled in the pollution sector of World3. Persistent global pollution includes long-lived, globally distributed pollutants that are incorporated widely in the biosphere and affect human health after a relatively long delay. They act by permeating the entire ecosystem, usually entering the human body through food or water. Examples are mercury, lead, many pesticides, polychlorobiphenyls, and radioactive wastes. Local pollution, on the other hand, consists of pollutants that are not of concern on a long-term global scale but are important to human health in industrialized, urban environments. Typically, local pollutants are absorbed by the human body with little delay after their generation, often through the lungs. Most of them are included in the designation "air pollution": sulfur and nitrogen oxides, carbon monoxide, complex hydrocarbons, asbestos, and airborne particles of some materials that are later dispersed to become global pollutants (mercury, lead, cadmium). Other important local pollutants may include contaminants of local water supplies and noise.

The relation between local pollution and human mortality has been documented in several large cities. Only a few examples from the growing epidemiological literature on air pollution will be cited here. During a two-week period in New York in 1963 an unusual increase in the concentration of sulfur dioxide (SO_2) to about twice its normal value resulted in an increase in overall mortality by a factor of about 1.2. There were statistically significant increases in deaths due to influenza-pneumonia,

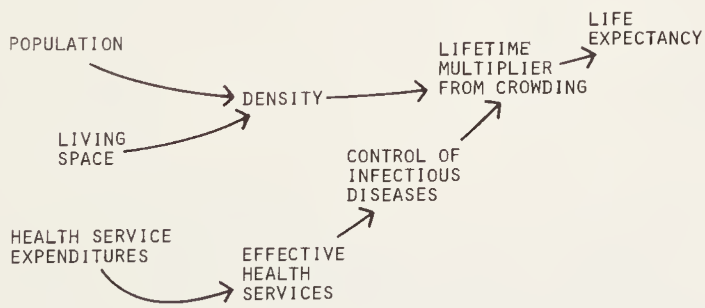


Figure 2-41 Influence of crowding on life expectancy through infectious diseases

vascular lesions affecting the central nervous system, and diseases of the heart. Accidents, homicides, suicides, and deaths in early infancy remained normal (Greenburg et al. 1967). A linear relationship between SO_2 concentration and excess mortality in Oslo and London has been demonstrated (Sweden 1972, p. 33). A two-year study in Buffalo, New York, divided the city into four areas on the basis of average measured pollution (suspended particulate levels) and then correlated the death rate from all causes with pollution and with economic level as shown in Figure 2-42.

A painstaking multiple regression analysis of the impact of air pollution and socioeconomic factors on the death rates in 114 U.S. metropolitan areas indicates a strong correlation between minimum measured air pollution and mortality (Lave and Seskin 1970). The conclusion of that study is that a 10 percent decrease in the minimum concentration of measured particles would decrease the total death rate by 0.5 percent; a 10 percent decrease in the concentration of sulfates would decrease the death rate by 0.4 percent; and an increase in density of 1 person per acre, holding all pollution and socioeconomic factors constant, would increase the death rate by 0.2 percent.

A proper dynamic representation of the local pollution aspect of crowding would relate population density to average exposure to various sorts of local pollutants and then relate pollution exposure to changes in life expectancy. For a particular geographic area such a model would require a great deal of information about human settlement patterns, industrial activities, and weather, as well as epidemiological data. On a broad global scale it is probably sufficient to recognize only the difference between rural and urban populations. If only 10 percent of the population lives in urban areas, 10 percent of the population is exposed to local urban pollution. The amount of exposure received by the urban population depends on the general type and level of industrial activity and on the measures taken to reduce pollution generation from that activity. The causal diagram in Figure 2-43 represents two assumptions: that all city dwellers are equally exposed to pollutants generated in cities, and that virtually all industrial air pollution is generated in the vicinity of cities.

Economic	Particulate Level				
Level	**1 (Low)**	**2**	**3**	**4 (High)**	**Total**
1 (low)	—	36	41	52	43
2	24	27	30	36	29
3	—	24	26	33	25
4	20	22	27	—	22
5 (high)	17	21	20	—	19
Total	20	24	31	40	26

Figure 2-42 Correlation between particulate levels and death rate

Note: Average annual death rates per 1,000 population from all causes according to economic and particulate levels: white males, 50–69 years of age, Buffalo and environs, 1959–1961.

Source: Winkelstein 1967.

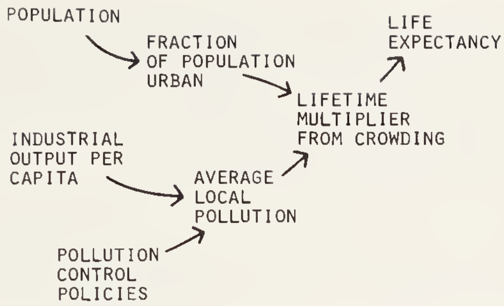


Figure 2-43 Influence of crowding on life expectancy through local pollution

4. Social stress. Since the triumph of medicine over infectious diseases, many researchers in epidemiology have turned to the study of the chronic, degenerative diseases that are now the leading causes of death in the industrialized countries of the world. From this study a new theory of disease is emerging, one that suggests two equally important factors in human health: the presence of harmful foreign substances or virulent microorganisms, and the ability of the body to resist the harmful incursions of these substances or microorganisms. For some diseases, but not all, the resistance or intrinsic health of the human body may be the determining factor in the manifestation of the disease.

> . . . the microbial diseases most common in our communities today arise from the activities of microorganisms that are ubiquitous in the environment, persist in the body without any obvious harm under ordinary circumstances, and exert pathological effects only when the infected person is under conditions of physiological stress. In such a type of microbial disease, the event of infection is of less importance than the hidden manifestations of the smouldering infectious process and than the physiological disturbances that convert latent infection into overt symptoms and pathology. [Dubos 1965, pp. 164–165]

The "physiological stress" leading to disease has been interpreted by several authors to include social or psychological stress that in turn seem to be associated with industrialization, urbanization, and crowding (for a review, see Dodge and Martin 1970, chap. 2). Numerous indications of a relationship between crowding and physiological stress have been cited. They range from observations of animal behavior under crowding (Calhoun 1962, Welch 1964) to measurements of blood pressure as a function of age in different rural and urban societies (summarized in Cassel 1971). A careful statistical analysis of crowding in the city of Chicago indicates a clear correlation between social pathologies, including higher mortality, and crowding (measured by persons per room and rooms per housing unit) even when other socioeconomic variables are controlled (Galle, Gove, and McPherson 1972). In the United States the age-adjusted death rate for arteriosclerotic heart disease is 301.3 per hundred thousand in highly urbanized California and only 155.5 in largely rural New Mexico. The age-adjusted death rate from coronary heart disease in New York City is consistently higher than the age-adjusted death rate from *all* causes in North Dakota (Dodge and Martin 1970, p. 8). Certainly these differentials may be partially attributed to local pollution, diet, and exercise rather than social stress. It is more difficult to explain why high rates of arteriosclerotic heart disease and malignant neoplasms are strongly associated with high suicide rates in urban areas, or why in most areas widowed persons have higher death rates than single, married, or divorced persons of the same age (Dodge and Martin 1970, p. 9).

The role of social stress as a factor in human health is by no means widely recognized by the medical profession or fully established by experiment. Still less certain is the association between social stress and crowding. Most authors agree that, although crowding is statistically correlated with high death rates from chronic or degenerative diseases, crowding per se may not be the causal factor but, rather, the perception of crowding. In other words, the crowding that may lead to a breakdown of an individual's resistance to disease may be related to that individual's past experience and to his present value system, in relation to the present value system of the crowded area in which he lives. According to Calhoun (1970, p. 117), "Crowding thus must also be assessed on the basis of degree of harmony among the held values of the individuals who are sufficiently contiguous to be aware of each other's presence."

Thus a dynamic model of the effect of crowding on human life expectancy through social stress might include an input from rate of change of crowding. According to this model a negative contribution to the aggregate health of a population would occur when the crowding change rate becomes greater than the time necessary to readjust living conditions and personal expectations to new degrees of crowding (Figure 2-44).

> . . . the relatively simplistic notion that crowding exerts its deleterious effects solely through facilitating the interpersonal spread of disease agents is no longer adequate to explain the known phenomena. A more appropriate formulation would seem feasible if we recognize that increased population density increases the importance of the social environment as a determinant of physiological response to various stimuli, including potentially disease-producing agents; that within this social environment the quality of social interactions and position within the group seem to be important factors; and that, given time, adaptation to these social changes can and does occur, but the newcomers to the situation will always be the segment of the population at highest risk. [Cassel 1971, p. 475]

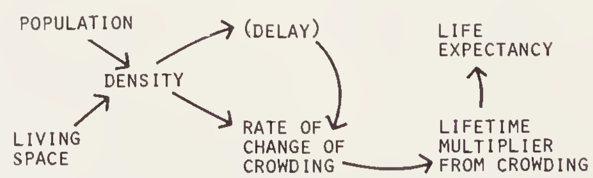


Figure 2-44 Influence of crowding on life expectancy through social stress

5. Crowding in World3. A thorough representation of the complicated effects of crowding on human health should probably include all the structures proposed here, and perhaps some other factors as well. Such a detailed crowding factor would not be appropriate for World3, given the poor quality of the data available and the low level of detail in other sectors. On the other hand, urbanization and increasing population density appear to be such important factors in the world situation that they should not be completely ignored in a representation of long-term global trends. In 1900, 11 cities in the world had populations exceeding 1 million; in 1950 there were 75; in 1985 there will probably be 273 (U. N. 1972*b*). Therefore, we attempted to include a crowding effect in the world model, but with as few variables as possible. In doing so we may have lost some important short-term dynamic behavior, but we are only interested here in the possible long-term impact of increasing urbanization and population density on global population growth.

The causal structure of the crowding influence in World3 is shown in Figure 2-45. We made crowding a function not only of total population, reflecting the spread of infectious diseases, but also of industrialization, reflecting both the positive health effect of industrialization on the prevention of those diseases and the negative health effect of large industrial cities through exposure to pollution and stress. A detailed discussion of the assumptions behind this structure and its quantification follows.

As Figure 2-45 indicates, crowding in World3 is represented by the fraction of the population living in urban areas. Thus by crowding we actually mean urbanization, defined not as the absolute number of people in cities but as the proportion of the total population in cities. A nation may have growing cities, but its urbanization does not increase unless the population of its cities is growing faster than its rural population.

There are two possible causes for increasing global urbanization. Historically, the formation and the growth of cities in different nations have been closely related to

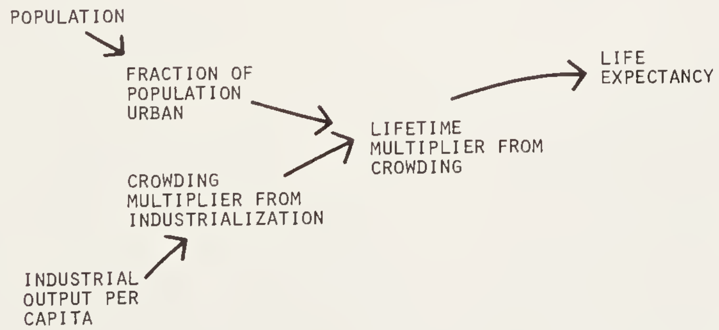


Figure 2-45 Influence of crowding on life expectancy as represented in World3

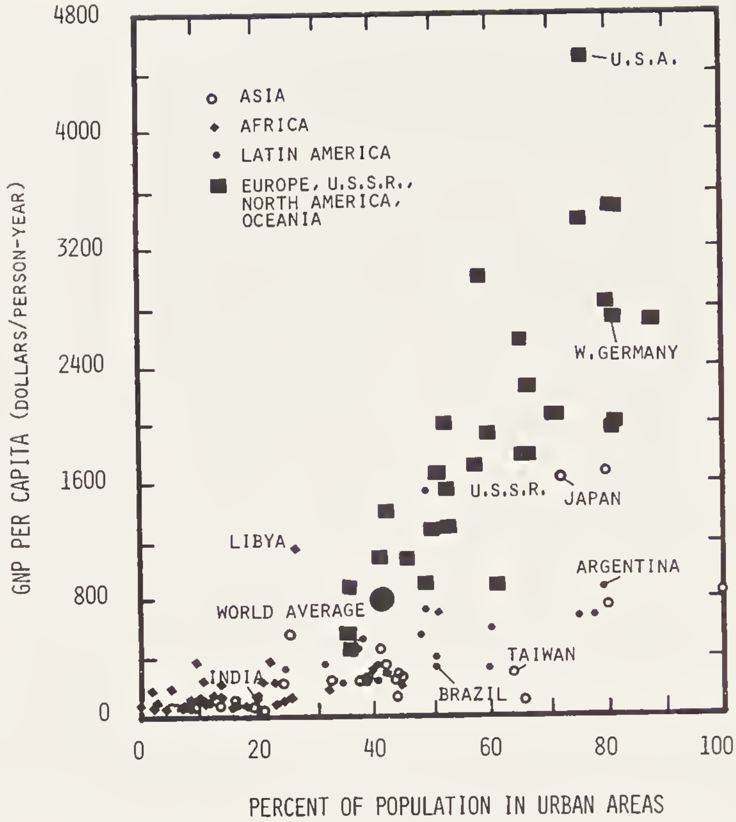


Figure 2-46 Urbanization versus GNP per capita, 1965
Source: J. L. Fisher and N. Potter, "The Effects of Population Growth on Resource Adequacy and Quality," in *Rapid Population Growth* (Baltimore: The Johns Hopkins University Press for the National Academy of Sciences, 1971), © 1971 by the Johns Hopkins University Press.

industrial development. Large industries both require and make possible the concentration of people in urban areas. To some extent this relationship still holds today (Figure 2-46). However, one might also argue that urbanization is simply a function of total population size. As the population grows, the new numbers must be accommodated in cities, since jobs and sustenance in rural areas are not increasing. There is also historical evidence to support this assumption; the globe's urban population has been a regularly increasing proportion of its total population (Figure 2-47). It is probably impossible to decide between these two causal hypotheses statistically, since industrialization and total population are themselves closely related.

We chose to express the fraction of population urban FPU as a table function of total population POP rather than of industrial or total output per capita. We did so primarily because several authors have suggested that the process of urbanization now occurring in nonindustrialized countries is different from the historical urbanization pattern and is more related to total population growth than to economic development (Davis 1965; U.N. 1972*a*, p. 26). As Figure 2-48 indicates, the developed countries

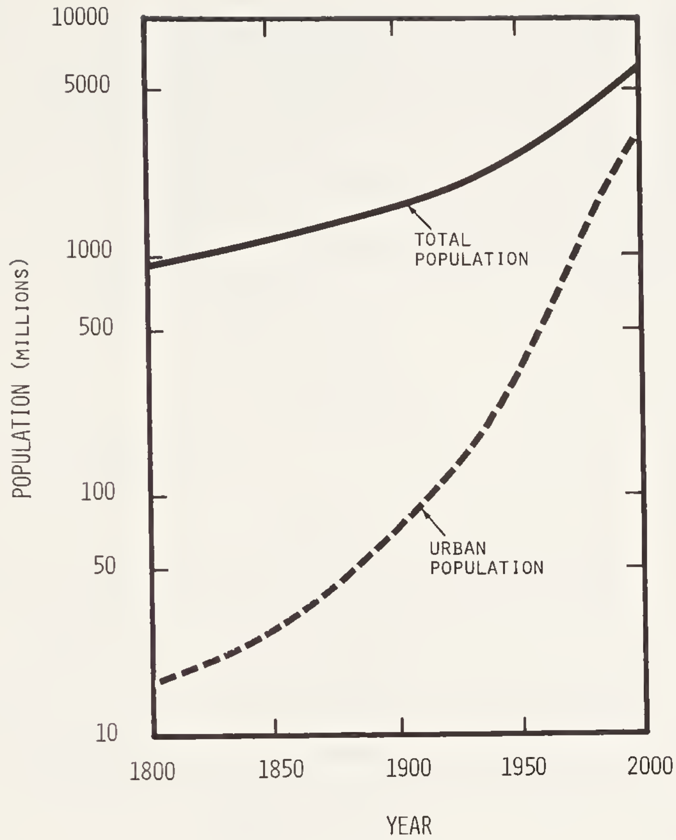


Figure 2-47 Global urbanization as a function of time
Source: From "The Urbanization of the Human Population" by Kingsley Davis. Copyright © 1965 by Scientific American, Inc. All rights reserved.

built their cities at least in part by attracting population away from the rural areas with urban industrial jobs. The developing countries, faced with population growth rates far higher than any ever observed before in the history of man, are currently forming cities much faster than the developed countries did; yet their rural populations are also growing. These cities are not necessarily growing because of economic support for greater urban population density.

> In some countries the growth of urban population is accompanied by a corresponding industrialization, development of transport and communications, and by decreases in the relative size, and increases in the efficiency, of the agricultural labour force. In many countries, however, this is far from being the case. All too often the movement of migrants from rural to urban areas causes an excessive accumulation of the labour force in marginal service activities, and of families and households in substandard or hastily improvised housing. Nevertheless, judging from the unbroken momentum of urbanization during several decades of the past, even inferior economic and social conditions are rarely a deterrent in this seemingly irreversible movement. [U. N. 1972*a*, *p*. *26*]

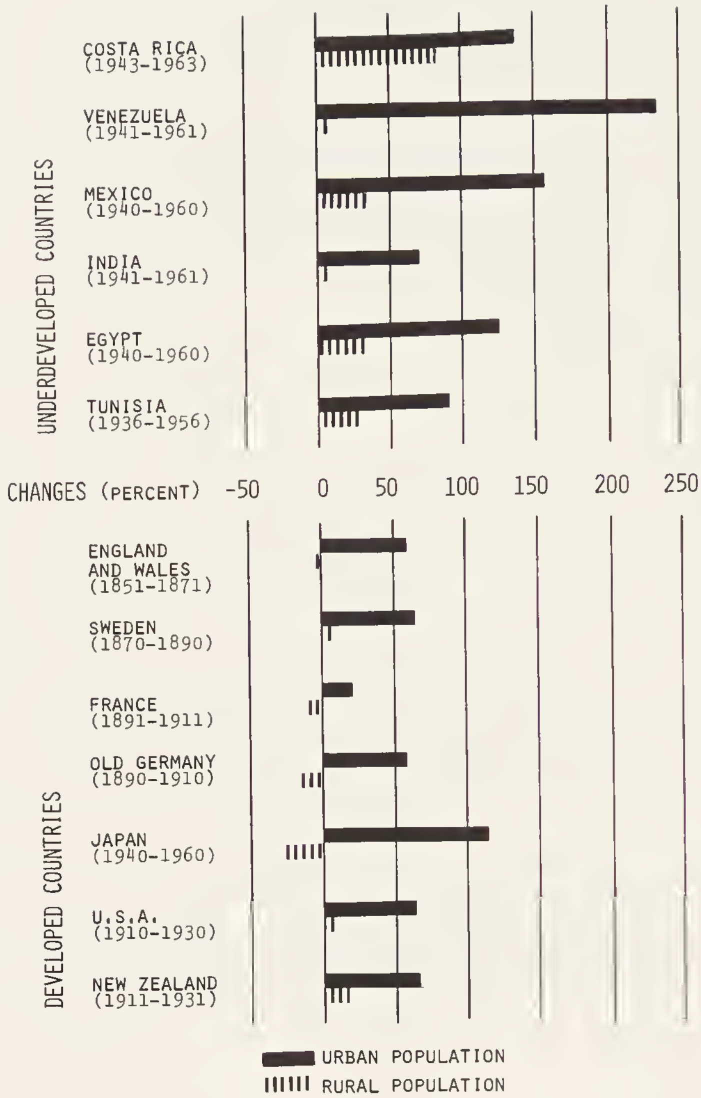


Figure 2-48 Patterns of urbanization in industrialized and nonindustrialized areas
Source: From "The Urbanization of the Human Population" by Kingsley Davis. Copyright © 1965 by Scientific American, Inc. All rights reserved.

The numerical relationship we chose to generate the fraction of population urban FPU as a function of total population POP is shown in Figure 2-49 and is expressed by the following equations:

```
FPU.K=TABHL(FPUT,POP.K,0,16E9,2E9)                     26, A
FPUT=0/.2/.4/.5/.58/.65/.72/.78/.80                     26.1, T
    FPU    - FRACTION OF POPULATION URBAN
                 (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FPUT   - FPU TABLE
    POP    - POPULATION (PERSONS)
```

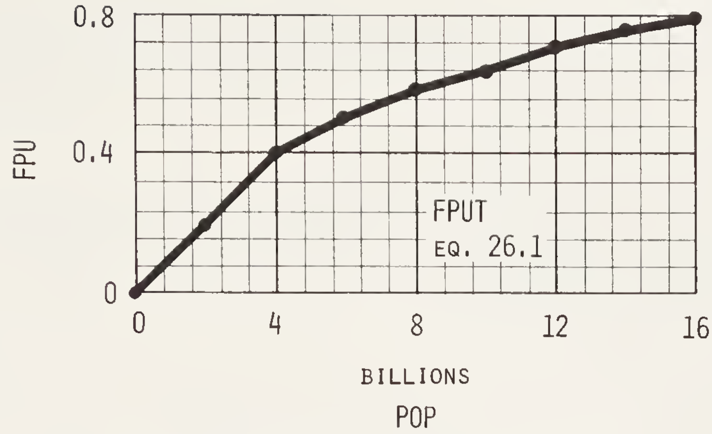


Figure 2-49 Fraction of population urban table

Figure 2-50 shows the same relationship, including United Nations estimates and projections for total and urban populations from 1950 to 2000.

The fraction of population urban FPU indicates the proportion of the human population that is exposed to the effects of crowding on health. The magnitude of these effects depends, directly or indirectly, on the level of industrialization. We assumed that this dependence is linear, with a variable slope, as shown in Figure 2-51. The slope, called the crowding multiplier from industrialization CMI, is a

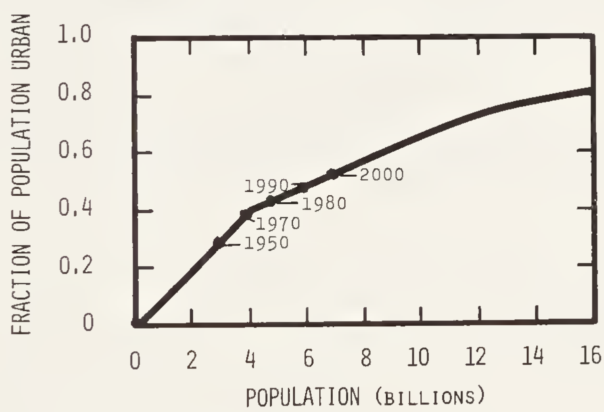


Figure 2-50 Fraction of population urban versus population, historical and estimated
Source: U.N. 1970, p. 24.

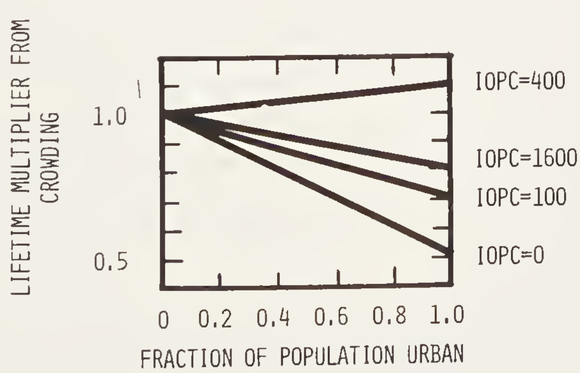


Figure 2-51 Lifetime multiplier from crowding versus fraction of population urban

function of industrial output per capita IOPC. The equations for the relationship follow, and the table illustrating the range of CMI is shown in Figure 2-52.

```
CMI.K=TABHL(CMIT,IOPC.K,0,1600,200)                         27, A
CMIT=.5/.05/-.1/-.08/-.02/.05/.1/.15/.2                     27.1, T
    CMI     - CROWDING MULTIPLIER FROM INDUSTRIALIZATION
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    CMIT    - CMI TABLE
    IOPC    - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                PERSON-YEAR)

LMC.K=1-(CMI.K*FPU.K)                                       28, A
    LMC     - LIFETIME MULTIPLIER FROM CROWDING
                (DIMENSIONLESS)
    CMI     - CROWDING MULTIPLIER FROM INDUSTRIALIZATION
                (DIMENSIONLESS)
    FPU     - FRACTION OF POPULATION URBAN
                (DIMENSIONLESS)
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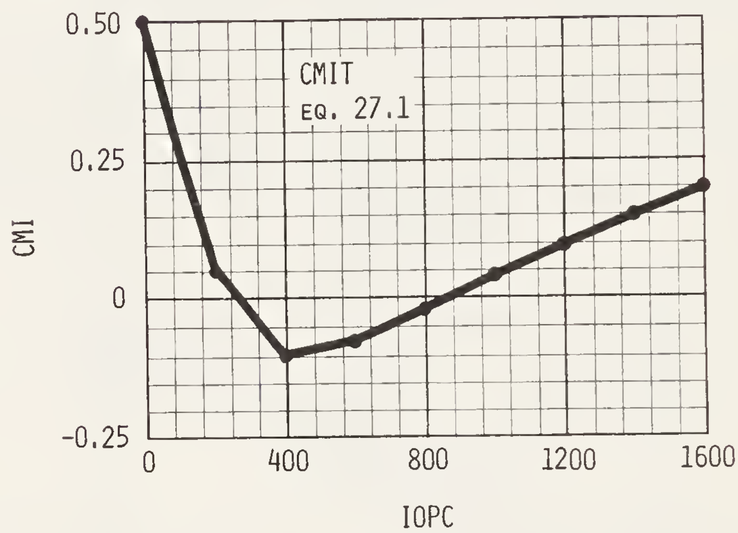

Figure 2-52 Crowding multiplier from industrialization table

The preceding equations incorporate the assumption that at very low industrial output per capita IOPC crowding affects life expectancy entirely through the spread of infectious disease. We estimate that the maximum reduction of life expectancy for urban populations under this condition is 50 percent, as illustrated by the line IOPC = 0 in Figure 2-51. Thus at IOPC = 0, the crowding multiplier from industrialization CMI equals 0.50 (see Figure 2-52). This estimate is based on the data from the seventeenth- and eighteenth-century European cities cited earlier. As IOPC rises, the threat of infectious disease decreases, and at an intermediate IOPC (225–900 dollars per person-year) we assumed that higher urbanization somewhat increases life expectancy by making health care programs easily accessible to the population (line IOPC = 400 in Figure 2-51). Above IOPC = 900, crowding again begins to have a deleterious effect because of local pollution and social stress-related diseases. Crowding at high IOPC never becomes as detrimental to health as crowding at low IOPC. The maximum reduction in life expectancy from crowding in economically developed cities was assumed to be 20 percent (CMI = 0.20 at IOPC = 1600).*

As represented in World3, crowding implies no absolute upper limit to population density, as did crowding in World2. The main dynamic effect of crowding occurs only under the condition of a very high population combined with very low industrialization, one that is rarely generated in world model runs. It may be that an absolute psychosocial limit to crowding and urbanization could be encountered after another doubling or two of the earth's population. Since present systems offer ample evidence of local populations living and growing in extremely high-density environments, however, we did not postulate an absolute crowding limit, at least within the few doublings that the population is allowed by other limits in World3. If other modelers feel that such a crowding limit is justified, it can easily be added to the model equations.

Lifetime Multiplier from Pollution LMP The lifetime multiplier from pollution LMP expresses only the effect of globally distributed, persistent pollutants on human health. The effect of short-lived local pollution is included in the lifetime multiplier from crowding LMC discussed earlier. Interference of pollution with other forms of life, and thus with the human food supply, is represented in World3 by the land yield multiplier from air pollution and the land fertility degradation rate, both described in the agriculture sector (Chapter 4).

A complete dynamic analysis of the relationship between any single pollutant and the health of the human population should ideally be based upon the following information:

1. The present ambient concentration and concentration trends over time of the pollutant in the primary substances that enter the human body—air, water, and food.
2. The rate of absorption of the pollutant into human body tissues as a function of its concentration in air, water, and food.
3. The rate of excretion or metabolic transformation to a harmless form, as a function of the concentration of the pollutant in various tissues.
4. The relation between the concentration of the pollutant in various tissues and the appearance of pathologic symptoms, both short term and long term.
5. The quantitative relationship and the average delay time between pollution-induced pathology and mortality.
6. The extent to which the effects of the pollutant are enhanced or mitigated by the presence of other pollutants.

*In future models the bimodal curve shown in Figure 2-52 could be resolved into the two influences it actually represents: a decreasing crowding multiplier from effective health services per capita and an increasing crowding multiplier from industrial output per capita.

Although some of these facts are known for some pollutants, all the information required for a dynamic analysis is not yet available for any single pollutant, much less for the entire mix of pollutants actually encountered by the globe's population. We shall give a few specific examples here merely to establish the fact that global pollutants may come to have a significant influence on human life expectancy, not to give an exhaustive summary of the field of environmental health.

The heavy metal lead is a fairly well understood and carefully measured persistent pollutant with proved deleterious effects on human health. As a local pollutant its concentration in the air averages 1.0 micrograms per cubic meter in U.S. cities; as a more widely distributed pollutant its air concentration averages 0.5 micrograms per cubic meter in U.S. rural areas (Chisolm 1971). Peak readings in New York City have reached 34 micrograms per cubic meter (Bazell 1971). As an aerosol, lead is globally distributed by air currents, and its rate of deposition in the Greenland ice sheet appears to be rising rapidly (Weiss, Koide, and Goldberg 1971; see also discussion in Dickson and Patterson et al. 1972). The intake of lead in food and water in the United States averages 300 micrograms per person per day (Schroeder 1970). Approximately 5 percent of the lead ingested and 40 percent of that inhaled are retained in the body (Patterson 1965).

Symptoms of lead toxicity begin to appear in adults with blood lead concentrations of 60–80 micrograms per 100 milliliters (ml). For comparison with that figure, blood samples from residents of the rural United States averaged 16 micrograms per 100 ml and urban citizens averaged 21 micrograms per 100 ml (Chisolm 1971). One-fourth of 80,000 preschool children tested in New York City had blood lead concentrations of 40 micrograms per 100 ml or more. Newborn babies in New York City average the same blood lead concentrations as their mothers—20–30 micrograms per 100 ml (Bazell 1971). The delay between high blood lead levels and observable symptoms may be only a few weeks when the levels are high (leading to acute plumbism) but as long as ten years when levels are maintained at the lower limits of 60–80 micrograms per 100 ml (leading to chronic nephritis) (Chisolm 1971). Little statistical information is available about the effects of lead pollution on aggregate mortality, and none about the interactions of lead with other pollutants in the body.

As an example of a very different sort of pollutant, one of the most recently discovered and least understood of the global pollutants is polychlorobiphenyl (PCB). The abbreviation PCB actually stands for a whole family of closely related chlorinated hydrocarbons that have been used for a variety of industrial purposes since the 1920s. Polychlorobiphenyl was first identified as a common environmental contaminant in 1966, when it was found in bird feathers, fish, and human fat tissues (for a review, see Jensen 1972). The present PCB concentration in U.S. water samples ranges from 0.1 to 4.0 parts per billion, and in the average U.S. diet it is about 0.5 parts per million (Maugh 1972). The typical concentration in adipose tissue from American subjects is 1 part per million (Maugh 1972); the blood of Swedish subjects carried 10 parts per billion (Jensen 1972). Japanese patients exhibiting acute PCB intoxication from an industrial accident had concentrations of about 29 parts per million. Although human deaths from acute PCB poisoning have occurred (Jensen 1972) and PCB has caused great disruption in wild and domestic animal populations (Maugh 1972), PCB is not believed to be very toxic in low concentrations. The long-term influence of low-level exposure on total mortality is unknown. PCB is chemically similar to DDT, and the retention of PCB in fat tissue seems to be enhanced by DDT (Södergren and Ulfstrand 1972). Other possible synergistic effects have not yet been explored.

Numerous other global persistent pollutants are known to have a negative influence on human health; obvious examples are cadmium, mercury, long-lived pesticides, and a number of radioactive isotopes. There are undoubtedly others that, like PCB, will only be discovered and fully characterized after years of regular use and accumulation in the environment. Given that even those pollutants that are recognized are not understood well enough to be represented in a complete dynamic model, it is clearly impossible to represent a lifetime multiplier from all pollutants on a global level with accuracy. On the other hand, some qualitative knowledge does exist, and that knowledge should be included in a global model, both as a summary of what is now known and as a placeholder for a more precise statement that may be added later as more information becomes available.

If an increase in the average 1970 global pollution level by a factor of 100 would have no effect on life expectancy, the lifetime multiplier from pollution would always be 1.0 and could be represented by the straight line A in Figure 2-53. Even the partial information currently available about global pollutants suggests that increases in ambient pollution levels by factors far less than 100 may have a significant negative effect on human life expectancy. Thus we have enough information about the effects of pollution on human health to rule out curve A and to eliminate all curves such as B that have a rising slope, which would imply that pollution increases life expectancy. The correct relationship must have a negative slope and must be included somewhere within the family of curves labeled C in Figure 2-53.

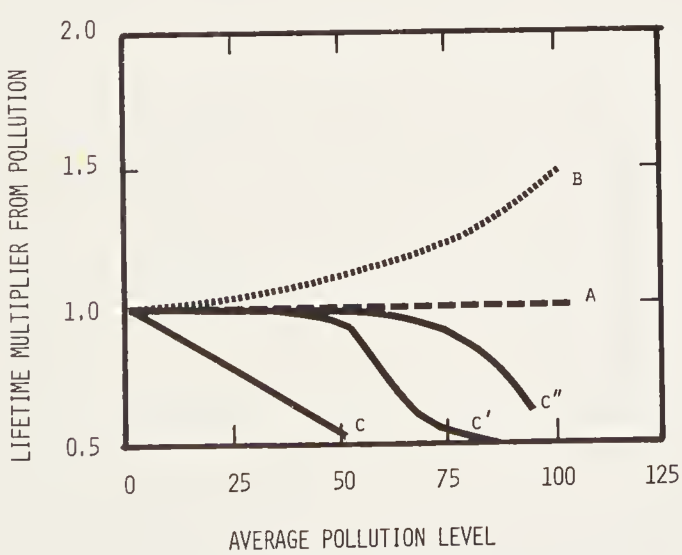

Figure 2-53 Possible effects of pollution on life expectancy

Which of the downward-sloping curves in Figure 2-53 best represents the real relationship between pollution and life expectancy? That question cannot be answered on the basis of currently available data. We arbitrarily chose for inclusion in World3 the curve illustrated in Figure 2-54 and described by the following equations. This relationship reduces life expectancy by only 10 percent under pollution levels 40 times the average 1970 level.

```
LMP.K=TABHL(LMPT,PPOLX.K,0,100,10)                       29, A
LMPT=1.0/.99/.97/.95/.90/.85/.75/.65/.55/.40/.20       29.1, T
    LMP    - LIFETIME MULTIPLIER FROM PERSISTENT
             POLLUTION (DIMENSIONLESS)
TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
LMPT   - LMP TABLE
PPOLX  - INDEX OF PERSISTENT POLLUTION
             (DIMENSIONLESS)
```

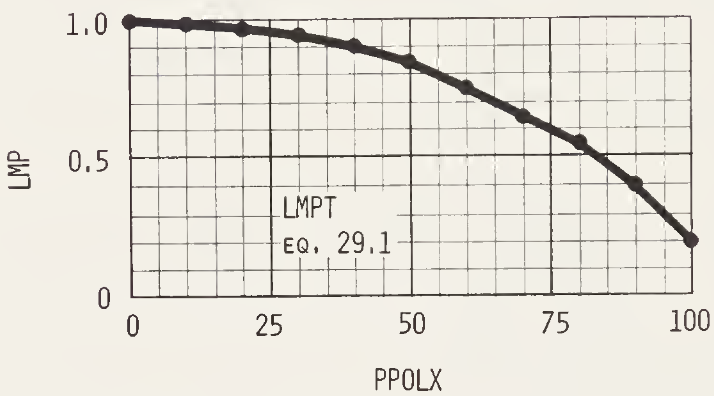

Figure 2-54 Lifetime multiplier from pollution

The numerical values we chose for the lifetime multiplier from pollution LMP probably err on the side of conservatism. The model runs in Chapter 7 will show that LMP has almost no effect on the model's behavior except under very extreme conditions—when the level of pollution grows so fast that any downward-sloping LMP curve would be activated. Alternative curves, more pessimistic and more optimistic, can be included in model runs as a test of the sensitivity of the total system behavior to variations in this poorly understood relationship. Variations in this function can have significant effects on the timing or severity of the population overshoot under conditions of high pollution. As long as the slope of the function is negative, however, the basic nature of the model behavior mode is insensitive to changes in its precise mathematical form.

Although the pollution and crowding multipliers of life expectancy LMP and LMC can be represented only tentatively at present, there is evidence that some such factors are beginning to affect aggregate mortalities in industrialized countries. In some Western countries the life expectancy at birth, which has risen steadily for decades, has not only leveled off but has turned slightly downward. This small decrease in life expectancy seems to be due to an increase in the incidence of chronic

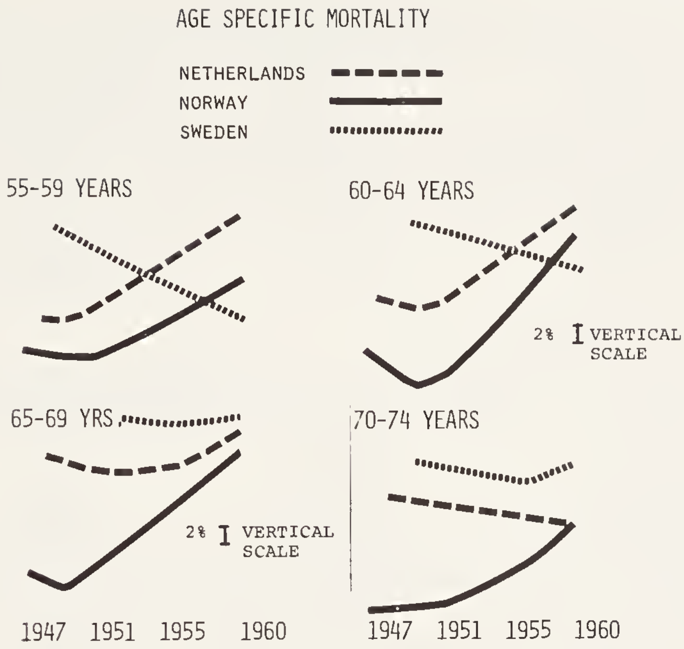

Figure 2-55 Rising age-specific death rates, Norway, Sweden, and the Netherlands
Source: Légaré 1967.

degenerative diseases in the population over age 55. The increase is illustrated by the rising age-specific death rates at high ages in three European countries, shown in Figure 2-55. It is not possible to tell whether this increase is due to pollution, crowding, or some as yet unidentified factor.

Fertility Equations

Birth Rate B The number of births per year B is calculated in World3 from a purely demographic factor, the number of fertile women in the population, and from a socioeconomic factor, the average number of births per woman per year.

The number of fertile women is determined by the total size and the age structure of the population, thereby reflecting the birth and death rates that the population has experienced over the past fifty years. In the more complete representations of population age structure (described later) the number of fertile women is calculated directly. In the simple one-level population model it is assumed that the fraction of the population consisting of women in the fertile age period (age 15–45, approximately) is constant. This constant, called the fraction of fertile women FFW, is set at 0.22. This approximation is accurate to about 10 percent, as indicated by theoretical age structures of stable populations with all combinations of low and high birth or death rates and by actual age structures of modern countries with varied demographic histories, as shown in Figure 2-56.

The average number of births per woman per year is influenced both by the total number of children borne by each woman during her lifetime and by the age of each woman at the birth of each child. The average total number of children borne per

1. Theoretical, stable populations

Gross Reproduction Rate	Life Expectancy	Fraction of Women 15–45
1.5	35	0.237
1.5	69	0.229
3.0	35	0.222
3.0	69	0.247

2. Real populations

Country	Date	Fraction of Women 15–45
Mauritius	1959	0.210
United Kingdom	1959	0.205
Japan	1960	0.245
India	1951	0.230
United States	1960	0.205

Figure 2-56 Fraction of women of fertile ages in theoretical and real populations
Sources: (1) Coale and Demeny 1966, pp. 184, 212; (2) Ehrlich and Ehrlich 1970, pp. 26–30.

woman over her entire reproductive lifetime is called the total fertility TF. In the models where age structure is specifically calculated, TF is allocated by age according to established age-specific fertility patterns. In the one-level model, TF is assumed to be distributed evenly over the entire reproductive lifetime. Thus the average number of births per woman per year is represented by total births per woman TF divided by the number of years of female reproductive lifetime (RLT = 30). The approximation of constant age-specific fertility tends to underestimate the real birth rate slightly, since more children are actually borne during the first half of the female reproductive period than during the second half.

The equation representing the birth rate in the one-level model is given below; the birth rate equations for the age-disaggregated models are shown later in this section.

```
B.KL=CLIP(D.JK,(TF.K*POP.K*FFW/RLT),TIME.K,PET)
FFW=.22
RLT=30
PET=4000
    B      - BIRTHS PER YEAR (PERSONS/YEAR)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    D      - DEATHS PER YEAR (PERSONS/YEAR)
    TF     - TOTAL FERTILITY (DIMENSIONLESS)
    POP    - POPULATION (PERSONS)
    FFW    - FRACTION FERTILE WOMEN (DIMENSIONLESS)
    RLT    - REPRODUCTIVE LIFETIME (YEARS)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PET    - POPULATION EQUILIBRIUM TIME (YEAR)
```

The CLIP function in the birth rate equation represents a test option that allows the modeler to set the birth rate equal to the death rate (and thus to stabilize the population) at any chosen population equilibrium time PET. If it is not specifically reset by the operator, PET is set at the year 4000 so that the CLIP function is not activated during a model run from 1900 to 2100.

The crude birth rate CBR, like the crude death rate CDR, is calculated only for purposes of display on output graphs and does not influence any other variable in the model. The world average crude birth rate in 1969 was about 36 per 1,000 persons (USAID 1971). National averages in that year ranged from 50 (Iran, Kuwait, Ghana) to 14 (Sweden, East Germany).

```
CBR.K=1000*B.JK/POP.K                                      31, S
    CBR     - CRUDE BIRTH RATE (BIRTHS/1000 PERSON-YEARS)
    B       - BIRTHS PER YEAR (PERSONS/YEAR)
    POP     - POPULATION (PERSONS)
```

The total fertility TF is a function of many factors—some biological, some cultural or psychological, some economic. The rest of the fertility sector of World3 is devoted to the representation of inputs to this function. Total fertility can vary widely from population to population, as indicated by the values shown in Figure 2-57.

In the world model we separated the inputs to total fertility into three functional categories:

1. involuntary biological factors that influence the fecundity,* or the ability of the population to bear children (maximum total fertility MTF);
2. voluntary or social factors that influence the desire of the population to bear children (desired total fertility DTF); and
3. the means available to the population to attain the desired rather than the maximum family size (fertility control effectiveness FCE).

Determinants of each of these categories will be discussed in detail later. Here we describe how they are brought together in an equation that generates actual total fertility TF.

```
TF.K=MIN(MTF.K,(MTF.K*(1-FCE.K)+DTF.K*FCE.K))        32, A
    TF      - TOTAL FERTILITY (DIMENSIONLESS)
    MIN     - MINIMUM VALUE FUNCTION
    MTF     - MAXIMUM TOTAL FERTILITY (DIMENSIONLESS)
    FCE     - FERTILITY CONTROL EFFECTIVENESS
                (DIMENSIONLESS)
    DTF     - DESIRED TOTAL FERTILITY (DIMENSIONLESS)
```

Fertility control effectiveness FCE is defined not in terms of particular birth control methods but in terms of the degree of control afforded by the entire spectrum of methods practiced by the population, for example, abortion, long lactation, and all forms of abstinence, including late marriage and sexual taboos. It is measured on a scale from 0 to 1. If a population has no control whatsoever over its own reproductive behavior, FCE = 0, and the actual total fertility TF will be equal to the biologically determined maximum total fertility MTF. If the population is able to practice perfect

*"Fecundity" and "fertility" are used here in the English sense, which is the reverse of the French usage. Fecundity here refers to the biological capability to produce children, fertility to the rate at which they are actually produced. Thus fecundity defines the biological upper limit of fertility.

Country	**Total Fertility** (average total live births per woman)
Japan	1.978
Sweden	2.296
Italy	2.362
United Kingdom	2.506
Argentina	2.962
Netherlands	3.174
United States (white)	3.674
Canada	4.075
Chile	4.537
China (mainland)	4.7–4.9
India	5.424
Brazil	5.768
Indonesia	6.115
Mexico	6.268
Nigeria	6.2–6.5
Ghana	6.860
Iraq	7.243
Ecuador	7.598

Figure 2-57 Total fertilities, various nations, 1955–1960

fertility control, FCE = 1, and its actual total fertility TF will equal its desired total fertility DTF. If the fertility control methods employed are effective just half the time, the actual total fertility will be halfway between the desired and the maximum fertilities. These statements are expressed mathematically by the equation

$$\text{TF} = \text{MTF} \times (1 - \text{FCE}) + \text{DTF} \times (\text{FCE}),$$

which is perhaps more easily understood in the algebraically equivalent form:

$$\text{TF} = \text{MTF} - (\text{MTF} - \text{DTF}) \times \text{FCE}.$$

It should be noted that under differing circumstances the factors DTF, MTF, and FCE can vary widely and produce a number of different fertility patterns. For example, even if fertility control is completely effective (FCE=1) the expression above can generate either a high or a low birth rate depending on whether the desired total fertility DTF is high or low. Similarly, if desired total fertility DTF is very low, the actual total fertility TF may be high or low, depending on the value of FCE.

It is possible that a population might desire more children than it is physiologically capable of bearing. Under this condition, the total fertility TF should equal the maximum total fertility MTF, regardless of the value of FCE. Therefore, a minimizing function MIN is added to the equation to ensure that the calculated fertility never exceeds the fertility that is biologically possible, whatever the desired fertility might be.

Population	Total Fertility Ages 20–44	Ratio to Hutterites
Hutterites: marriages, 1921–1930	10.635	100.0
Canada: marriages, 1700–1730	10.645	100.1
Hutterites: marriages before 1921	9.650	90.7
Bourgeoisie of Geneva: wives of men born 1600–1649	9.335	87.8
Europeans of Tunis (notabilities excluded): marriages, 1840–1850	9.070	85.3
Sotteville-les-Rouen (Normandy): marriages and births, 1674–1742	8.900	83.7
Crulai (Normandy): marriages, 1674–1742	8.275	77.8
Norway: marriages, 1874–1876	7.930	74.6
Bourgeoisie of Geneva: wives of women born before 1600	7.380	69.4
Iran (villages): marriages, 1940–1950	7.375	69.3
Taiwan (rural region of Yunlin): women born about 1900	6.910	65.0
India (Hindu villages of Bengal): marriages, 1945–1946	6.025	56.7
Guinea (villages of Fouta-Djalon): marriages, 1954–1955	6.035	56.7

Figure 2-58 Comparison of total marital fertility rates for some natural fertility populations

Maximum Total Fertility MTF What is the maximum rate at which a human population can produce children if there are no voluntary or societal checks on reproduction? Actual data on natural fertility, or fecundity, of populations are scarce, since it is difficult to find a society in which it can be proved that every woman is reproducing at a truly maximum rate throughout her entire reproductive lifetime. The apparent individual record for human fecundity is 39 single live births to one woman (Thomlinson 1965, p. 144), clearly a case of extraordinary fecundity combined with extraordinary motivation. No aggregate population has come close to maintaining such a high reproductive rate.

The highest sustained total fertility actually documented in a population is 10.6 live births per married woman in the Hutterite population of North America (Eaton and Mayer 1953). This fertility does not represent an absolute physiological maximum, since marriage occurs at an average age of more than twenty in the Hutterite society. If the Hutterite total fertility is corrected for the unutilized reproductive time between puberty and marriage, the average total fertility of the population would be approximately 12 children per woman (Heer 1968, p. 49).

Theoretical maximum total fertilities have been calculated on the basis of a range of assumptions about coital frequency, probability of conception, and length of postpartum amenorrhea (Bourgeois-Pichat 1965). A representative maximum total fertility from these calculations is 13.2 births per woman (Hawthorn 1970, p. 13).

Many societies that use no apparent form of birth control and express no conscious desire to limit the number of children nevertheless fall far short of the biologically possible total fertility of 12–14 children per woman. A partial list of such "natural fertility" societies is given in Figure 2-58. It is not possible to know how much of the reduced fertility in those societies was caused by impaired fecundity and how much by covert individual or societal restraints on childbearing. Henry (1961) believes that these societies do not practice any voluntary fertility restriction, with the possible exception of delayed marriage and sexual taboos, for example, during lactation. He presents convincing evidence for this belief by showing that the age-specific fertilities in all these societies follow a common pattern—fertility is reduced from the Hutterite fertility by approximately the same factor at all ages. It might be expected that families deliberately controlling family size would do so selectively at the end of the reproductive lifetime, when the desired number of children had been achieved. Thus the ratio of observed age-specific fertility to Hutterite age-specific fertility (a rough measure of fecundity) would be expected to be constant through age 30 or 35, and then to decrease as voluntary controls begin to be utilized. Numerous other populations with a markedly decreasing fertility as a function of age have been observed. Espenshade (1971) has used the decrease in the ratio of age-specific fertility relative to Hutterite fertility to estimate both the natural fecundity (from fertilities in ages 20 to 30) and the degree of control practiced by these ''birth-controlling'' societies (from fertilities in ages 35 to 45).

Davis and Blake (1956) have greatly clarified the discussions of variations in human fertility by classifying all the possible variable aspects of human fertility under three basic biological categories: intercourse, conception, and gestation-parturition. The Davis-Blake classification of the ''intermediate variables'' of human fertility is:

I. Factors affecting exposure to intercourse:
   A. Formation and dissolution of sexual unions.
      1. Age of entry into sexual unions.
      2. Extent of permanent celibacy.
      3. Amount of reproductive period spent after or between unions.
         a. Unions broken by divorce, separation, desertion.
         b. Unions broken by death of spouse.
   B. Exposure to intercourse within unions.
      4. Voluntary abstinence.
      5. Involuntary abstinence (impotence, illness, separations).
      6. Coital frequency, excluding periods of abstinence.

II. Factors affecting conception:
      7. Fecundity affected by involuntary causes.
      8. Use of contraception.
      9. Fecundity affected by voluntary causes (voluntary sterilization).

III. Factors affecting gestation and parturition:
      10. Fetal mortality from involuntary causes (miscarriage, stillbirth).
      11. Fetal mortality from voluntary causes (induced abortion).

Four of these factors—3b, 5, 7, and 10—are variables that reflect the influence of external, involuntary, environmental factors on maximum human fertility. All the other factors are subject to some degree of conscious human control, on either an individual or a societal level. They will be discussed later. Here we shall examine the four involuntary factors as potential influences on human fecundity.

To repeat and somewhat expand the Davis-Blake analysis, the factors that influence maximum total fertility must operate through:

3b. Interruption of sexual unions by death.

5. Involuntary sexual abstinence within sexual unions: impotence, illness, or involuntary separation.

7. Infecundity occasioned by the primary or secondary sterility of either member of a sexual union or by the partial infecundity of either member. The latter may be caused by infrequency of ovulation or an abnormally short duration of the female fertile period, an insufficient number or viability of sperm, postpartum infecundity, or a reduced length of reproductive lifetime.

10. Involuntary fetal mortality, leading to spontaneous abortion, miscarriage, or stillbirth.

With the possible exceptions of impotence and involuntary separation, all these factors are influenced in some way by the general health of the population. All are summarized in World3 by one variable, the fecundity multiplier FM, which expresses the general influence of health on maximum total fertility MTF through all possible mechanisms. We shall first discuss separately what little is known about each mechanism and then describe how they were combined into the fecundity multiplier FM.

The influence of health on fecundity is perhaps most obvious in the interruption of sexual unions by death. In a typical society with a thirty-year life expectancy, only 60 percent of fifteen-year-old brides will survive to the end of their reproductive period. If we assume that they all marry men five years older than themselves, almost half of the women who survive will lose their husbands before they themselves reach the age of forty-five. The deaths of reproductive-age females can be accounted for in a demographic model by proper representation of the population age structure. The effect of the deaths of reproductive males on total fertility depends partly on the social customs regarding the remarriage of widows, for these customs vary widely in different societies (Davis and Blake 1956).

Little is known about the importance of involuntary sexual abstinence during illness, but we would certainly expect such abstinence to decrease as the general health of a population improves.

Sterility appears to be an important variable in the differential fecundity of populations, especially of populations with inadequate medical care. Moni Nag (1968), in a survey of 65 nonindustrial societies, finds sterility a major factor in 7 of the 10 societies that exhibited very low fertility (for 2 of these 10 societies no information on sterility was available). In most cases the sterility was medically avoidable, since it resulted from venereal disease or from infections associated with childbirth. The potential importance of primary fertility (secondary fertility appearing after the birth of one child is not included) on the reproductive rate can be seen in data from several African populations, shown in Figure 2-59 (U. N. 1965, p. 24). In contrast, Wyon and Gordon (1971, p. 163) found an extraordinarily low incidence of primary sterility (1–3 percent) in North Indian villages.

Country and Area or Ethnic Group	Year	Percentage of Women Aged 45–49 Years Reported as Never Having Borne a Child Alive	Estimated Gross Reproduction Rate
Angola	1950	14	2.7[a]
Cameroon:			
North Cameroon	1960	12	2.3
Mbalmayo Subdivision	1956	32	1.3
Ebolowa City	1958	51	1.2
Central African Republic:			
Central Ubangi	1959	21	2.4[b]
Congo (Brazzaville)	1960–1961	20[c]	2.8
Congo (Leopoldville)	1955–1957	20[d]	2.4
Ivory Coast:			
First Agricultural Sector	1957–1958	9	3.0
Mali	1957–1958	7	3.4[e]
Mozambique	1950	15	2.6[f]
Senegal:			
Middle Valley	1957		
Rural sedentary population		7	3.1
Rural Maures		9	2.1
Low Valley	1957	7	3.0
Upper Volta	1960–1961	6[g]	2.9
Zanzibar and Pemba:	1958		
Zanzibar town		38[h]	1.3
Zanzibar island, excluding Zanzibar town		25[h]	2.1

[a]1940–1945.
[b]1958–1959.
[c]For women 40–49 years of age.
[d]For women 45 years of age and over.
[e]1960–1961.
[f]1945–1950.
[g]For women 50 years of age and over.
[h]For women 46 years of age and over.

Figure 2-59 Sterility in African populations
Source: U.N. 1965, p. 24.

The relationship of partial infecundity—the impaired production of viable eggs and sperm—to general health, medical care, or nutrition is generally unknown. There is some evidence, however, that reproductive functions may be temporarily impaired under conditions of starvation (Keys et al. 1950 p. 749).

Postpartum infecundity—the absence of ovulation for some time after the birth of a child—can vary greatly from one society to another and can be an important factor in reducing total fertility in societies where it persists for an extended period. There is a clear link between infant survival, the duration and intensity of breast-feeding, and the period of postpartum infecundity in villages of North India (Wyon and Gordon 1971). It has been suggested (Peters, Israel, and Purshottam 1958) that improved nutrition and better general health decrease the period of postpartum infecundity, even under equivalent habits of lactation. Empirically, it is true that Hutterite women, who practice long lactation, averaged a postpartum infecundity period of 6.1 months and an interval between live births of 26 months (Tietze 1957), whereas less well-fed North Indian women, also practicing long lactation, experienced a postpartum amenorrhea of about 11 months and an average birth interval of about 31 months (Wyon and Gordon 1971). This small difference in birth interval, when sustained over an average 30-year reproductive lifetime, would result in a difference in maximum total fertility of 2 children per woman.

Reproductive lifetime, the period between menarche and menopause, may vary substantially under different conditions of health and nutrition. The age of menarche in the United States and Europe has been declining steadily for the last century; it now occurs at least three years earlier on the average than it did one hundred years ago (Backman 1948). There is evidence from a number of sources that this secular trend may be closely related to improvements in nutrition (Keys et al. 1950; Nag 1968, p. 106). Frisch and Revelle (1967) report a mean age of female adolescent growth spurt (and accompanying menarche) of 12.2 years in areas that supply more than 2,300 calories per person per day, and 13.5 years in areas supplying less than 2,300 calories per person per day. At the same time that the age of menarche seems to be decreasing in industrialized areas, the age of menopause seems to be increasing (Backman 1948; Jaszmann, Van Lith, and Zaat, 1969). This trend may also be related to better nutrition and health. Wyon and Gordon (1971) cite the average age of menarche in the Indian Punjab as 14.5 years and the average age of menopause as 42.6 years, for a total female reproductive period of 28.1 years. In contrast, studies in the United States indicate an average age of menarche of 12.7 years (Zacharias, Wurtman, and Schatzoff 1970) and an average age of menopause of 48 years (MacMahon and Worcester 1966), for an average reproductive period of 35.3 years. The average reproductive lifetime is thus about 27 percent longer in the United States than in India.

There is most probably a relationship between the general health of a population and the frequency of miscarriage or stillbirth, although the available data are not adequate to make a direct comparison between various societies (Nag 1968, p. 138).

The state of nutrition and medical care in a population can have a substantial impact on fecundity through several of the physiological variables that have been mentioned here. However, the numerous physiological processes involved have not been characterized quantitatively, especially in nonindustrial populations where they would be expected to have the greatest impact on total fertility. Again, in the absence of complete information we simply attempted to express the general trend in World3. Life expectancy in the model is a composite measure of the general health of the population. We therefore included a link from life expectancy LE to maximum total fertility MTF through the variable fecundity multiplier FM. This variable expresses a positive relationship between life expectancy and maximum total fertility. The actual causal mechanism is, of course, much more complicated, since each input to life expectancy—food per capita, health services, pollution, and crowding—certainly has a specific, separate influence on fecundity. These specific influences are not well enough understood to represent them separately at this time. The exact relationship assumed between LE and MTF is given by the following equations and illustrated in Figure 2-60.

```
MTF.K=MTFN*FM.K                                              33, A
MTFN=12                                                      33.1, C
     MTF     - MAXIMUM TOTAL FERTILITY (DIMENSIONLESS)
     MTFN    - MAXIMUM TOTAL FERTILITY NORMAL
                  (DIMENSIONLESS)
     FM      - FECUNDITY MULTIPLIER  (DIMENSIONLESS)

FM.K=TABHL(FMT,LE.K,0,80,10)                                 34, A
FMT=0/.2/.4/.6/.8/.9/1/1.05/1.1                              34.1, T
     FM      - FECUNDITY MULTIPLIER  (DIMENSIONLESS)
     TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
     FMT     - FM TABLE
     LE      - LIFE EXPECTANCY (YEARS)
```

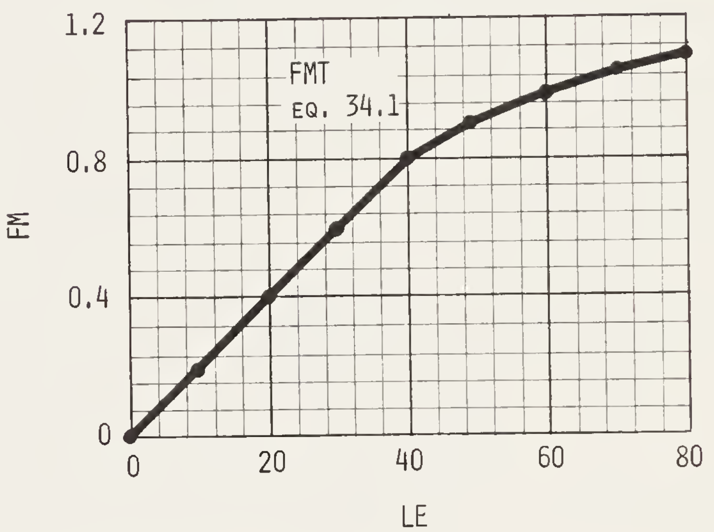

Figure 2-60 Fecundity multiplier table

The fecundity multiplier FM is mathematically a modifier of a constant maximum total fertility normal MTFN. Like all "normal" constants in the model, this MTFN is an arbitrary number that must be defined consistently with its modifying table function. We chose MTFN to equal 12 children per woman, the probable maximum total fertility of the Hutterite population. Thus when life expectancy equals that of the Hutterites (about 60 years?) the fecundity multiplier must equal 1.0 to give a maximum total fertility of 12.

It is assumed that the Hutterite fertility might have increased by 10 percent with better medical care, so the maximum fecundity generated by this function, with an 80-year life expectancy, is 13.2 children (in agreement with the calculations of Bourgeois-Pichat 1965). At a life expectancy of 40 years, FM = 0.8 and MTF = 9.6 children. Below LE = 40, maximum total fertility is assumed to decrease linearly to zero.

To relate this postulated fecundity multiplier to the observed total fertility of preindustrial societies, Figure 2-61 was derived from data assembled by Moni Nag (1968). Life expectancies were calculated on the basis of observed (usually guessed) infant mortalities, using model life tables derived by the United Nations (U.N. 1956). It must be emphasized that all the numbers given in Figure 2-61 are subject to uncertainty and error, both in the original data-gathering processes and in the conversion from infant mortality to indicated life expectancy. It is also fairly certain that none of the societies listed in the table have achieved their actual maximum total fertility—even the Hutterites practice some fertility limitation through late marriage. Nevertheless, these tentative data can at least define minimum fecundities. The fecundity multiplier table FMT must generate values of maximum total fertility MTF at all life expectancies that are at least as high as those actually observed. The postulated relationship does meet this requirement, as shown in Figure 2-62, where the observed fertilities are plotted on the same graph as the FM function included in the World3 equations.

Society	**Estimated Total Fertility**	**Estimated Infant Mortality** (deaths before age 1 per 1,000 live births)	**Approximate Indicated Life Expectancy**
Africa			
Ashanti	6.2	96	56
Ganda	3.1	169	41
Haya	3.7	274	24
Tallensi	6.0	150	45
Yako	3.0	150	45
America			
Havasupai	7.4	64	62
Hutterite	10.4	45	64
Navaho	7.8	124	50
Puerto Rico (1940)	6.8	115	51
Walapai	6.4	129	48
Asia			
Bengali Hindu	6.5	21	70
Bengali Muslim (low economic level)	4.4	59	62
Bengali Muslim (high economic level)	7.0	62	60
Lue	6.6	99	55
North Chinese	5.1	186	36
Taiwan	6.6	120	51
Pacific			
Dusun	5.0	168	41
Tabar	2.8	145	46

Figure 2-61 Total fertilities of preindustrial societies
Source: Derived from Nag 1968.

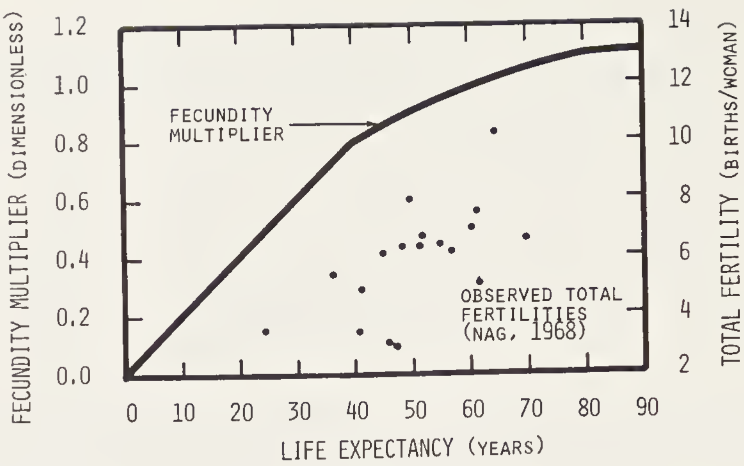

Figure 2-62 Comparison of model-generated maximum total fertility with observed fertilities in preindustrial societies

Desired Total Fertility DTF Demographers and sociologists generally agree that nearly every human population has some identifiable set of common desires and social norms with regard to fertility. It is certainly reasonable to expect that such an important occurrence for the family and for the community as the birth of a child would be subject to some degree of conscious individual volition and social control. Although, as we shall see, the measurement of human reproductive goals is an exceedingly difficult task, it is nevertheless certain that some goals, however vague, do exist and do influence reproductive behavior.

> Norms about family size are likely to be in terms of a range in numbers of children that are permissible or desirable. While specifying clearly that childlessness is an unspeakable tragedy and an only child very undesirable, the norm for a particular culture or group may be as vague as "at least three or four children" or "as many as possible." But I know of no organized society, primitive or modern, in which the question of how many children are born is a matter of indifference either to the reproducing unit or to the community. [Freedman 1963]

Preliminary measurements of reproductive goals come from the responses of people in different societies to queries about their family-size desires. Surveys of attitudes about childbearing have been carried out in many countries of the world in the past decade (see Mauldin 1965, Berelson 1966). They have rarely found in any culture an inability to specify a desired range of family size. Often the individual answers to surveys have been both precise and eloquent. For example:

> *India:* If we are not in a position to maintain our children we should check their birth. I am not in a position to maintain a big family. After two or three births I will get my wife operated. It is better for me and my country. [Driver 1963, p. 129]
>
> *Puerto Rico:* If one is poor he shouldn't have more than two children. The rich can have more because they have money to educate them and do not sacrifice or even kill themselves working as the poor do. . . . The wife of the poor man gets sick

> with many children, because she can't feed herself well nor have the proper medicines if she needs them. [Stycos 1968, p. 68]
>
> *United States:* We both like four children. . . . I think four is ideal because there's more interest and congeniality in large families. We know we can't afford more than four, but that will be better than one or two. [Rainwater 1960, p. 30]
>
> *Ceylon:* Fate decides how many children we have, but of course if we were to have more we would be happy. Every woman wishes to have many children. They are a blessing. I would like ten. [Nag 1968, p. 47]

The concept of "desired family size" is often discussed in the population literature, but the term is seldom defined carefully enough to permit the design or unambiguous interpretation of research to determine what the average desired family size of any given population actually is. In particular, there is often confusion between (1) the desired number of surviving children and the desired number of births (these numbers may be significantly different under conditions of high infant mortality), and (2) the socially defined "ideal" number of children and the average operating goal of individual families (these numbers will tend to be different if the benefits and costs associated with child-raising are unevenly distributed within the society).

In World3 we defined desired total fertility DTF as the average number of *total births* per woman desired by *individual* members of the population. This number is immediately dependent on two other factors: the average number of surviving children actually desired by families within the population (desired completed family size DCFS), and the degree to which the families feel they must compensate for the probability of child mortality by bearing more children than they actually desire (compensatory multiplier from perceived life expectancy CMPLE). For example, if an average family desires two surviving children but believes that about half of all children are likely to die before maturity, it will probably aim to produce at least four children to ensure that the actual goal of two is attained. In this case, the desired completed family size is 2, the compensatory multiplier from perceived life expectancy is 2, and the desired total fertility is 4. The equation uniting these three variables is the following:

```
DTF.K=DCFS.K*CMPLE.K                                     35, A
    DTF    - DESIRED TOTAL FERTILITY (DIMENSIONLESS)
    DCFS   - DESIRED COMPLETED FAMILY SIZE (DIMENSIONLESS)
    CMPLE  - COMPENSATORY MULTIPLIER FROM PERCEIVED LIFE
               EXPECTANCY (DIMENSIONLESS)
```

It has been suggested with regularity in the literature on population policy that parents deliberately compensate for a high probability of death in childhood by bearing more children than they actually desire in their completed families (for a review of this argument, see Frederiksen 1969). Little experimental evidence for this hypothesis has been produced; indeed, evidence is difficult to obtain, since so many other variables in the population system become important under conditions of high mortality. For example, Nag (1968, p. 140) finds an inverse association between infant mortality and fertility in his survey of sixty-one nonindustrial societies. He points out, however, that this association may result from the poor health conditions and impaired fecundity of women in those societies. The low fecundity or maximum total fertility may dominate an underlying positive relationship between high mortality and desired total fertility.

Evidence for compensatory childbearing from a population where low fecundity is not a dominant factor has been given by Wyon and Gordon (1971, pp. 196–200). Figure 2-63 shows the child mortality and total fertility in North Indian village families. In this population, larger numbers of surviving children are clearly associated with fewer high-parity births. Figure 2-63 illustrates the two opposing effects of high mortality on the population growth rate: a direct effect on mortality, and an indirect compensatory effect on fertility. In these villages the direct effect of child mortality on the death rate dominates its indirect effect in stimulating more births. Families (generally low caste) that experience high mortality produce more live births but end up with significantly fewer surviving children.

A detailed calculation (Heer and Smith 1968) has determined the theoretical effect on the rate of natural increase (birth rate minus death rate) if populations experiencing varying mortality conditions have a reproductive goal of one son surviving on the father's sixty-fifth birthday. Figure 2-64 illustrates how the rate of increase would vary with increasing life expectancy, assuming that the desired certainty of one-son survival ranges from 50 percent to 95 percent. These hypothetical populations are assumed to have exact, up-to-date survivorship information and perfect birth control. The calculations indicate that the net rate of population increase necessary to ensure one surviving son for each family with a 90 percent or greater degree of certainty is extremely high until the life expectancy rises to 60 years or more. As life expectancy exceeds 60 years, the birth rate necessary to achieve the stated goal finally falls faster than the death rate, and the rate of population increase approaches zero. A scatter plot of actual rates of increase and life expectancies for various nations of the world, also shown in Figure 2-64, does not fit any of the theoretical curves. The lack of agreement is not surprising, because reproductive goals, fecundity, birth control effectiveness, and survivorship information are all variant in real-world populations. A detailed statistical analysis (Repetto 1972) of parity-specific birth rates also indicates that observed fertility patterns in India, Pakistan, and Morocco are much more complicated than would be predicted by the simple model of Heer and Smith (1968).

	Survivors from the First 6 Live Births						
	0	**1**	**2**	**3**	**4**	**5**	**6**
Number of wives	6	22	47	106	116	106	57
Mean number of live births after parity 6	3.5	3.1	2.9	2.5	2.4	2.2	2.0
Mean number of live births, all parities	9.5	9.1	8.9	8.5	8.4	8.2	8.0
Mean number of surviving children, all parities	2.5	3.1	3.6	4.9	5.7	6.5	7.3
Percent of children who died, parity 7 or more	29	32	44	23	27	33	35

Figure 2-63 Child mortality and total fertility, India, 1959
Source: Wyon and Gordon 1971, p. 199.

Since there are no satisfactory global data on which to base the compensatory multiplier from perceived life expectancy CMPLE, we had to choose among several possible hypotheses. One hypothesis was that used in the Heer and Smith (1968) calculations: parents perceive the probability of child survival correctly, and they immediately adjust their desired number of total births to correct for changing survivorship possibilities. If that were the case, the resulting relationship between life expectancy and CMPLE would approximate the upper dashed curve in Figure 2-65. (The probability of survival until age 15 used to calculate this curve was taken from the model life tables in U.N. 1956.)

Another hypothesis is that parents perceive changing survival possibilities inaccurately and only after some delay. In this case, the horizontal axis in Figure 2-65 would represent perceived rather than actual life expectancy. Perceived life expec-

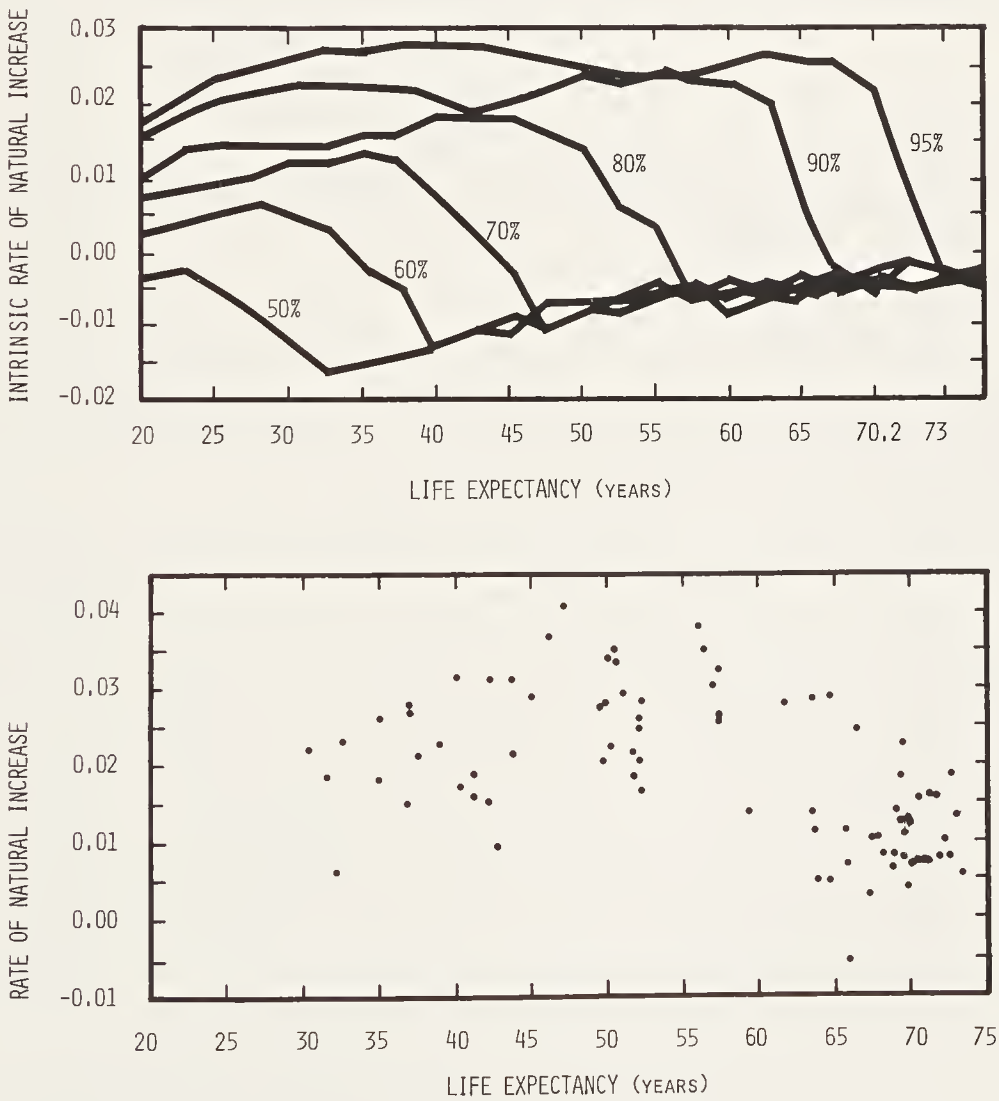

Figure 2-64 Rates of natural increase versus life expectancy, theoretical and empirical
Source: Heer and Smith 1968.

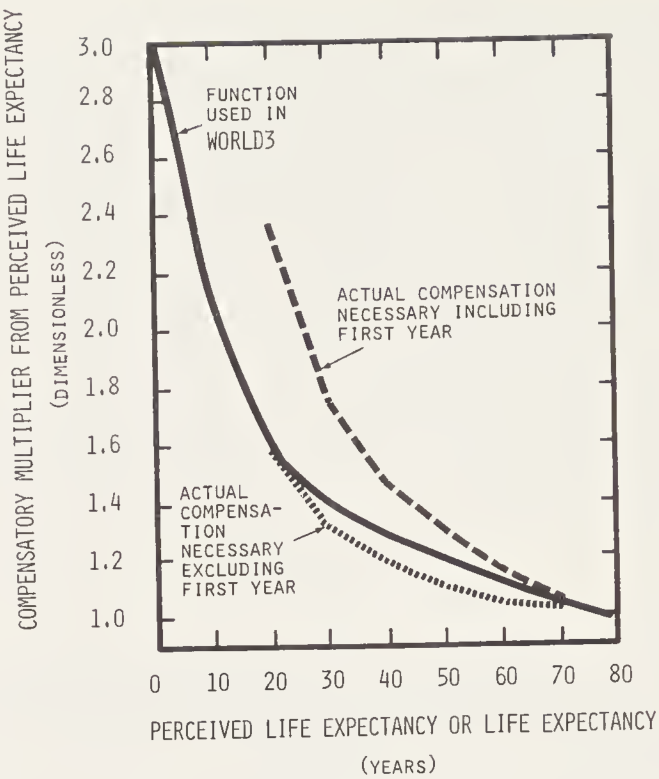

Figure 2-65 Different assumptions for the compensating multiplier from perceived life expectancy

tancy PLE is a delayed and perhaps biased function of the actual life expectancy at any time. A bias function would shift the dashed line up or down if there is evidence that parents consistently tend to overcompensate or undercompensate for the survival probabilities that they perceive.

In World3 we assumed that there are two components to parents' perceptions of survival probabilities—one short-term and accurate, one long-term and delayed. The accurate, short-term component reflects the fact that parents who actually experience an infant death can (within the bounds of the fecundity multiplier) have another child to replace the one that died. This component is immediate and accurate, since there is no need for the whole reproductive population to perceive and compensate for infant deaths. Parents who lose a child can adjust their own desired total fertility to attain their ultimate family-size goals. The effect of this short-term compensatory component is negligible in considerations of long-term population dynamics because infant deaths, at any prevailing mortality level, are balanced by new births (except in cases of severely impaired fecundity). Thus this short-term feedback loop is omitted in the world model; infants that die within the first year are assumed to be replaced with a short delay and with no effect on the average desired total fertility.

The second, long-term component of the compensatory multiplier from perceived life expectancy may be more important both to the rate of population growth and to the design of population policy. This component arises from the tendency of parents to compensate for the possible loss of a child, even after the child survives the hazardous first years of life. In this case, the parents must extend their perception of mortality probability over a longer period, probably at least until their children are old enough to marry and have children of their own. Since there is no short-term feedback telling them whether their own children will be among the survivors, their perception must be a function of the common societal mortality experience; thus it must be delayed. The delay is explicitly included in World3 as the lifetime perception delay LPD.

Some preliminary data on the length of the lifetime perception delay LPD come from the studies of D. M. Heer (personal communication), who has conducted surveys asking residents of rural Kentucky, U.S.A., and Shenking township, Taiwan, to estimate the probability that a baby born today will live to age 15. The apparent perception delay was around 30 years in Kentucky and 3 years in Taiwan. (It may be that the difference in these delay times was caused by a difference in the relative rates of change of infant and total mortalities in the two areas. The rapid perception change in Taiwan may be a result of recent changes in infant mortality only, so that the short-term compensatory perception has been influenced, with no need to change the long-term one.)

The long-term compensatory multiplier in World3 is modeled as a function of perceived life expectancy PLE. The perceived life expectancy PLE is related to the actual life expectancy LE by a third-order delay (lifetime perception delay LPD) of 20 years. The actual form of the compensatory multiplier from perceived life expectancy CMPLE used in the model is shown as a solid line in Figure 2-65 and in Figure 2-66. The two dashed lines in Figure 2-65 show the approximate actual fertility compensation that would statistically be necessary if survival to age 15 is the goal and if first-year mortality is included (the upper line) or excluded (the lower line). To exclude the short-term compensatory component associated with infant mortality, we chose a function approximating the lower line. In the absence of any information about a bias in perceived life expectancy, we assumed that there is none, that the compensatory behavior of parents is based on delayed but not systematically biased information.

Although this compensatory multiplier from life expectancy is at present only a hypothesis, it is consistently cited as a basis for population policy (see Frederiksen 1969) on the assumption that active campaigns to reduce infant mortality will reduce fertility and, presumably, population growth rates. Of course, a program to reduce infant mortality can be justified for reasons other than reducing population growth rates. However, such a program as a measure for population control can succeed only if two conditions hold true. First, the delay between reduced death rate and the response through reduced birth rate must be quite short. Otherwise, the large gap created between the newly imposed lower death rate and the not-yet-adjusted birth rate will lead to a large increase in population growth rate, an increase that might persist for decades. Second, under high mortality conditions, parents must consistently overcompensate for the actual prevailing mortality probabilities, and under conditions of low mortality they must either undercompensate or compensate correctly. Otherwise, in addition to the short-term increase in the population growth

```
CMPLE.K=TABHL(CMPLET,PLE.K,0,80,10)                    36, A
CMPLET=3/2.1/1.6/1.4/1.3/1.2/1.1/1.05/1                36.1, T
     CMPLE  - COMPENSATORY MULTIPLIER FROM PERCEIVED LIFE
                 EXPECTANCY (DIMENSIONLESS)
     TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
     CMPLET - CMPLE TABLE
     PLE    - PERCEIVED LIFE EXPECTANCY (YEARS)

PLE.K=DLINF3(LE.K,LPD)                                 37, A
LPD=20                                                 37.1, C
     PLE    - PERCEIVED LIFE EXPECTANCY (YEARS)
     DLINF3 - THIRD-ORDER EXPONENTIAL INFORMATION DELAY
     LE     - LIFE EXPECTANCY (YEARS)
     LPD    - LIFETIME PERCEPTION DELAY (YEARS)
```

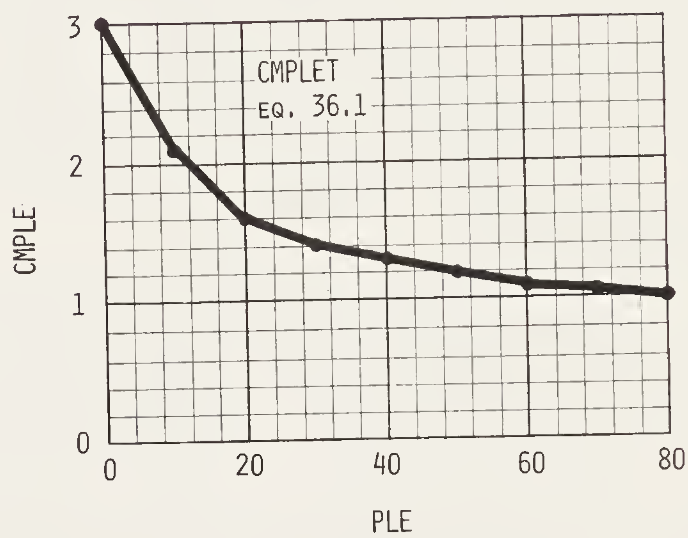

Figure 2-66 Compensatory multiplier from perceived life expectancy table

rate caused by the slow social response to the lowered mortality, the long-term balance between birth and death rates could also lead to an increase in the net growth rate, or at best the same rate that prevailed before.

To assess the possible effectiveness of reduced infant mortality as a policy for regulating population growth rates, it is necessary to understand better the delays and biases in the information individual families receive about survival probabilities. If it is assumed, as in the World3 standard model, that the perception delay is relatively long but the information is accurate, then mortality reduction as a population control policy is counterproductive in the short term and ineffective in the long term. Other assumptions can easily be incorporated in the model by changing the numerical values of the lifetime perception delay LPD and the table expressing the compensatory multiplier CMPLE. The sensitivity of the system to such changes is shown in section 2.6.

In World3 the second variable contributing to total fertility TF is the desired completed family size DCFS, which is the ultimate average number of surviving children each family strives to achieve. The desired completed family size DCFS in World 3 is represented as a function of two contributing factors: the average number of children considered ideal by the society as a whole, and the average number of children actually desired by families within the society as they weigh their own resources against this socially established norm. In World3 we call the general societal norm the social family size norm SFSN and the individual response to that norm the family response to social norm FRSN. These two variables are formulated as nonlinear table functions multiplying a normalized constant, the desired completed family size normal DCFSN.

```
DCFS.K=CLIP(2.0,DCFSN*FRSN.K*SFSN.K,TIME.K,ZPGT)    38, A
ZPGT=4000                                            38.1, C
DCFSN=4                                              38.2, C
     DCFS    - DESIRED COMPLETED FAMILY SIZE (DIMENSIONLESS)
     CLIP    - A FUNCTION SWITCHED DURING THE RUN
     DCFSN   - DESIRED COMPLETED FAMILY SIZE NORMAL
                  (DIMENSIONLESS)
     FRSN    - FAMILY RESPONSE TO SOCIAL NORM
                  (DIMENSIONLESS)
     SFSN    - SOCIAL FAMILY SIZE NORM (DIMENSIONLESS)
     TIME    - CURRENT TIME IN THE SIMULATION RUN
     ZPGT    - TIME WHEN DESIRED FAMILY SIZE EQUALS 2
                  CHILDREN (YEAR)
```

The CLIP function allows the modeler to test the impact on the system of an invariant desired completed family size of two children at any specified time ZPGT. This option does not assure an actual total fertility of two, since the factors of birth-control effectiveness and compensation for perceived child mortality are still operative. It merely assumes that the family size goal of the global society is constant at two children. This option must be specifically activated by the modeler; it does not operate in standard model runs.

In World3 the desired completed family size normal DCFSN was set at four children. The two multiplying table functions, SFSN and FRSN, operate to adjust the average desired completed family size from a high of 5 to a low of 1.5 children, depending on the social and economic conditions affecting the population. Again, the normal value does not signify any inherent property of the real-world system; it is an arbitrary number to serve as a base for constructing the modifying table functions.

Although a great many surveys of desired family size have been carried out, it is not always possible to determine whether those studies have measured desired total fertility (including compensation for infant mortality), desired completed family size for individual couples, or the societal "ideal." The wording of the question regarding desired family size is obviously important, and in most surveys the words seem to emphasize either the social norm or the individual decision, including mortality compensation. For example, surveys in various countries (Mauldin 1965) have included the following questions:

> *United States:* What do you think is the ideal number of children for the average American family?
> —Just before you were married, how many children did you think you would want during your married life?
> —A year after your first child was born how many children did you want to have altogether?

—If you could have (more) children in coming years how many children would you want to have altogether (counting those you have now)?

India: How many children make an ideal-sized family?

Korea: What could be an ideal number of children, if you could control the number as you wish?

Puerto Rico: Supposing you were about to get married again for the first time. How many children would you want to have?

Jamaica: If you could live your life over, how many children would you like to have?

Lebanon: Suppose you have a very close friend, in the same circumstances as yourself, and she asked you for advice on the convenient number of children for her. What is the number of children you would advise her to have, if she could?

The importance of a careful selection of survey questions in studies of reproductive desires is illustrated by two surveys carried out in the United States in 1955 and 1960. Four slightly different questions generated different responses (Whelpton, Campbell, and Patterson* 1966):

The number of children ideal for the average American family	3.4–3.5
The number individually desired if life could be relived under ideal circumstances	3.6–3.7
The number wanted under actual and anticipated circumstances	3.1–3.4
The number actually expected	2.8–3.5

It might be expected that the same questions would produce even more varied responses in countries where infant mortality is high and birth-control methods uncertain.

A summary of desired family size surveys is shown in Figure 2-67. The numbers shown may be biased slightly downward because respondents with no expressed numerical preference (''as many as God sends'') were not counted in most surveys. All the average desired family sizes in Figure 2-67 are moderate: none are below 2 or above 6. The only obvious trend is that the desired family size is generally lower in industrialized countries than in nonindustrialized areas.

Figure 2-68 illustrates the relationship between industrialization and family size goals more quantitatively. The percentage of respondents in each country indicating that they would like 4 or more children (from Figure 2-67) is plotted against the GNP per capita in that country. Again, an inverse relationship between industrialization and family-size goals is seen, especially below a GNP value of 500 dollars per capita. Illustrations of the inverse relationship between income and *actual* fertility are given in Figures 2-8, 2-11, and 2-69.

Because it is not certain whether the stated family size goals listed in Figure 2-67 represent individual or societal goals, with or without mortality compensation, the conclusions to be drawn from the data are qualitative at best; families in all areas seem to want only a moderate number of children, and that number seems to be lower in industrialized populations than in nonindustrialized populations. That is a rather

*A more recent U.S. national fertility survey shows less variation in answers to questions on ideal, actual, and intended family size (Ryder and Westoff 1971).

tenuous empirical base upon which to rest a hypothesis about changing social family-size norms, especially since other contributing factors, such as fertility control effectiveness and infant mortality, also change with industrialization. However, it is possible to add to the direct empirical evidence considerable indirect evidence, social theory, and common experience, all of which underscore the observation that industrial development leads to profound changes in the pressures, rewards, values, and sanctions that each family responds to in its reproductive decisions. This entire spectrum of social pressures and inducements regarding childbearing is represented by the variable we call social family size norm SFSN. It includes such varied factors as taxes based on family size, representations of families in school textbooks, statements by community or religious leaders, and the nature of the subtle everyday comments directed at couples with no children, three children, or ten children.

> The assumption is that family size norms will tend to correspond to a number which maximizes the net utility to be derived from having children in that society. Obviously, different aspects of the society may exert opposing pressures on the norms, as a balance must be struck. Therefore, we must look for important aspects of the social organization which support the norms of family size by providing explicit or implicit social rewards or penalties depending on the number of children. [Freedman 1963]

The first causal theory of the change in social family size norm that accompanies industrialization was put forward by Leibenstein (1957) and later developed by Spengler (1966) and Lorimer (1967). This theory, in its most general form, states that the potential benefits awarded by society for having children tend to decrease in the process of industrialization, while the costs imposed by the system for having and raising children increase.

In this theory both the benefits and the costs of childbearing are interpreted very broadly. For example, in a nonindustrialized society, children represent not only the economic benefits of a labor force for the family enterprise and a security for old age but also an important source of prestige and pleasure for which no substitutes are available. Children may be necessary for the fulfillment of religious duties and for the full acceptance of the parents as mature participating members of the community. As a society develops economically, however, many (but by no means all) of the social benefits of children are replaced by institutions independent of the family. Insurance or social security arrangements provide for old age, prestige is gained by material as well as reproductive means, a supply of labor outside the immediate family can be obtained, and child labor is discouraged. The necessity for division of labor, mobility, and urban living breaks up the kinship-extended-family ties and results in nuclear families that depend on organizations outside the family for both economic and social interchange.

At the same time that relative benefits decline, childbearing costs increase in an industrialized society. For example, children must be educated; thus they remain economically dependent longer, even if education is free. Social approval is gained not so much by raising many children but by raising some children ''well.'' Medical care, clothing, food, and housing standards are much higher in an industrialized

Area	Date	Sex of Respondent	Type of Sample	Size of Sample	Average Number Children	Range of One Standard Deviation Around Average	Percentage Wanting 4 or More Children	Percentage Wanting 5 or More Children
Austria	1960	F	GP	na	2.0	na	4	na
West Germany	1960	F	GP	na	2.2	na	4	na
Czechoslovakia	1959	F	NP	3,192	2.3	na	na	na
Hungary	1958–1960	F	NP	6,732	2.4	0.8–4.0	13	6
Great Britain	1960	F	GP	na	2.8	na	23	na
	1946	F	NP	10,000	2.1	0.6–4.8	25	15
France	1960	F	GP	na	2.8	na	17	na
	1956	F	N	10,645	2.2	na	na	na
Japan	1961	F	NP	2,753	2.8	1.5–4.1	22	8
Switzerland	1960	F	GP	na	2.9	na	22	na
Puerto Rico	1947	F	Reg P	5,475		(2.4–3.2)	19	na
	1953	F	N	888	3.0	(2.4–3.9)	19	na
	1953	F	Clinic	3,000		(2.2–4.1)	12	na
Italy	1960	F	GP	na	3.1	na	18	na
Norway	1960	F	GP	na	3.1	na	25	na
Netherlands	1960	F	GP	na	3.3	na	39	na
U.S.A.	1960	F	NP	2,414	3.3	1.7–4.9	40	15
	1955	F	NP	2,684	3.4	2.1–4.7	49	8
	1945	F	GP	na	3.3	2.2–4.4	41	10
	1941	F	GP	na	3.0	1.8–4.2	27	6
Ceylon	1963	M	R	302	3.2	na	25	12
Jamaica	1957	F	U/R	1,368	3.4–4.2	na	48	19
Turkey	1963	M	NP	2,387	3.8	2.1–5.5	48	32
	1963	F	NP	2,735	3.2	1.7–4.7	36	18
South Africa	1957–1958	F	U	1,022	3.6	2.4–4.8	54	10
Taiwan	1962–1953	F	U	2,432	3.9	2.9–4.9	62	22
	1962	M	U	241	3.8	2.7–4.7	57	19
	1962	F	U	241	3.8	2.7–4.9	57	18
Thailand	1964	F		1,207	3.8	2.4–5.2	54	26

Pakistan	ca 1960	M	U	989	4.0	2.8–5.2	66	26
	ca 1960	F	U	1,097	3.9	2.3–5.5	64	25
Chile	1959	F	U	1,970	4.1	2.6–5.6	58	26
Canada	1960	F	GP	na	4.2	na	70	na
India								
Mysore	1952	M	U	1,011	3.7	na	na	na
	1952	F	U	793	4.1	na	na	na
	1952	M	R	392	4.7	na	na	na
	1952	F	R	323	4.6	na	na	na
Central India	1958	M & F	U/R	2,314	3.8	2.2–5.4	57	25
New Delhi	1957–1960	M	R	311	4.1	2.7–5.5	60	34
	1957–1960	F	R	765	4.2	3.0–5.4	63	33
Indonesia	1961–1962	M & F	R	2,208	4.3	na	66	36
Korea	1962	M	R	914	4.3	3.1–5.6	73	42
	1962	F	R	970	4.4	3.3–5.5	80	45
Sundong Gu	1964	F	U	3,204	3.3	2.4–4.2	35	10
Ghana	1963	M	U	296	5.5	na	89	67
	1963	F	U	341	5.1	na	88	56
Philippines	1963	F	U/R	7,807	5.0	3.6–6.4	71	53

na—Not available.

Notes: Percentages not specifying number of children are excluded from the base in calculating percentages wanting a specified number. Excluded percentages are: Hungary, 5; Jamaica, 3; Puerto Rico, 1.9 for Hatt's sample, 16.1 among out-patient department respondents, and 5.3 in the stratification sample of Hill and colleagues; Chile, 1; South Africa, 1; Egypt, 45 in completed families, 34 in incompleted families; Lebanon, 75 among rural uneducated to a low of 10 among the urban educated; Turkey, 7 among men, 15 among women; Pakistan, 24 among men, 26 among women; Central India, 30; Japan, 1; Korea, 1 for men and 1 for women; Taiwan, 2 for women, 1 for men.

Type of sample:
GP Gallup Poll
NP National probability sample
N National but not a probability sample
R Rural area
U Urban area
Clinic Patients coming to a hospital clinic

Range: Figures in parentheses refer to the middle 50 percent of the range; it was not possible to calculate the standard deviation because of the way in which the data were presented.

Figure 2-67 Desired family size, 1958–1964
Source: Mauldin 1965.

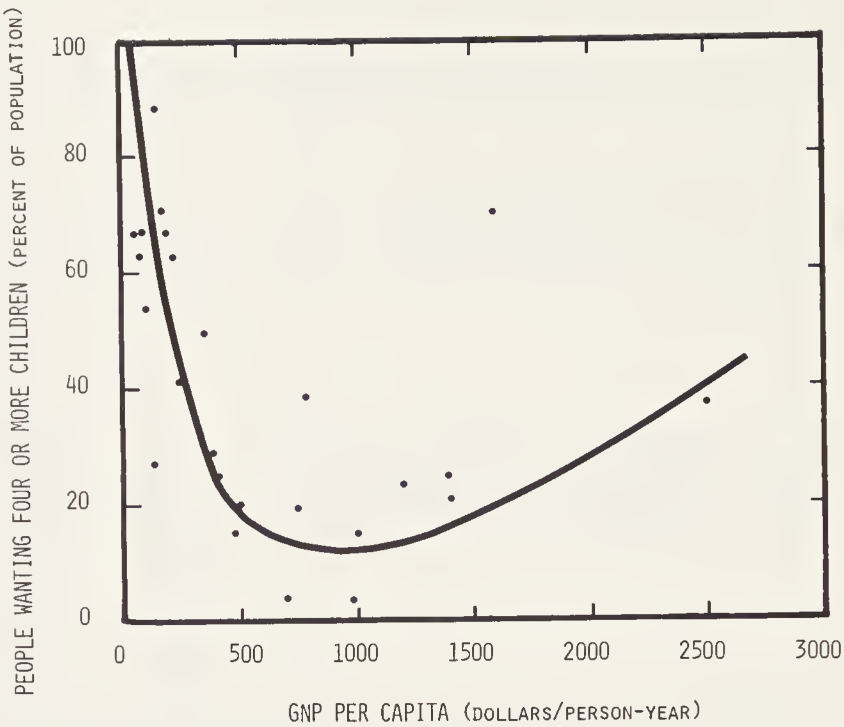

Figure 2-68 Desired family size versus GNP per capita
Source: Mauldin 1965.

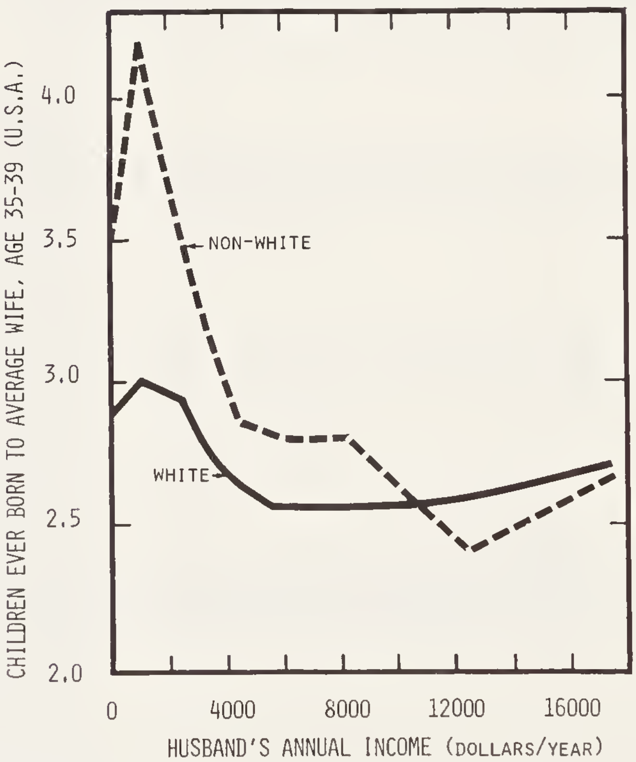

Figure 2-69 Family size versus income, United States, 1965
Source: C. V. Kiser, W. H. Grabill, and A. A. Campbell, *Trends and Variations in Fertility in the United States*, Cambridge, Mass.: Harvard University Press, 1968. Copyright ©1968 by the Harvard University Press.

society, as is the cost of substitute child care, since the extended family is no longer extant. Opportunity costs are also higher, since the wife is literate and capable of holding a paying job as an alternative to caring for children. Other opportunities made possible by increasing income—travel, recreation, and luxury consumption—are to some extent incompatible or competitive with large families.

As industrial output per capita rises, the ratio of benefits to costs of children in the changing socioeconomic system decreases, thus decreasing the socially optimal number of children. However, the benefits still outweigh the costs in every society. To ensure the perpetuation of the reproductive value structure, an institution is built into the system, which strongly reinforces the noneconomic benefits of childbearing. That institution is the family itself.

> Although it cannot be denied that modernization has brought about many changes in family organization, the complex of roles and goals we call the family is still a major focus of individuals' expectations and activities. This means, by definition, that children are high on the list of adult utilities. Offspring are not simply outlets (and inlets) of affection, they are the instrumentalities for achieving virtually prescribed social statuses (''mother'' and ''father''), the almost exclusive avenues for feminine creativity and achievement, and the least common denominator for community participation. [Blake 1965]

A lower family size norm in industrialized societies is not a planned or even a very well understood result of industrialization. It might be considered an accidental and unforeseen side effect of an economic and technological revolution. One can envision a completely different social response to the changed social environment caused by industrialization, but it is difficult to postulate a change in an established social norm without some alteration in the economic or environmental circumstances of the society. In other words, it is likely, though it is not certain, that currently nonindustrialized areas will also experience a lower fertility norm as they industrialize. It is highly unlikely that they will lower their present relatively high fertility norms if their present socioeconomic systems persist unchanged.

In World3 we quantified this shifting social family size norm SFSN as a function of industrial output per capita as shown in Figure 2-70 and the following equations:

```
SFSN.K=TABHL(SFSNT,DIOPC.K,0,800,200)                39, A
SFSNT=1.25/1/.9/.8/.75                               39.1, T
    SFSN   - SOCIAL FAMILY SIZE NORM (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    SFSNT  - SFSN TABLE
    DIOPC  - DELAYED INDUSTRIAL OUTPUT PER CAPITA
               (DOLLARS/PERSON-YEAR)

DIOPC.K=DLINF3(IOPC.K,SAD)                           40, A
SAD=20                                               40.1, C
    DIOPC  - DELAYED INDUSTRIAL OUTPUT PER CAPITA
               (DOLLARS/PERSON-YEAR)
    DLINF3 - THIRD-ORDER EXPONENTIAL INFORMATION DELAY
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
               PERSON-YEAR)
    SAD    - SOCIAL ADJUSTMENT DELAY (YEARS)
```

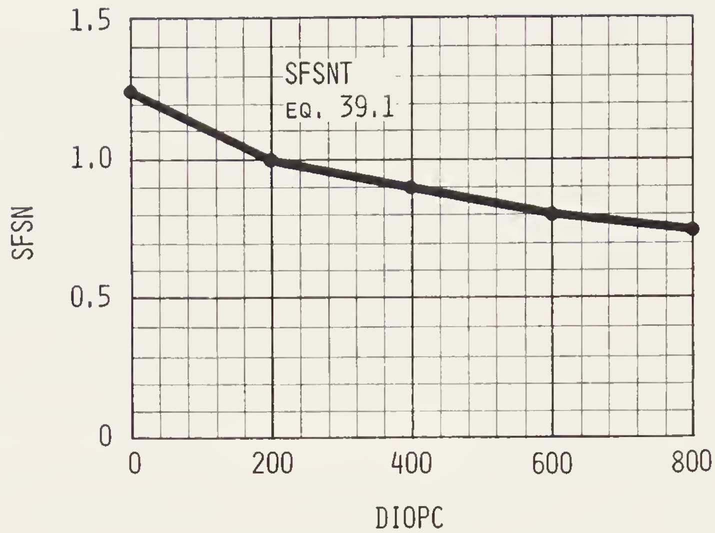

Figure 2-70 Social family size norm table

The social family size norm SFSN was assumed to be a delayed function of industrial output per capita DIOPC, since there seems to be general agreement that social norms, which are expressed through numerous interacting institutions and practices, change only very slowly. We assumed that the delay is third-order in nature, with a delay time (social adjustment delay SAD) of 20 years. This is probably a minimum delay time for widespread social change in a society with high literacy and good communications.

The social family size norm SFSN, when multiplied by the desired family size normal DFSN of 4.0 results in a socially ideal completed family size goal that varies from 5 children to 3 children, with most of the change occurring as the delayed industrial output per capita DIOPC rises to 500 dollars. It may be that the socially defined goal is actually much higher than 5 children in some nonindustrialized societies, but it is difficult to determine whether the few very high goals that have been reported include an allowance for infant mortality. It is also possible that a social family size norm may be lower than 3 children, but as yet there is very little evidence for such a low norm anywhere in the world (individual expectations may well be less than the norm and may lead to a desired completed family size DCFS value as low as 1.5 children, as discussed in the next section). In the most industrialized society in the world, the United States, the family size norm has been consistently higher than 3 children for at least 30 years (Blake 1967). There is excellent evidence (Blake 1965) that a similarly high norm prevails in Europe, although individual families on the average fall short of that norm in their actual reproductive behavior, probably for economic reasons.

It is conceivable that under some economic, environmental, or social circumstances the global society might effectively adjust its complex of sanctions and inducements to encourage the two-child family, with an explicit goal of population stabilization. It must be remembered that such an adjustment implies a consistent goal of two children, voiced and accepted by the majority of citizens, reinforced by government policy and economic sanctions, and systematically transmitted to new generations. As yet, no major society has experienced such a social change. In a few industrialized countries such as the United States and Great Britain, citizen movements to establish a two-child norm have recently arisen, but to date they have received more opposition than approval in the public media (Wallich 1970, Wattenberg 1970) and from governments. In other countries, when actual reproductive performance has temporarily decreased to two or fewer children per family, both governmental and private organizations have acted with alarm to encourage a higher birth rate.*

World3 can easily be altered to represent the evolution of a social norm of two or fewer children, if any subsequent modeler would like to hypothesize the environmental stimulant from the rest of the system and the causal mechanism through which such a development would operate. We have included the switch ZPGT, as already described, to test the effect of such a value change at any specified time in the model run.

In countries where infant mortality is low and birth control is effective, there seems to be a consistent trend for individual families to expect and to have fewer children than the number considered ideal according to the prevailing social norm. This discrepancy between ideal and actual, or intended, fertilities has been noted for all of Europe (Stoetzel 1955), for West Germany (Freedman, Baumert, and Bolte 1959), for Japan (Berelson 1966, p. 658), and for the white population of the United States (Freedman, Goldberg, and Sharp 1955; Ryder and Westoff 1971, p. 29). It seems that in these countries families, comparing their own resources with the balance of costs and benefits of childbearing dictated by the social norm, have often found themselves unable to afford all the children that they consider ideal or desirable. It would follow from this hypothesis that the same families, given more resources, would produce numbers of children closer to the established ideal. If they were deprived of resources, they would presumably fall even shorter of the goal than they already do. Thus one might expect that, in addition to the slowly shifting social family size norm, there would be a more short-term direct relationship between income or wealth and individual family size goals.

The direct association between income and fertility has been observed in the industrialized countries, where infant mortality and ineffective birth control do not complicate the picture. Baby "booms" during times of unusually rapid economic growth and extremely low fertility during economic depressions have occurred regularly in the United States and Europe, despite the fact that, in the United States at least, the stated ideal family size did not vary significantly throughout an entire cycle of fluctuating actual fertility (Blake 1967). Excellent statistical analyses of the relationship between short-term economic trends and birth rates in the United States have been made (Easterlin 1962, 1966).

Thus it seems that the *individual* operational goal for family size, at least among populations of industrialized countries, is that most often found by Rainwater in his

*Examples are Sweden (Myrdal 1941), Japan (Boffey 1970), and Romania (David and Wright 1971).

study of family size desires: "One should not have more children than one can support, but one should have as many as one can afford" (Rainwater 1965). The standard of "support" is defined by society; what the average member of society can "afford" is determined by the state of the economy and by the equality of the distribution of economic resources among the population.

Again, the detailed dynamics of this system are worth a separate study and can be only approximated in a highly aggregated model. We made two simplifying assumptions to represent the dynamics of the individual family's reaction to the prevailing family size norm. First, we assumed that income distribution in all populations is skewed toward the lower end of the income scale—that most people receive less than the average GNP per capita—and that this inequality of distribution does not change as a function of time. Second, we assumed that people adjust their reproductive goals to their personal expectations of income, and that their expectations about the future are determined by the average *rate of change* of their incomes.

```
FRSN.K=TABHL(FRSNT,FIE.K,-.2,.2,.1)                          41, A
FRSNT=.5/.6/.7/.85/1                                         41.1, T
FRSN=.82                                                     41.2, N
     FRSN   - FAMILY RESPONSE TO SOCIAL NORM
                 (DIMENSIONLESS)
     TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
     FRSNT  - FRSN TABLE
     FIE    - FAMILY INCOME EXPECTATION (DIMENSIONLESS)

FIE.K=(IOPC.K-AIOPC.K)/AIOPC.K                               42, A
     FIE    - FAMILY INCOME EXPECTATION (DIMENSIONLESS)

     IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                 PERSON-YEAR)
     AIOPC  - AVERAGE INDUSTRIAL OUTPUT PER CAPITA
                 (DOLLARS/PERSON-YEAR)

AIOPC.K=SMOOTH(IOPC.K,IEAT)                                  43, A
IEAT=3                                                       43.1, C
     AIOPC  - AVERAGE INDUSTRIAL OUTPUT PER CAPITA
                 (DOLLARS/PERSON-YEAR)
     SMOOTH - FIRST-ORDER EXPONENTIAL INFORMATION DELAY
     IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                 PERSON-YEAR)
     IEAT   - INCOME EXPECTATION AVERAGING TIME (YEARS)
```

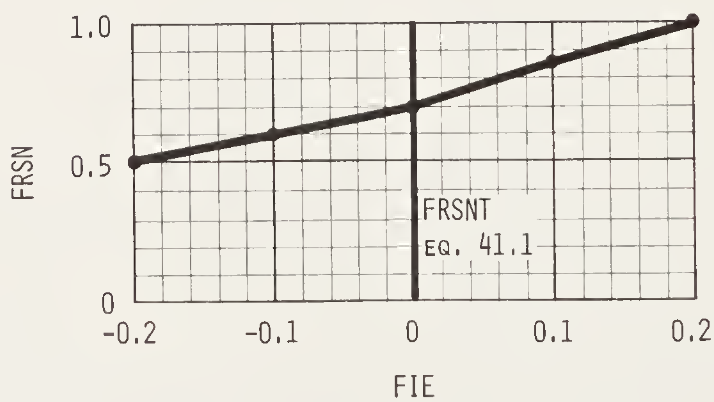

Figure 2-71 Family response to social norm table

Family income expectation FIE is calculated by comparing a running average industrial output per capita AIOPC over a three-year averaging time with the actual present income IOPC. Thus family income expectation FIE is a measure of whether and how fast income is increasing or decreasing:

$$\mathrm{FIE} = \frac{\mathrm{IOPC} - \mathrm{AIOPC}}{\mathrm{AIOPC}}$$

If income has been stagnant, FIE = 0. If income has been growing steadily at 3 percent per year, FIE equals approximately +0.07, and if income is falling, FIE is a negative number. The family response to social norm FRSN is then a function of family income expectation as shown in Figure 2–71. If income is stagnant or falling, the value of FRSN is 0.7 or below, indicating that most families will not feel that they can afford the socially ideal number of children. If income is rising, the slope of the function is slightly steeper, representing the probability that families under good economic conditions will be highly motivated to achieve the social reproductive norm. There is no delay in this function, other than the three-year time period during which families are assumed to observe present income trends and form their expectations of future income. It should be clear that the numerical values chosen for this function are hypothetical; we only tried to create a function with a positive slope and with a value less than 1.0 under normal economic circumstances.

The two multipliers SFSN and FRSN create a long-term, slowly moving inverse relationship between industrialization and family-size goals, superimposed on a short-term, rapidly fluctuating direct relationship. In the early stages of industrialization, when falling child mortality and improving methods of fertility control reinforce the trend toward decreasing fertility, the inverse relationship predominates. When the industrial system has reached high output and maintained it long enough for all other factors to stabilize, the direct relationship through FRSN is the only dynamic function still active.

The hypothesis that industrialization brings about two opposing effects on human fertility, with widely differing time constants, offers a possible resolution of the confusion in the population literature on this point. Attempts to analyze the influence of different fertility determinants by regression techniques have generally concluded that there is no relationship, or a weak positive relationship, between per capita income and fertility (Heer 1966, Weintraub 1962, Adelman 1963). On the other hand, the same studies have found a strong negative relationship between education and fertility, although it is well known that education and per capita income are strongly and positively correlated.

This apparent dilemma was clarified when Friedlander and Silver (1967) carried out a statistical analysis on fertility in the industrialized and the nonindustrialized countries separately. They discovered that per capita income was indeed correlated with fertility, but that the relationship was negative for the nonindustrialized countries and positive for the industrialized countries. Thus the previous regression analyses over all countries, slightly weighted in favor of developed countries with better statistics, produced confusing results. Further evidence for the bimodal influence of

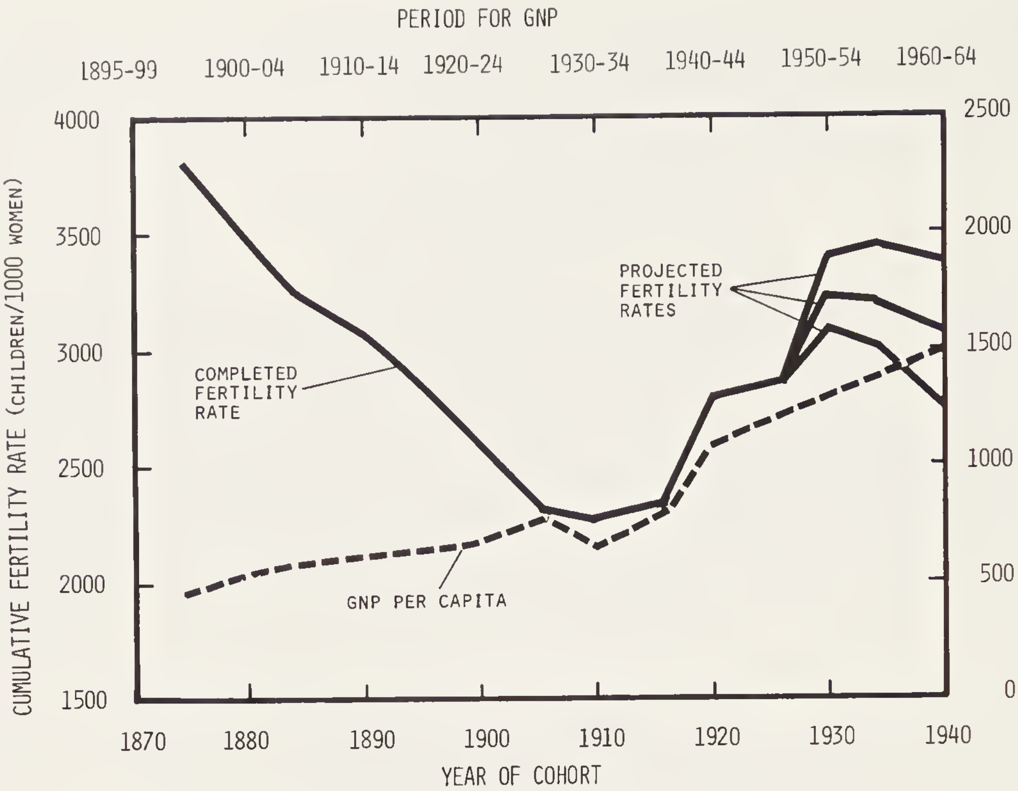

Figure 2-72 Total fertility versus GNP per capita, United States, 1870–1940
Source: C. V. Kiser, W. H. Grabill, and A. A. Campbell, *Trends and Variations in Fertility in the United States*, Cambridge, Mass.: Harvard University Press, 1968. Copyright © 1968 by the Harvard University Press.

income on fertility is cited in the exhaustive literature survey of Mason et al. (1971), who reached the following conclusion about the relation between family wealth and fertility:

> . . . for the least developed nations the tendency of the relationship was inverse; for transitional societies the tendency of the relationship was one of inconsistency; while for developing nations the tendency is for a direct relationship. [Mason et al. 1971, p. x]

The behavior of the fertility rate in the United States as the population passed through these three stages in industrial development is shown in Figure 2-72.

Fertility Control Effectiveness FCE Traditionally, birth control effectiveness has been defined in terms of specific contraceptive methods and specific populations of users. For any given method the most simple measure of use-effectiveness is the "Pearl pregnancy rate"—the number of accidental pregnancies divided by the total months of contraceptive use, usually multiplied by 1,200 to give pregnancies per 100 woman-years of use (Pearl 1939). More sophisticated measures of use-effectiveness based on life table statistical techniques have also been calculated (Potter 1966).

Fertility control effectiveness FCE in World3 refers not to any specific contraceptive method but to the average effectiveness of the entire spectrum of means actually used by the population to control family size. These means could include any of the Davis and Blake (1956) "intermediate variables" that can be considered subject to voluntary or societal control, namely:

1. Age of entry into sexual unions
2. Extent of permanent celibacy
3a. Unions broken by divorce, separation, desertion
4. Voluntary abstinence
6. Coital frequency
8. Use of contraception
9. Voluntary sterilization
11. Induced abortion

Operationally, fertility control effectiveness FCE is defined as the aggregate ability of the population to achieve its average desired total fertility DTF rather than the maximum total fertility MTF that is biologically possible. If a population actually desires to reproduce at a maximum rate, the effectiveness of fertility control available to that population is unimportant in determining its fertility. The greater the difference between desired total fertility and maximum total fertility, the more necessary and important the effective practice of fertility control becomes.

How can the overall effectiveness of a population in controlling its fertility be measured? Unfortunately, none of the standard family-planning data (for example, Pearl pregnancy rates, number of IUD acceptors, or percentage of target population contacted) can be translated directly into the summary of general fertility control effectiveness needed for the World3 equations. Two possible ways of approaching the estimation of fertility control effectiveness FCE are discussed here: a macro point of view, based on actual observed fertility, and a micro point of view, based on knowledge of the acceptability of individual methods in a given society. We did not attempt to compile a complete table of FCE values for real-world populations by either approach, since very little of the necessary information is available without further field studies specifically designed to gather such data. Rather, we made sample calculations to indicate the general range and direction of the relationships needed for the model. Further empirical and statistical studies in this area would be quite useful.

The macro approach to estimating FCE follows directly from the equation for total fertility TF given earlier in this chapter:

$$\mathrm{TF} = \mathrm{MTF}(1 - \mathrm{FCE}) + \mathrm{DTF}(\mathrm{FCE})$$

or

$$\mathrm{FCE} = \frac{\mathrm{MTF} - \mathrm{TF}}{\mathrm{MTF} - \mathrm{DTF}}$$

Thus the fertility control effectiveness FCE of a population equals the difference between the maximum possible fertility MTF and the actual observed fertility TF, divided by the difference between the maximum fertility MTF and the desired fertility DTF. According to this equation, if the actual total fertility is exactly equal to the desired total fertility, FCE = 1.0. If the actual total fertility equals the maximum, FCE = 0. If the desired fertility equals or exceeds the maximum, FCE is a meaningless concept, since no control will be practiced or needed.

For some populations, enough information is available or can be inferred about average values of MTF, DTF, and TF to calculate an approximate value for FCE from the preceding equation. For example, in the villages of the Khanna district of North India in 1959, the average total fertility was 7.5 children, of whom 4.7, or 62.5 percent, survived childhood (Wyon and Gordon 1971, p. 170). The minimum family size goal widely agreed upon by the population was 2 sons, which would imply, on the average, 4 children. Allowing for the very high infant and child mortality in the region, an average of 6.4 children would have to be born to ensure a goal of 4.0 survivors. If the actual operational goal was about 4.0 surviving children (most surveys in rural India indicate an ideal between 4 and 5 children) and if parents were compensating accurately for both infant and child mortality, the fertility control effectiveness FCE under various maximum fertility assumptions would be:

$$\text{MTF} = 12 \qquad \text{FCE} = \frac{12-7.5}{12-6.4} = \frac{4.5}{5.6} = 0.80$$

$$\text{MTF} = 11 \qquad \text{FCE} = \frac{11-7.5}{11-6.4} = \frac{3.5}{4.6} = 0.76$$

$$\text{MTF} = 10 \qquad \text{FCE} = \frac{10-7.5}{10-6.4} = \frac{2.5}{3.6} = 0.70$$

If the completed family size goal were higher than 4.0 children or if parents tended to overcompensate for mortality, the value of FCE would be higher than that calculated here.

Given the many assumptions involved, the precise value of FCE estimated for these North Indian villages is not significant. It is interesting to note, however, that in this nonindustrial Asian population, generally unexposed to modern family-planning techniques, the fertility control effectiveness actually practiced was on the order of 0.7–0.8 rather than 0.5 or less. These calculations can be made for other nonindustrial populations with similar results:

Tunisia, 1964 (Morsa 1966)

Total fertility		5.9
Surviving children		4.7
Percent survival		80.0
Desired surviving family size		4.0
Desired total fertility		5.0
Fertility control effectiveness	MTF = 12	0.87
	MTF = 11	0.85
	MTF = 10	0.82

Thailand, 1964 (Hawley and Prachuabmoh 1966)

Total fertility	6.2
Surviving children	5.2
Percent survival	84.0
Desired surviving family size	4.2
Desired total fertility	5.0

Fertility control effectiveness	MTF = 12	0.83
	MTF = 11	0.80
	MTF = 10	0.76

A calculation of fertility control effectiveness in an industrialized population can be made from results of the 1965 national fertility survey in the United States (Bumpass and Westoff 1970). The cohort of women aged 35 to 44 in that survey reported an average total fertility of 3.0 and stated that 16 percent of these births were unwanted (of course, self-admission of an unwanted birth leads to underreporting and thus a value for FCE that is probably too high). Thus for this cohort of American women:

Total fertility		3.0
Surviving children		3.0
Percent survival		100 (assumed)
Desired surviving family size		2.5
Desired total fertility		2.5
Fertility control effectiveness	MTF = 13	0.95
	MTF = 12	0.95
	MTF = 11	0.94

These sample calculations indicate that the operational FCE in diverse areas of the world does not vary numerically over a wide range. We assumed, as will be explained further, that the global average FCE under all conditions will remain within the 0.75 to 1.0 range.

This assumption does not imply that family-planning policies designed to increase FCE will necessarily prove ineffective in changing the behavior of the model. Under conditions where MTF is relatively high and DTF is low, such as in the United States, a small change in the value of FCE can have a large effect on the population growth rate. For example, using the figures MTF = 13 and DTF = 2.5, if FCE = 1.0 the total fertility actually experienced would be 2.5 children, quite close to the replacement value that would lead to a zero growth rate. If FCE = 0.90 the resultant total fertility would be 3.6 children, and if FCE = 0.85 it would be 4.1 children, which would lead to a doubling of the population nearly every generation.

On the other hand, in populations where MTF is low and DTF is high (as in most of the nonindustrialized populations), the same change in FCE would have considerably less effect on the population growth rate. In the Khanna population, for example, if MTF = 10 and DTF = 6.4, increasing FCE from 0.75 to 0.95 would reduce total fertility from 7.5 to 6.6, or only one child per family. In contrast, changing the FCE of the American family by the same amount, 0.75 to 0.95, would change total fertility from 5.1 to 3.0 children, or more than two children per family. Model runs illustrating the effectiveness of FCE as a control variable on the whole model system are shown in section 2.6 and in Chapter 7.

Another way of assessing the fertility control effectiveness FCE practiced by any population is to examine in detail the various methods of control actually available to that population in terms of the cost and potential effectiveness of their use. This approach is more tedious and requires more detailed information about the population in question than the macro approach described previously. On the other hand, it can yield a much greater understanding on which to base policies for improving fertility control effectiveness. Ideally, of course, both a macro and a micro estimate of FCE should be available for any population, and the two estimates should agree.

Assessment of fertility control methods in use should begin with the recognition that even the most primitive human populations practice a number of different methods of controlling their fertility (Himes 1936, Nag 1968, Omran 1971). At least three of these primitive methods have an intrinsic effectiveness of 100 percent, namely, infanticide, abortion, and abstention from sexual intercourse. There is ample evidence that each method has been or is being used to a significant extent by human populations.

> Infanticide was an almost universal custom from very early times and is still quite common in many parts of the world. . . . Indeed, it is such a common practice that one notices its absence rather than its presence when reading the accounts of explorers and anthropologists. . . . In Europe it was not until well into the Middle Ages that infanticide came to be looked upon as a crime. [Thompson 1953, pp. 10–11]

> It is the author's opinion that when developing societies are highly motivated to accelerate their transition from high to low fertility, induced abortion becomes such a popular method of fertility control that it becomes a kind of epidemic. . . . [In Japan] following World War II, abortions reached the high proportion of 716.3 per 1000 live births. . . . According to Chilean hospital data for the 24 years ending in 1960, the number of deliveries increased by 1.8 times, whereas the corresponding figure for postabortion hospital admissions increase was 4.4. . . . In Turkey, a study showed that 39.4 percent of the 496 women coming for contraceptive advice in Ankara Maternity Hospital had had induced abortions at some time in their past. . . . Kenya statistics for 1964 indicate that the number of deaths from abortion was almost half that attributed to malaria. [Omran 1971]

> Ireland is the best contemporary example of abstinence—achieved in this instance through not marrying. According to the 1951 census, 31 percent of the men and 26 percent of the women of age 50 have never married. Average age at first marriage was 31 years for grooms and 27 for brides. [Thomlinson 1965, p. 196]

Although nearly every population seems to know about these and other theoretically effective methods of fertility control, in practice very few populations use these methods to control their fertility with theoretical 100 percent efficiency. In fact, any fertility control method can be assigned two effectiveness ratings: an *intrinsic* effectiveness that pertains when it is used universally, consistently, and correctly; and a *practical* effectiveness or use-effectiveness that is attained by an actual population containing individuals with varying degrees of motivation, will power, and understanding. The range of actual use-effectiveness of different contraceptive methods is illustrated by Figure 2-73.

The difference between intrinsic effectiveness and use-effectiveness of fertility control methods can be understood by taking into account not only the intrinsic effectiveness of each method but also the perceived cost of using it. No fertility control method can be practiced without some cost, where "cost" refers not only to monetary expense but also to social or psychological costs, such as embarrassment, inconvenience, physical risk, or fear of social reprisal. An intrinsically effective method, such as abortion or abstinence, can be ineffective in a real population because its high cost prohibits consistent use.

Cost is here, as always, a relative concept. The perceived cost of a given fertility control method can vary greatly from society to society. For example, an abortion in Romania could be legally obtained in any hospital or outpatient clinic for 3 dollars from 1957 to 1966. The procedure took only about two hours and was medically safe and governmentally approved (David and Wright 1971). Widespread use of abortion by the Romanian population during this period indicated that the perceived cost of this method was relatively low (though not, of course, zero). In contrast, in the United States abortion laws until recently have been overwhelmingly restrictive, the cost of a hospital abortion has been 500 dollars or more, the health risk of an illegal abortion has been high, and the procedure has been socially and officially disapproved. Although many abortions nevertheless took place under these circumstances, the perceived cost was clearly higher than in Romania and the frequency of use was lower.

The costs of fertility control not only vary from society to society; they also vary in a single society over time. Since 1966, abortion has been illegal in Romania and has become more socially accepted (Blake 1971) and partially legalized in the United States.* One might expect the use-effectiveness of abortion to decrease in Romania and to increase in the United States in the future, although its intrinsic effectiveness is unchanged.

For a given society at a given time, the spectrum of available birth control methods can be evaluated in terms of the intrinsic effectiveness and apparent cost of each method to give a set of cost-effectiveness curves, as shown in Figure 2-74 for a hypothetical Western industrialized population. Maximum and minimum effectiveness figures for each method are taken from Figure 2-73. Apparent costs were assigned on a scale from 0 to 10, with the cost of no control defined as 0 and the cost of infanticide (unacceptable in this society) as 10. For several methods, cost-effectiveness must be defined as a line rather than a point, since more effective use entails higher cost. The classic example of such a method is rhythm, which becomes more effective and more psychologically costly as it approaches complete abstinence.

A cost-effectiveness curve such as that shown in Figure 2-74 is not sufficient to define the aggregate fertility control effectiveness of a population, since the cost of taking any action is meaningful only in comparison with the cost of *not* taking that action. In the case of fertility control, the perceived cost of using any preventive measure must be weighed against the perceived cost of producing an unwanted child, with cost again interpreted in the broadest sense of the word. Clearly, no method will be used unless the perceived net cost of producing a child approximates the cost of using that method. Thus there are two subjective and difficult-to-measure quantities that must be understood before the FCE of a population can be estimated by the

*In early 1973 legal restrictions on abortions during the first trimester of pregnancy were declared unconstitutional by the U.S. Supreme Court.

Method	**Failure Rate** (pregnancies per 100 woman-years of use)		
	High	**Average**	**Low**
No method		90*	
Aerosol foam			29
Sponge and foam powder	35		28
Lactation	26		24
Douche	41		21
Foam tablets	43		12
Coitus interruptus	38		10
Condom	28		7
Suppositories	42		4
Jelly or cream	38		4
Diaphragm and jelly	35		4
Intra-uterine device (IUD)		2.4	
Rhythm	38		0
Steroid pill	2.7		0
Abstinence			0
Abortion			0

*This figure, suggested by Pearl almost forty years ago, is almost certainly too low (D. M. Heer; personal communication).

Figure 2-73 Use-effectiveness of various fertility control methods
Source: Adapted from Southam 1966.

micro approach. First, the apparent costs of various available fertility control methods must be assessed. This assessment can be made largely from data on the mix of methods actually used, the average failure rates, and the stated reasons for using or not using various methods. Second, the perceived cost of producing an unwanted child must be estimated, which is much more difficult, since this assessment depends on a present evaluation of a future event. Individuals as well as institutions often tend to discount future costs when comparing them with immediate costs. It is probable that the undiscounted cost of a child must be perceived as considerably greater than the cost of control before the control method will be utilized. The hypothetical diagram in Figure 2-74 shows the resultant FCE, given the available spectrum of control methods and three different perceptions of the cost of an unwanted child.

The horizontal lines of Figure 2-74, expressing the average cost a population is willing to pay to control its fertility, are influenced by the same social and economic factors that influence the desired total fertility DTF—for example, required standards of raising children, housing limitations, need for mobility, economic role of women, and expectations about future assets. Thus the fertility control model presented here would suggest that industrial development, as it lowers the desired family size by shifting the social cost-benefit balance of having children, also automatically leads to improved fertility control effectiveness by making people more willing to use higher-cost and more effective methods. In World3 we assumed that this motivational

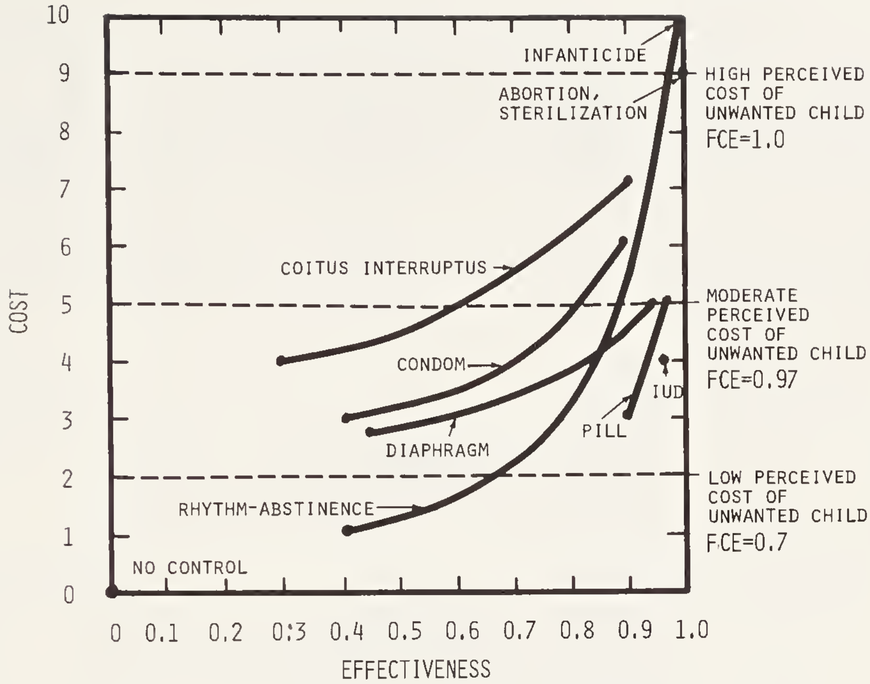

Figure 2-74 Cost-effectiveness curves for birth-control methods

mechanism leading to increased fertility control effectiveness is enhanced by a technological mechanism—the development of more effective, lower-cost methods of fertility control. Two of the relatively low-cost and high-effectiveness measures shown in Figure 2-74, the pill and the IUD, are recent technologies, the result of investment in research and development to fill a newly recognized social need for fertility control.

In World3 the causal mechanism that determines FCE begins with the assumption that fertility control effectiveness will remain at its preindustrial value of about 0.75 unless a recognized *need* for better control exists. The need for fertility control NFC increases when either maximum total fertility MTF increases or desired total fertility DTF decreases. Mathematically, the need for fertility control NFC is defined as:

$$NFC = \frac{MTF}{DTF} - 1.$$

If desired fertility equals maximum fertility, NFC = 0, and no need to improve control is recognized. If, however, DTF is less than MTF, the need for fertility control NFC assumes a positive value, triggering a chain of events that leads to higher fertility control effectiveness FCE.

```
NFC.K=(MTF.K/DTF.K)-1                                   44, A
    NFC     - NEED FOR FERTILITY CONTROL (DIMENSIONLESS)
    MTF     - MAXIMUM TOTAL FERTILITY (DIMENSIONLESS)
    DTF     - DESIRED TOTAL FERTILITY (DIMENSIONLESS)
```

First, the greater need for fertility control NFC leads to a larger fraction of service output allocated to fertility control FSAFC. The assumed relationship between these two variables is shown in Figure 2-75. This allocation includes all economic and institutional aspects of fertility control technology—basic research and development, training and salaries for family-planning personnel, educational programs, clinics, and equipment. The fraction of service allocated to these purposes is then multiplied by the total value of service output per capita SOPC each year to give the dollar value of fertility control allocations per capita FCAPC.

```
FCAPC.K=FSAFC.K*SOPC.K                                    47, A
    FCAPC   - FERTILITY CONTROL ALLOCATIONS PER CAPITA
                (DOLLARS/PERSON-YEAR)
    FSAFC   - FRACTION OF SERVICES ALLOCATED TO FERTILITY
                CONTROL (DIMENSIONLESS)
    SOPC    - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
                YEAR)

FSAFC.K=TABHL(FSAFCT,NFC.K,0,10,2)                        48, A
FSAFCT=0/.005/.015/.025/.03/.035                          48.1, T
    FSAFC   - FRACTION OF SERVICES ALLOCATED TO FERTILITY
                CONTROL (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FSAFCT  - FSAFC TABLE
    NFC     - NEED FOR FERTILITY CONTROL (DIMENSIONLESS)
```

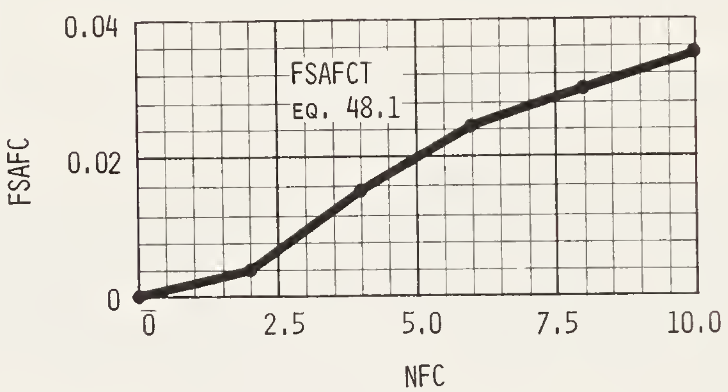

Figure 2-75 Fraction of service output allocated to fertility control table

Recent values of fertility control allocations per capita FCAPC in several nonindustrialized countries are shown in Figure 2-76. The last column indicates proposed per capita expenditures for a more modern and complete family-planning program; the annual expenditures in these proposed programs range from \$0.32 to \$1.65 per person in the population per year (Taylor and Berelson 1971).

We assumed in World3 that there is a third-order delay between the allocation of fertility control expenditures and the development and implementation of low-cost, effective fertility control throughout the population. Because this delay involves both time for research and time for change of deeply ingrained social and private behavior, we assumed a rather long delay time of 20 years, the same as the health service impact delay HSID. Thus, after a given expenditure of fertility control allocations per capita FCAPC, there is a delayed increase in established and accepted fertility control facilities per capita FCFPC.

Country	Family Planning as Percentage of Total Government Budgets	Annual per Capita Budget for Family Planning (all sources—current dollars)	Per Capita Costs of Proposed Program (dollars/ person-year)
Fiji (1970)	0.29	0.23	
Guatemala (1971)	0.07		
Ghana (1971)		0.11	0.93
Honduras (1972)	0.06		
Hong Kong (1970)		0.079	
India (1966–1971)	2.0	0.146	0.32–0.36
Indonesia (1971)		0.064	0.41
Iran (1971)	0.07	0.24	0.92
Kenya (1970)	0.01	0.085	1.65
Malaysia (West) (1970)	0.10	0.086	
Mauritius (1971)	0.12	0.25	
Morocco (1972)	0.04	0.026	
Nepal (1970)	0.14	0.035	
Pakistan (1965–1970)	0.5	0.118	
Philippines (1971)	0.43	0.073	0.60
Singapore (1971)	0.02		
South Korea (1971)	0.12	0.18	
Taiwan (1972)	0.20	0.068	
Thailand (1971)	0.13	0.14	0.38
Turkey (1969)	0.05	0.046	0.55

Figure 2-76 National family-planning expenditures
Source: Taylor and Berelson 1971

```
FCFPC.K=DLINF3(FCAPC.K,HSID)                          46, A
    FCFPC   - FERTILITY CONTROL FACILITIES PER CAPITA
                (DOLLARS/PERSON-YEAR)
    DLINF3 - THIRD-ORDER EXPONENTIAL INFORMATION DELAY
    FCAPC   - FERTILITY CONTROL ALLOCATIONS PER CAPITA
                (DOLLARS/PERSON-YEAR)
    HSID    - HEALTH SERVICES IMPACT DELAY (YEARS)
```

Fertility control effectiveness FCE is defined as a nonlinear function of fertility control facilities per capita FCFPC, as shown in Figure 2-77. It is assumed in this relationship that fairly modest per capita investments in fertility control facilities can lead to significant improvements in fertility control effectiveness. A CLIP function in the FCE equation allows the model operator to set FCE to 1.0 at any specified time FCEST, to test the effect of 100 percent effective fertility control on the population system.

```
FCE.K=CLIP(1.0,(TABHL(FCET,FCFPC.K,0,3,.5)),TIME.K, 45, A
  FCEST)
FCEST=4000                                              45.1, C
FCET=.75/.85/.9/.95/.98/.99/1                           45.2, T
    FCE     - FERTILITY CONTROL EFFECTIVENESS
                (DIMENSIONLESS)
```

```
CLIP   - A FUNCTION SWITCHED DURING THE RUN
TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
FCET   - FCE TABLE
FCFPC  - FERTILITY CONTROL FACILITIES PER CAPITA
           (DOLLARS/PERSON-YEAR)
TIME   - CURRENT TIME IN THE SIMULATION RUN
FCEST  - FERTILITY CONTROL EFFECTIVENESS SET TIME
           (YEAR)
```

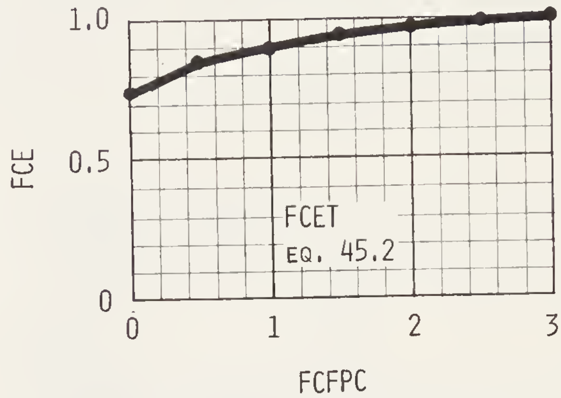

Table 2-77 Fertility control effectiveness table

The causal structure leading to fertility control effectiveness in World3 must be regarded as tentative, pending better information on the real costs and delays of implementing new fertility control methods. Our intent here was to emphasize that costs and delays do exist and that there must be a recognized need before society is willing to bear the costs of fertility control. A more detailed dynamic examination of this relationship might establish several causal chains incorporating different intrinsic delays. For example, a sudden decrease in desired total fertility DTF, which increases the need for fertility control NFC, may cause a small immediate increase in FCE as some people begin to utilize the high-cost methods already available, such as abortion and abstinence. This initial increase may then be followed by a larger increase, after a longer delay, as the new need stimulates the development of lower-cost methods, such as the IUD, which a larger fraction of the population may accept. The interesting behavior of Romanian fertility after abortions were made illegal in 1966 (David and Wright 1971) indicates that, at least in educated societies accustomed to effective fertility control, there may be a social response time of only a few years to adjust fertility control effectiveness to that needed by the population, even in the absence of modern fertility control technologies and government support.

Age-Structure Equations

We have already suggested that the determinants of population growth rates can be separated conceptually into two categories. The first consists of the many social and economic forces acting to increase or decrease mortality and fertility. This group of forces determines the aggregate probabilities of a person of a given sex and age dying or reproducing that characterize a population at any given time. The preceding description of the population sector equations has concentrated on our representation of this set of socioeconomic factors.

A second category of dynamic determinants of the behavior of the population system arises from the age structure of the population. These demographic determinants influence *how many* persons of each age and sex exist in the population at any time and are exposed to the mortality and fertility probabilities determined by the socioeconomic system.

Here we present three age-structure models at three different levels of complexity and accuracy that can be used interchangeably within the framework of the socioeconomic model to study the relative contribution of demographic factors to overall population behavior modes. The one-level population model, already described, essentially ignores the dynamics inherent in the population age structure. After reviewing that model, we discuss alternate age-structure models in order of increasing complexity, keeping in mind that for the purposes of this model we are searching for the minimum degree of complexity necessary to represent the demographic contribution to population dynamics.

One-Level Population Model The following equations summarize the simplified assumptions contained in the one-level population model:

```
L      POP.K=POP.J+(DT)(B.JK-D.JK)
N      POP=POPI
C      POPI=1.61E9

R      D.KL=POP.K/LE.K
S      CDR.K=1000*D.JK/POP.K

R      B.KL=CLIP(D.JK,(TF.K*POP.K*FFW/RLT),TIME.K,PET)
C      FFW=.21
C      RLT=30
C      PET=4000
S      CBR.K=1000*B.JK/POP.K
```

These equations imply that women of reproductive age constitute a constant fraction of the population, that death occurs with equal probability to persons of all ages, and that changes in fertility or mortality probabilities have a single, instant effect on the population growth rate. These simple approximations would obviously not be permissible if the goal of the modeling process were short-term, accurate population prediction. For a long-term model designed only to investigate behavior modes, such approximations may be acceptable for the sake of simplicity of the model as a whole. The most serious dynamic defect of the one-level model is its omission of the delays inherent in the population age structure. For example, it implies that a 1 year-old child can immediately be counted as part of the reproductive population; it also implies that a 10 percent change in the mortality risk of 60-year-olds has the same effect on the population growth rate as a 10 percent change in the mortality risk of 1-year-olds. This failure to represent aging delays will certainly introduce error into the calculation of exact population growth rates. More important, it may alter the resultant behavior mode by which the population approaches an environmental limit or terminates a growth phase by ignoring a destabilizing delay between an environmental stimulus and a demographic response. Therefore, we must investigate more accurate ways of representing the delays in the age structure of the population, by disaggregating the single population level.

Four-Level Model Two population age groups are of particular interest for relationships elsewhere in World3: the reproductive population (as an input to the birth rate) and the labor force (as an input to industrial production). To formulate these two age groups and keep track of the size of the total population as well, we can disaggregate the population into four age groups: prereproductive P1 (ages 0–14), reproductive working P2 (ages 15–44), nonreproductive working P3 (ages 45–64), and elderly P4 (ages 65+). The ages used to bound these four functional groups are only rough averages and are subject to much individual variation. The 15–44 delineation of the reproductive age is based on females only. The DYNAMO flow diagram of the four-level age structure is shown in Figure 2-78.

The total population is the sum of the four age levels as just defined:

```
1    A    POP.K=P1.K+P2.K+P3.K+P4.K
```

The 0- to 14-year-old age level P1 is increased by births B, decreased by deaths D1, and decreased by the maturation of 14-year-olds MAT1 into the next age group. The other age levels are formulated similarly, except that they are increased by maturation from the level below, rather than by births:

```
2     L    P1.K=P1.J+(DT)(B.JK-D1.JK-MAT1.JK)
      N    P1=P1I
      C    P1I=65E7

6     L    P2.K=P2.J+(DT)(MAT1.JK-D2.JK-MAT2.JK)
      N    P2=P2I
      C    P2I=70E7

10    L    P3.K=P3.J+(DT)(MAT2.JK-D3.JK-MAT3.JK)
      N    P3=P3I
      C    P3I=19E7

14    L    P4.K=P4.J+(DT)(MAT3.JK-D4.JK)
      N    P4=P4I
      C    P4I=6E7
```

Since the age structure of the world population in 1900 is not known, the initial values for the four population age levels were taken from a typical age structure of a nonindustrialized country (Bogue 1969, p. 148) as shown in Figure 2-79.

The number of deaths in each age level each year is calculated from the number of people in the level PN (N=1−4) times the age-specific mortality for that age level MN (N=1−4).

```
3     R    D1.KL=P1.K*M1.K
4     A    M1.K=TABHL(M1T,LE.K,20,80,10)
      T    M1T=.0567/.0366/.0243/.0155/.0082/.0023/.001

7     R    D2.KL=P2.K*M2.K
8     A    M2.K=TABHL(M2T,LE.K,20,80,10)
      T    M2T=.0266/.0171/.0110/.0065/.0040/.0016/.0008

11    R    D3.KL=P3.K*M3.K
12    A    M3.K=TABHL(M3T,LE.K,20,80,10)
      T    M3T=.0562/.0373/.0252/.0171/.0118/.0083/.006

15    R    D4.KL=P4.K*M4.K
16    A    M4.K=TABHL(M4T,LE.K,20,80,10)
      T    M4T=.13/.11/.09/.07/.06/.05/.04
```

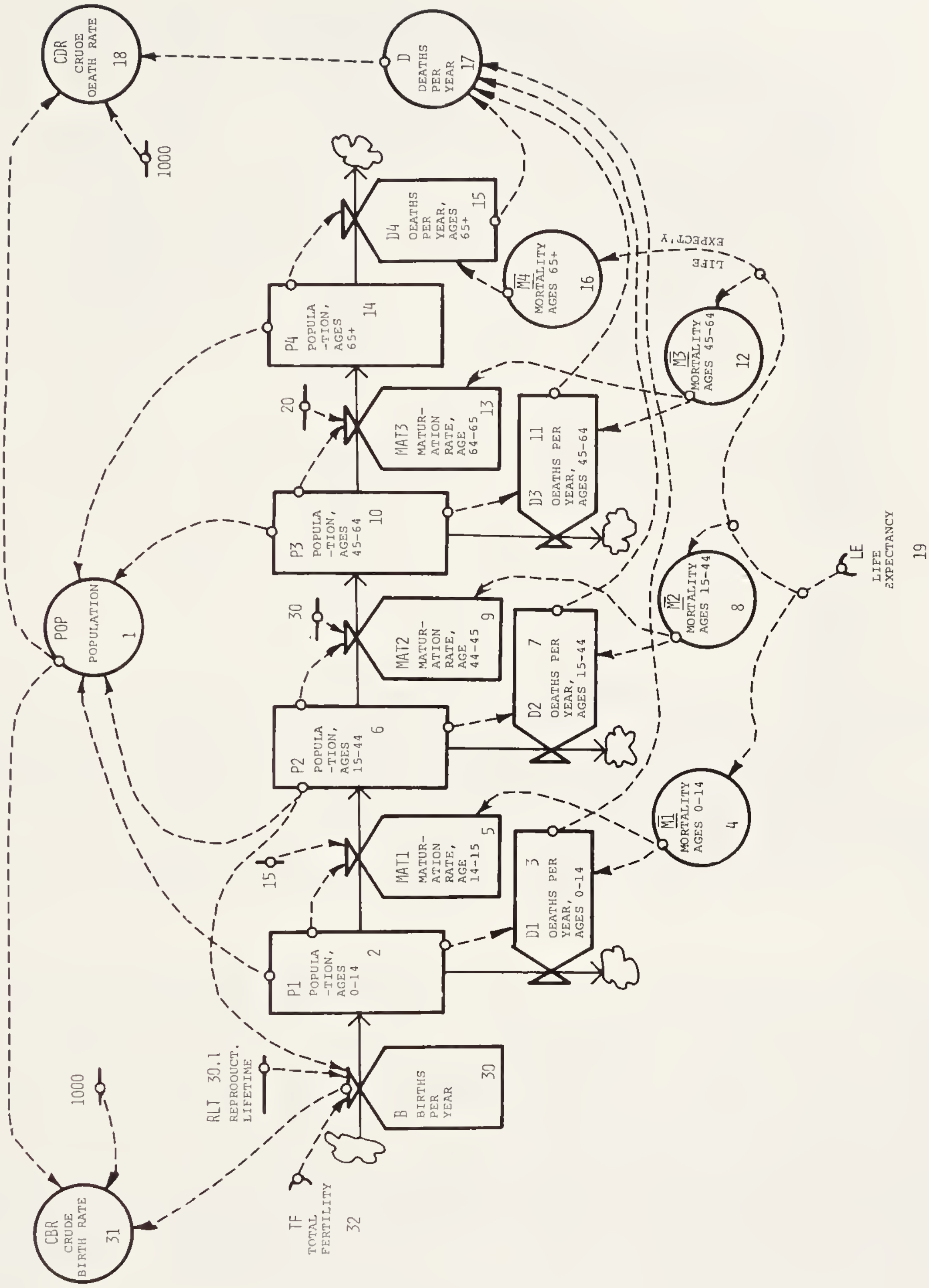

Figure 2-78 DYNAMO flow diagram, four-level age structure

Ages	Percentage of Population[a]	Initial Values, 15-Level Model	1900[b] (millions) 4-Level Model
0–4	16.1	260[c]	
5–9	13.0	210	650
10–14	11.2	180	
15–19	9.9	160	
20–24	9.2	145	
25–29	7.9	120	700
30–34	6.8	105	
35–39	5.8	90	
40–44	5.0	80	
45–49	4.1	65	
50–54	3.4	55	190
55–59	2.7	40	
60–64	2.0	30	
65–69	1.4		
70–74	0.8		
75–79	0.4	60	60
80–84	0.2		

[a]Taken from typical age structure, developing country (Bogue 1969, p. 148).
[b]Calculated, assuming a total world population of 1.6 billion in 1900 (Carr-Saunders 1936, p. 42).
[c]Age 0–1, 50; age 1–4, 210.

Figure 2-79 Initial values for population levels in age disaggregations

Ideally, each age-specific mortality should be a direct function of the four factors selected as inputs to the death rate: food per capita, health services per capita, pollution, and crowding. Unfortunately, there is not yet enough knowledge to express the influence of each of these factors on the probabilities of death in the different age groups. To represent the variations in age-specific death rates as these four influences vary, we made one assumption: that the basic nonlinear pattern of the curve of human age-specific death rates will not change radically in the future. The relative constancy of this pattern over widely different mortality conditions and in widely different populations is shown in Figure 2-80. The great susceptibility of the very young and the very old to unfavorable environmental conditions seems to be a fundamental biological characteristic of the species regardless of the exact mix of environmental factors involved.

In both the four-level and the fifteen-level age disaggregations, life expectancy at birth was taken as the general indicator of population health. Age-specific mortalities were then determined as nonlinear functions of life expectancy. Although there is not necessarily a one-to-one relationship between a given life expectancy and a set of age-specific mortalities, variations from one population to another are negligible, given the degree of accuracy we seek with this model (for model life tables representing regional differences, see Coale and Demeny 1966). A model life table,

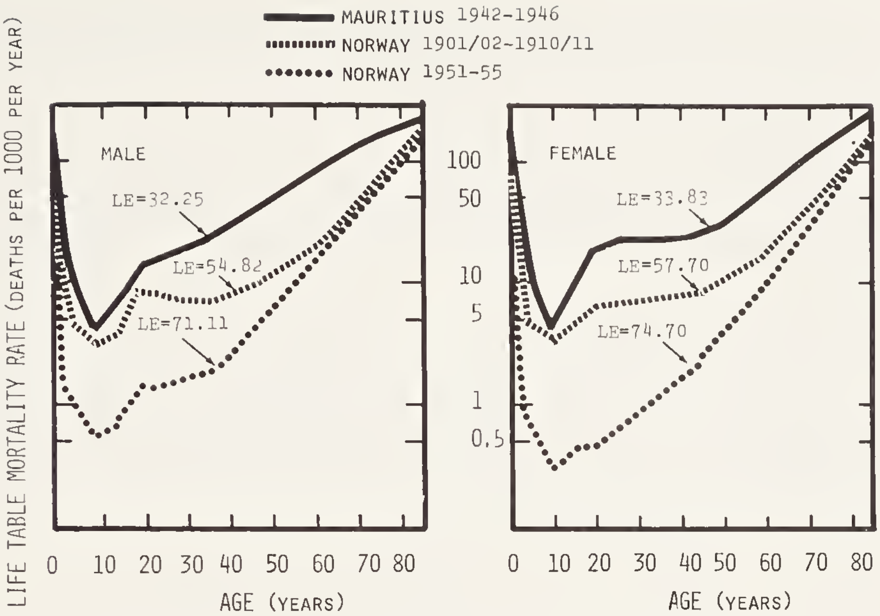

Figure 2-80 Age-specific mortality rates, Norway and Mauritius
Source: U.N. 1962.

based on data averaged from many different national populations (U.N. 1956), was used as the basis for the age-specific mortality functions in all the age disaggregations described here.

For the four-level model, age-specific death rates were calculated from the 1_x column of the life table (U.N. 1956) under the simplifying assumption that deaths occur within each age level as a process of simple exponential decay with a constant rate:

$$l_t = l_o e^{-Mt}$$

which can be solved for M as follows:

$$\ln(l_t/l_o) = Mt$$

$$M = \frac{\ln(l_t/l_o)}{t}$$

For example, with a 20-year life expectancy the model life table indicates that only 42,805 of an initial cohort of 100,000 will survive to age 15. Therefore $l_0 = 100{,}000$, $l_t = 42{,}805$, and $t = 15$. The exponential decay constant M then equals:

$$\frac{\ln(42{,}805/100{,}000)}{15} = 0.0567.$$

Similarly, for a 60-year life expectancy, 88,500 of the initial 100,000 live to age 15, and M is:

$$\frac{\ln(88{,}500/100{,}000)}{15} = 0.0082.$$

The age-specific mortality of the age group P4 (age 65+) is also assumed to be an exponential decay constant, which is calculated from both the l_x and L_x columns of the life table. At life expectancy = 20 years there are 6,324 survivors of a cohort of

100,000 at age 65 (l_x column). These survivors will collectively live a total of 49,873 more years (sum of the last 5 values of L_x column), or an average of 7.9 years per person (49,873/6,324); therefore:

M4 = 1/7.9 = 0.126.

Since we are not concerned with the age structure within each of the four age levels, this assumption of exponential decay at a constant rate is within the computational accuracy we require.

The maturation rate MATN (N=1−3) from each population level to the next higher level is also formulated in the simplest possible way—as a first-order delay, with the delay time equal to the average number of years each person spends in the age level. The number of deaths each year is subtracted from the age level, so only survivors are moved into the next higher level.

```
5    R    MAT1.KL=(P1.K)(1-M1.K)/15
9    R    MAT2.KL=(P2.K)(1-M2.K)/30
13   R    MAT3.KL=(P3.K)(1-M3.K)/20
```

This formulation assumes that deaths within the level are evenly distributed by age. Such an assumption introduces a slight error into the calculation, the error being greater under conditions of high mortality. As we shall see in the comparative model runs in section 2.6, this small discrepancy does not seriously alter the dynamic behavior modes of the model system.

The total death rate in the four-level model is the sum of the deaths in each age level. The birth rate can now be expressed as a function of the size of the reproductive-age population P2. Thus the expression POP.K*FFW in the birth rate equation of the one-level model can be replaced by P2.K*0.5 in the four-level model. The factor 0.5 arises from the assumption that half the population in P2 is female.

```
17   A    D.K=D1.JK+D2.JK+D3.JK+D4.JK
18   S    CDR.K=1000*D.K/POP.K

30   R    B.KL=CLIP(D.K,(TF.K*P2.K*0.5/RLT),TIME.K,PET)
     C    RLT=30
     C    PET=4000
31   S    CBR.K=1000*B.JK/POP.K
```

This four-level population model is an improvement over the one-level model in that it recognizes the existence of a delay between the birth rate and the reproductive population. It also incorporates some of the known nonlinearities in human death rates as a function of age. However, the four-level model is still far from accurate, since it represents the proper *time lags* in the age structure but misrepresents the *order*, or response-shape, of the delay. (The dynamic distinction between various orders of delay is illustrated in Appendix F at the end of this book.) If there were a sudden rise in the birth rate, a real population would show a rise in the reproductive population only after a delay of about 15 years. The shape of that rise would probably be best represented with an intermediate-order delay (third- to sixth-order). The delay would not be infinite-order, since that would imply that all children reach sexual maturity at exactly the same age. It would also not be first-order, since that would imply that some portion of the newborn children mature with no delay. The one-level population model assumes no delay at all between birth and sexual maturity. The four-level model assumes a 15-year, first-order delay. The more complex age disaggregation that follows represents a 15-year, fourth-order maturation delay between birth and reproduction; it also captures accurately the nonlinearities in the distribution of human deaths as a function of age.

Fifteen-Level Model The fifteen-level age-structure model is similar in concept to the four-level model, but the levels encompass an age span of five years or less. A partial DYNAMO flow diagram of this model is shown in Figure 2-81.

To represent the particularly high mortality risk characteristic of the first year of life, the first age level P1 contains only the population aged 0–1. The level P1 is increased by births B, decreased by deaths D, and decreased by maturation MAT1. The initial value of this level, as well as all succeeding levels, is taken from Figure 2-79. The number of deaths of 0- to 1-year olds D1 is calculated from the number of persons in the level P1 times the age-specific mortality M1 (derived from the variable life expectancy LE as described previously). The table values are taken directly from the m_x column of the model life table (U.N., 1956) and are illustrated in Figure 2-82. The maturation rate each year MAT1 from P1 to the next age level P2 simply equals the total number of 0- to 1-year-olds P1 minus the number that died D1.

```
NOTE  AGE 0-1
L     P1.K=P1.J+(DT)(B.JK-D1.JK-MAT1.JK)
N     P1=P1I
C     P1I=5.3E7
A     D1A.K=P1.K*M1.K
A     M1.K=TABHL(M1T,LE.K,20,70,10)
T     M1T=.40/.28/.20/.14/.07/.02
R     D1.KL=D1A.K
R     MAT1.KL=P1.K-D1A.K
```

The level of 1- to 4-year olds P2 is modeled similarly, except that it encompasses 4 years instead of 1 year. Therefore, the maturation rate MAT2 to the next level is 1/4 of the contents of level P2 minus the number of deaths that have taken place. This formulation of the maturation rate again assumes that within the four-year level the population is evenly distributed by age and that the deaths occur equally at all ages. This assumption is more accurate in the fifteen-level model than it was in the four-level model.

```
NOTE  AGE 1-4
L     P2.K=P2.J+(DT)(MAT1.JK-D2.JK-MAT2.JK)
N     P2=P2I
C     P2I=2.1E8
A     D2A.K=P2.K*M2.K
A     M2.K=TABHL(M2T,LE.K,20,70,10)
T     M2T=.08/.05/.03/.02/.008/.002
R     D2.KL=D2A.K
R     MAT2.KL=(P2.K-D2A.K)/4
```

The formulation of the P3 level is exactly analogous to that of P2, except that P3 is a five-year level, so the maturation rate MAT3 is divided by 5. All subsequent

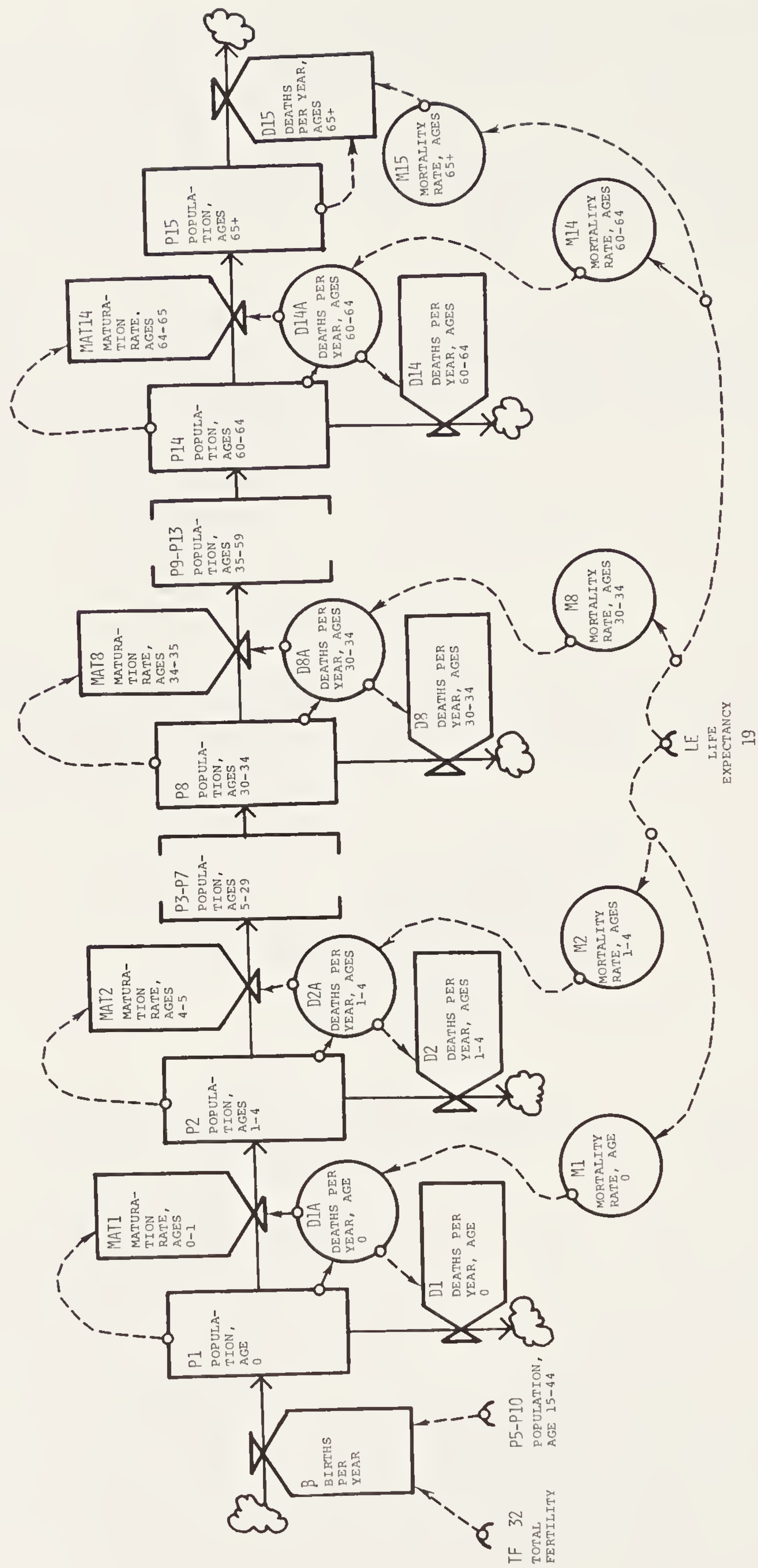

Figure 2-81 DYNAMO flow diagram, fifteen-level age structure

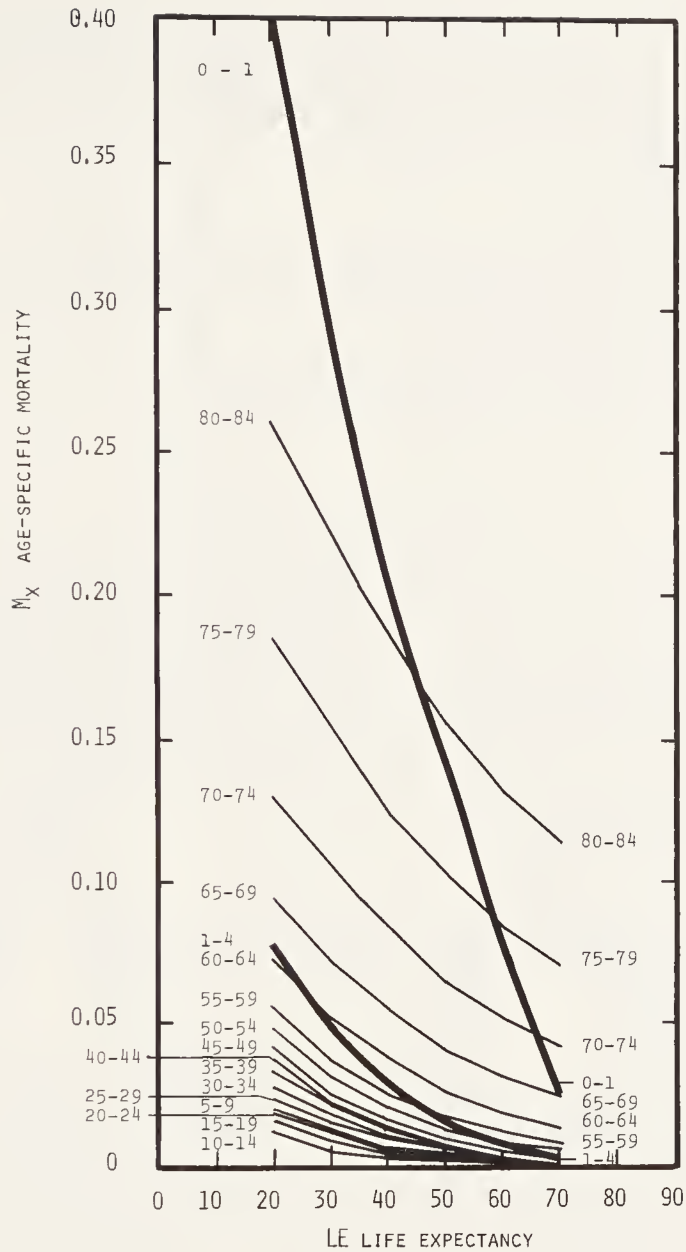

Figure 2-82 Mortality table functions, fifteen-level age structure
Source: U.N. 1956.

levels are represented exactly as this one is, except that the mortality tables vary according to the model life table. The final level, P15, representing the population over age 65, is modeled exactly as in the four-level representation.

```
NOTE   AGE 5-9
L      P3.K=P3.J+(DT)(MAT2.JK-D3.JK-MAT3.JK)
N      P3=P3I
C      P3I=2.2E8
A      D3A.K=P3.K*M3.K
A      M3.K=TABHL(M3T,LE.K,20,70,10)
T      M3T=.02/.01/.007/.004/.002/.001
R      D3.KL=D3A.K
R      MAT3.KL=(P3.K-D3A.K)/5
```

The total number of deaths each year D is a sum of the deaths in each age level. The total population POP is the sum of the population in all the age levels. The fraction of the population in the four age groups of the four-level model is also calculated.

```
A    D.K=D1.JK+D2.JK+D3.JK+D4.JK+D5.JK+D6.JK+D7.JK+D8.JK+D9.JK+D10.JK+
X    D11.JK+D12.JK+D13.JK+D14.JK+D15.JK
A    POP.K=P1.K+P2.K+P3.K+P4.K+P5.K+P6.K+P7.K+P8.K+P9.K+P10.K+P11.K+
X    P12.K+P13.K+P14.K+P15.K
A    PC.K=(P1.K+P2.K+P3.K+P4.K)/POP.K
A    PF.K=(P5.K+P6.K+P7.K+P8.K+P9.K+P10.K)/POP.K
A    PW.K=(P11.K+P12.K+P13.K+P14.K)/POP.K
A    PE.K=P15.K/POP.K
```

The age structure is now represented in enough detail to take into account variations in age-specific fertilities of the female population. Figure 2-83 shows the curve used in the model to account for age-specific fertilities, an aggregate curve averaged from data from seventy-two countries (U. N. 1965). The figure also shows the variations from this average pattern observed in different specific populations. In the fifteen-level model we weighted the number of women in each level P5–P10 by the percentage of total fertility contributed by women of that age, according to the model age-specific fertility curve.

```
A    EXTRA.K=P5.K*.06+P6.K*.25+P7.K*.28+P8.K*.21+P9.K*.13+P10.K*.07
R    B.KL=CLIP(D.K,((TF.K/10)*EXTRA.K),TIME.K,PET)
```

The weighted sum of age levels is multiplied by the total fertility and by a factor of 0.5 (since women make up only half the population in each level), and divided by 5 (since we are interested in *yearly* birth rates and the levels represent five-year aggregations). For example, if the total number of births TF expected by women in the population is 6, an average 0.25 of the total, or 1.5 children, will be born to each woman between the ages of 20 and 25 (P6). Thus women in the P6 age group will produce on the average 1.5/5 or 0.3 children per woman per year. The total number of births expected from the P6 age group each year is then:

$0.5 \times$ P6	$\times$ 6	$\times$ 0.25	$\div$ 5
(total number of 20-to 24-year-old women)	(total number of births during each woman's lifetime)	(fraction of those births expected between the ages of 20 and 25)	(number of years in the age interval)

The age-specific fertility curve can of course be adjusted to express possible changes in age-specific fertility patterns, such as postponement of marriage as a deliberate policy to reduce the population growth rate. The effects of such a change are shown in the next section.

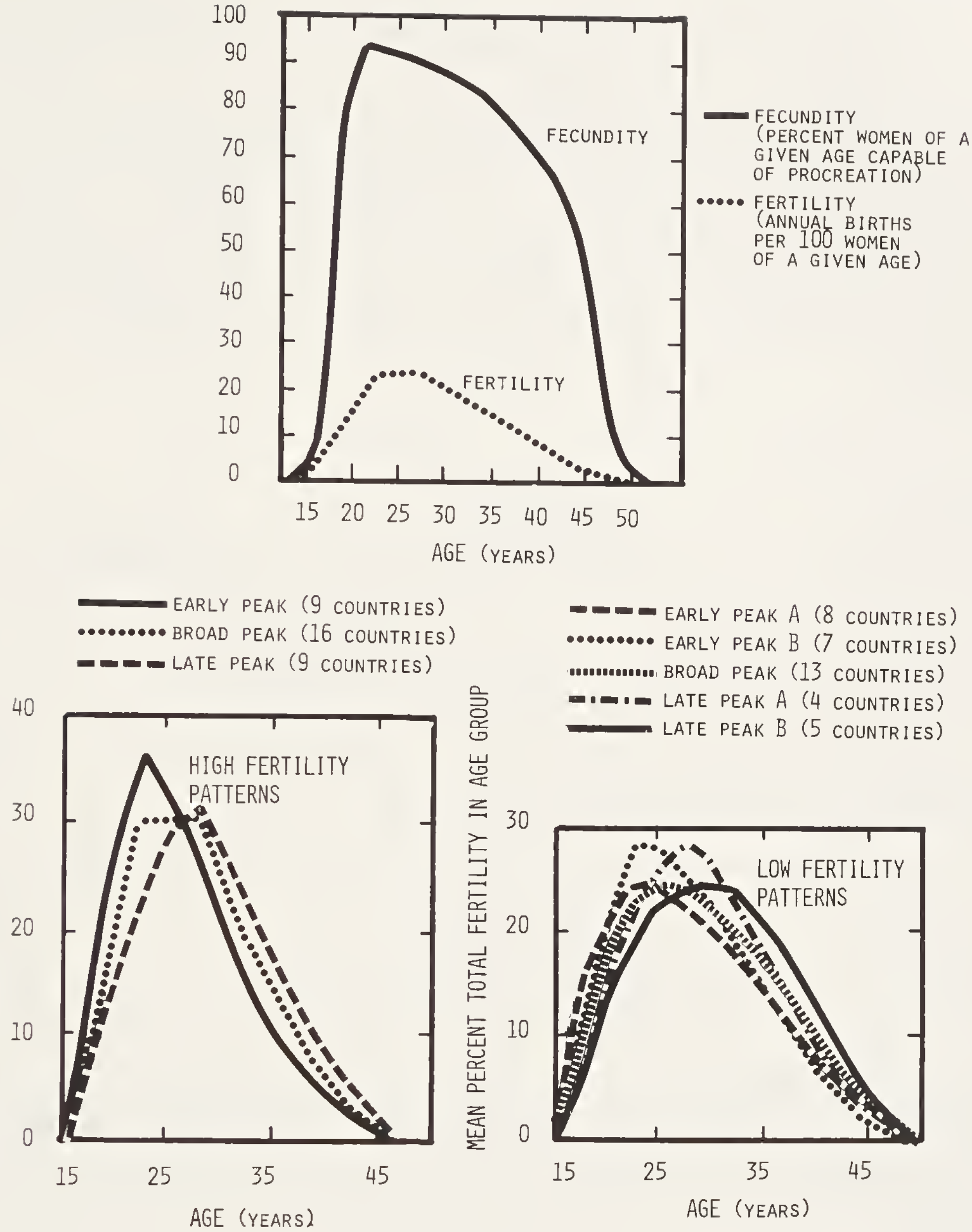

Figure 2-83 Age-specific fertility patterns
Source: U.N. 1965.

2.6 SIMULATION RUNS

We have described each assumption in the population sector of the world model, discussed the rationale behind it in terms of causal factors, and presented data to quantify it if the data were available. The first step in criticizing or extending the model is to examine each assumption separately in the light of the best knowledge available about the real world, keeping in mind the purpose of the model. The second step is to put the assumptions together and examine the dynamic behavior of the postulated system as a whole, compared with the behavior of the real-world system as a whole. Only when both steps have been completed, and when the model system generates a reasonable simulation of the real system under a wide variety of conditions, can we begin to have confidence that the model is a useful representation of reality.

In this section we present numerous computer simulations of the population system alone. Chapter 7 presents simulations of the population sector incorporated into the rest of the world model. Since the sector is not a complete model in itself, but requires inputs reflecting the natural and economic environment, the model runs shown in this section are all driven by assumptions about the system external to the population sector. The values of total industrial output, service output, food output, and pollution must be specified as exogenous functions of time to simulate the population sector.

Comparison of Different Levels of Aggregation

Historical Behavior A minimum requirement for a useful simulation model is that it duplicate the historical behavior of the real system within the desired degree of accuracy. In Run 2-1 (Figure 2-84) we simulated the population sector under driving assumptions that roughly duplicate world economic behavior from 1900 to to 1975.* Total industrial, service, and food outputs were set at their 1900 values and driven by smooth exponential functions, calculated to intersect their known 1970 values. The initial conditions and assumed rates of growth are:

	Initial Value†	Annual Growth Rate†
Industrial output	7.10^{10} dollars	3.7 percent
Service output	15.10^{10} dollars	3.0 percent
Food output	40.10^{10} vegetable-equivalent kilograms	2.0 percent

The value for population size generated by the model is used to calculate values for industrial, service, and food output per capita. Pollution is held constant at a low level so that it does not become important in these runs. The complete equations for generating the runs shown in this section are listed in Appendices A, B, and C to this chapter.

Run 2-1 (Figure 2-84) shows a comparison of the behavior of the three age-disaggregated models under identical historical driving conditions. The general behavior patterns of the three models are very similar, the only differences being small, quantitative ones that are well within the margin of error expected from this model. In each case the population grows exponentially, reaching a value of approximately 4 billion after 75 years (1975). All per capita economic variables also grow, the increase in industrial output per capita IOPC being considerably greater than the increase in food per capita FPC. The fifteen-level model generates a slightly faster population growth rate, and thus a slightly slower rate of per capita economic growth than do the one- and four-level models.

*Appendix E to this volume describes how to read DYNAMO output graphs.

†See the capital and agriculture sectors, Chapters 3 and 4, for discussions of these values.

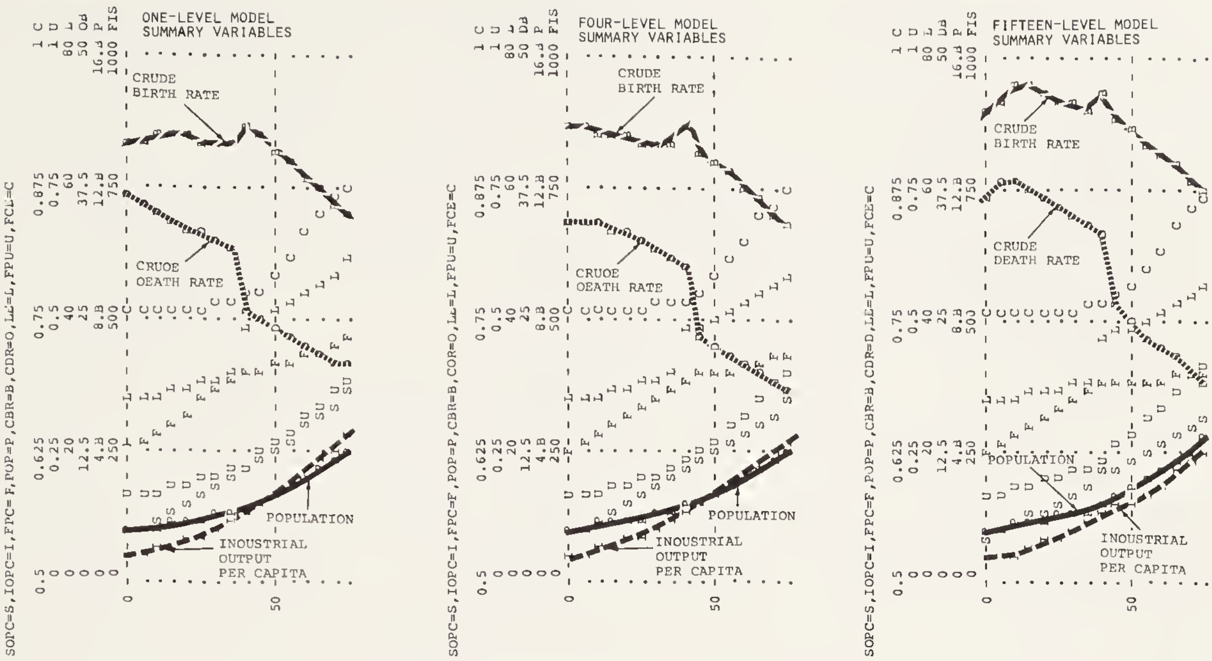

Figure 2-84 Run 2–1: historical behavior, 1900–1975

In all three models the calculated crude birth rates in the initial time interval (year 0) are between 40 and 45 per thousand. The birth rates all decrease gradually to a value of about 33 per thousand in the year 70. The calculated birth rate in the fifteen-level model is always somewhat higher than that in the simpler models, because the pattern of age-specific birth rates generates more births to younger women than to older women. In all models the crude death rates decline gradually until year 40, at which point the CLIP in the lifetime multiplier from health services brings about a step increase in life expectancy. After a precipitous drop at year 40 the crude death rates continue to decrease fairly rapidly. They begin at year 0 at about 36 per thousand and reach values of 15–20 per thousand in year 70. In all three models life expectancy in year 70 is about 50 years, the fraction of population urban is 35 percent, and fertility control effectiveness is about 0.9 and rising rapidly. Industrial output per capita is approximately 250 dollars, service output is 325 dollars per capita, and food output is 450–500 vegetable-equivalent kilograms per person, or about twice the subsistence level.

The behavior of each variable plotted in Run 2-1 generally agrees with our knowledge of the real world from 1900 to 1970: population has increased exponentially, the birth rate has fallen, the death rate has fallen faster, industrialization and urbanization have increased, and birth control has become more widespread and more effective. The model produces a fair quantitative fit, given the uncertainties in the real-world data and the simplifying assumptions in the equations. The most serious quantitative error is in the death rate, which is too high in the model year 70, thus making the calculated net population growth rate too low. This discrepancy could be eliminated by altering any one of the lifetime multiplier tables or the timing or extent of the CLIP function in the lifetime multiplier from health services. If the death rate were lowered in the model, however, the calculated total population in the year 70 would be too high. It should not be surprising that the model cannot fit real-world data exactly, since it is not intended to. The model's economic driving functions ignore known irregularities in the real system, such as the depression of the 1930s that lowered birth rates, and the world wars that both lowered birth rates and increased death rates. From a long-term view, such temporary discontinuities act as "noise" that interrupts and sometimes obscures the long-term dynamic behavior modes of the system. They affect the quantitative outcome of the behavior modes, but not their qualitative characteristics.

To gain a better understanding of the interplay of variables that generated the outcome of Run 2–1, in Run 2–2 (Figure 2-85) we plotted all the population sector variables that determine the death rate calculation, and in Run 2–3 (Figure 2–86) the variables that underlie the birth rate. Run 2–2 shows that increases in the lifetime multipliers from health services and from food are responsible for the decline in the death rate in all three models. Crowding and pollution have little or no effect in this run. The outputs of the four- and fifteen-level models in Run 2–2 also show the calculated fractions of the population in different age groups. The four-level model somewhat underestimates the proportion of the population in the reproductive ages and overestimates the proportion in older age groups; otherwise, the shift in age structure during the run is similar in the two age-disaggregated models.

In Run 2–3 the development of the inputs to the calculated fertility are almost identical in the three models. In year 0 maximum total fertility MTF is low (at about 6.5), and desired total fertility DTF is relatively high (at about 4.5 children), because of high perceived child mortality and a social structure that reinforces a large-family norm. The compensatory multiplier from perceived life expectancy CMPLE falls steadily in response to decreasing mortality, and the social family size norm SFSN decreases from about 1.15 (4.6 children) to 1.0 (4.0 children) as a delayed result of industrialization. The family response to social norm FRSN fluctuates slightly about the value 0.78.

As industrialization proceeds in the model, the maximum number of births increases with improving health conditions; desired total fertility decreases as a result of the changing social norm and the perception of decreasing child mortality; and fertility control effectiveness (plotted in Run 2–1) increases rapidly enough to keep actual total fertility close to desired total fertility, in spite of the increasing gap between desired fertility and that maximally possible.

Constant Income per Capita In the model runs that follow, there is no recourse to global data to verify the behavior of the model, because they show the effects of using driving functions to push the population system into unrealistic extremes of behavior. These apparently artificial runs were carried out for two reasons. The first was to be sure that the model would be robust under as many behavior modes as we could imagine. Since a model is usually constructed with historical conditions in mind, modeling errors most often become apparent when conditions begin to vary from those considered "normal." We can often locate such errors by driving the model into different behavior modes and looking for anomalous responses. The second reason was to gain a better understanding of the model system. Although the

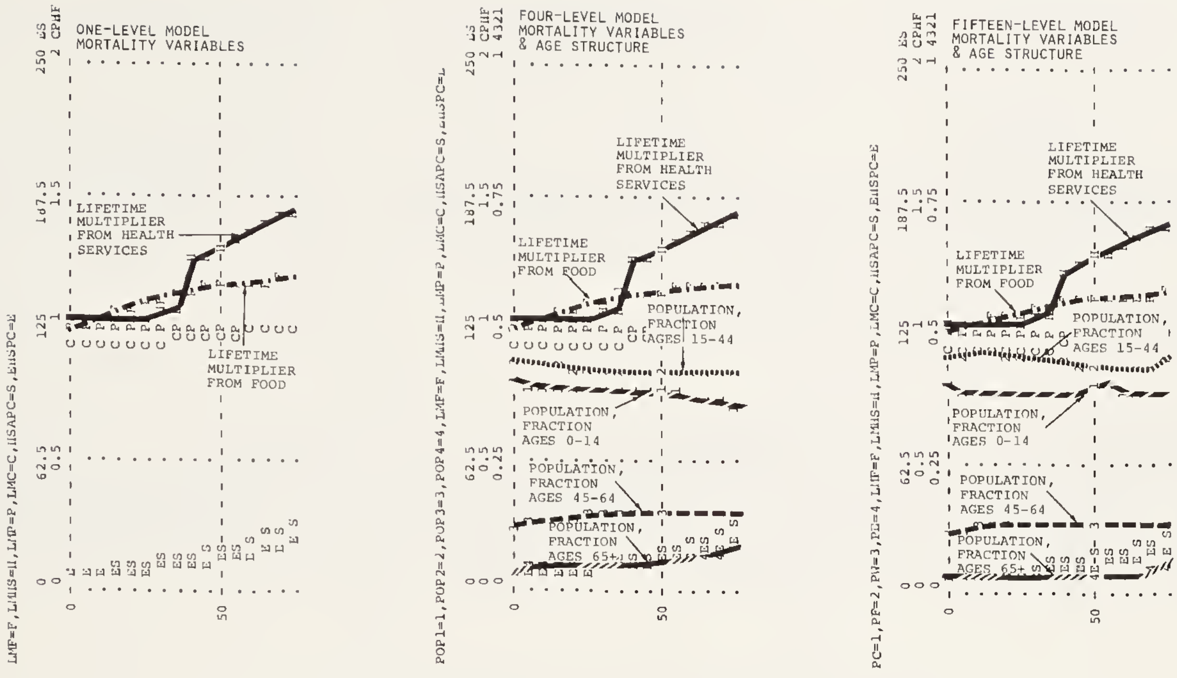

Figure 2-85 Run 2–2: historical behavior, 1900–1975, mortality variables

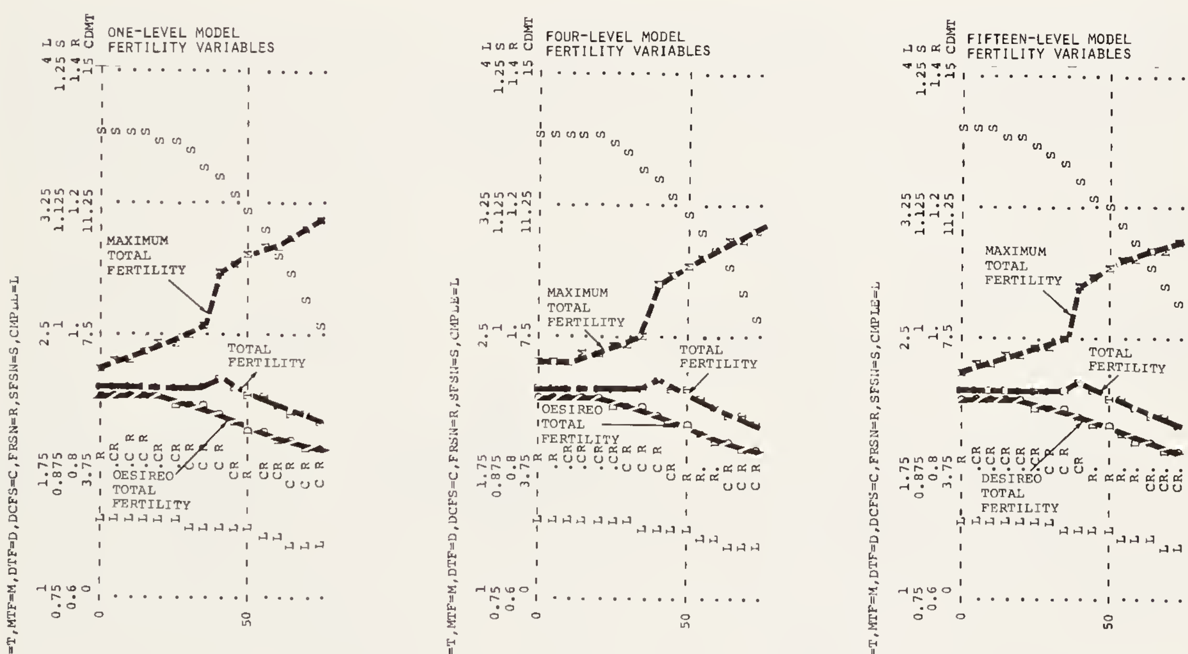

Figure 2-86 Run 2–3: historical behavior, 1900–1975, fertility variables

whole world population has not undergone any of these extreme economic conditions, some smaller segments of the human population have experienced conditions closely resembling the ones represented here. Our knowledge of their behavior under those conditions gives us some expectation of how the model population "should" behave.

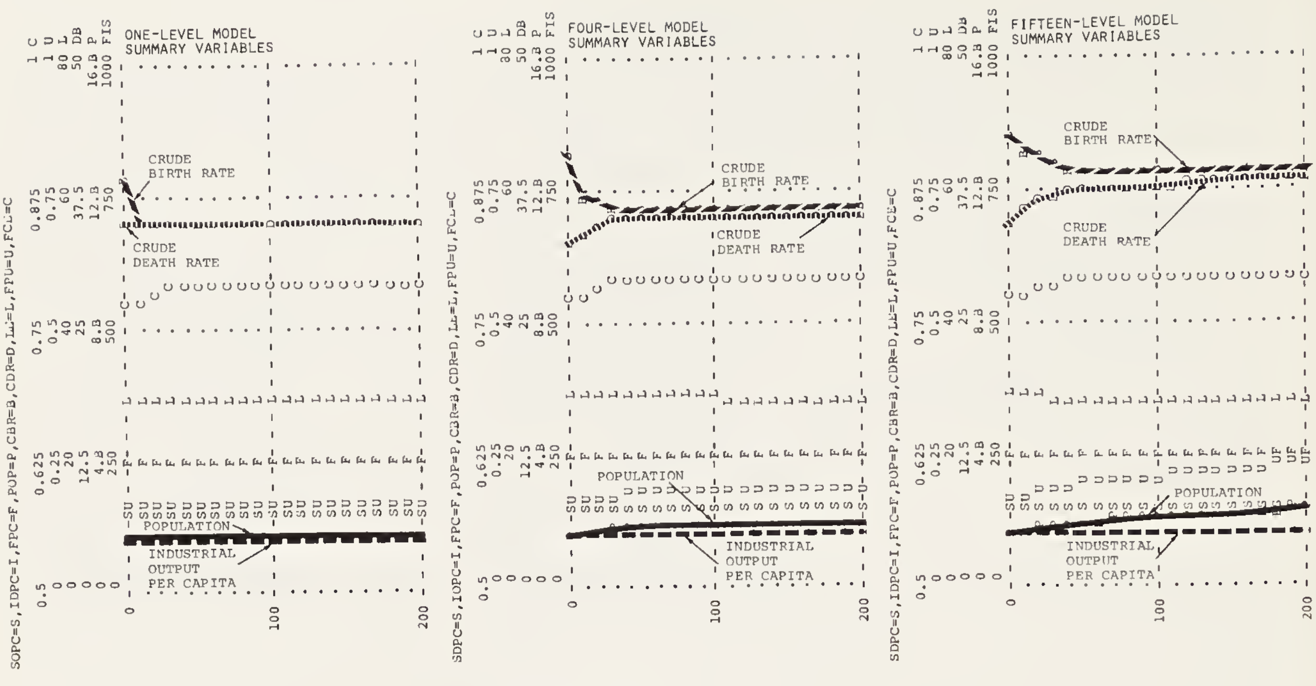

Figure 2-87 Run 2–4: constant low income

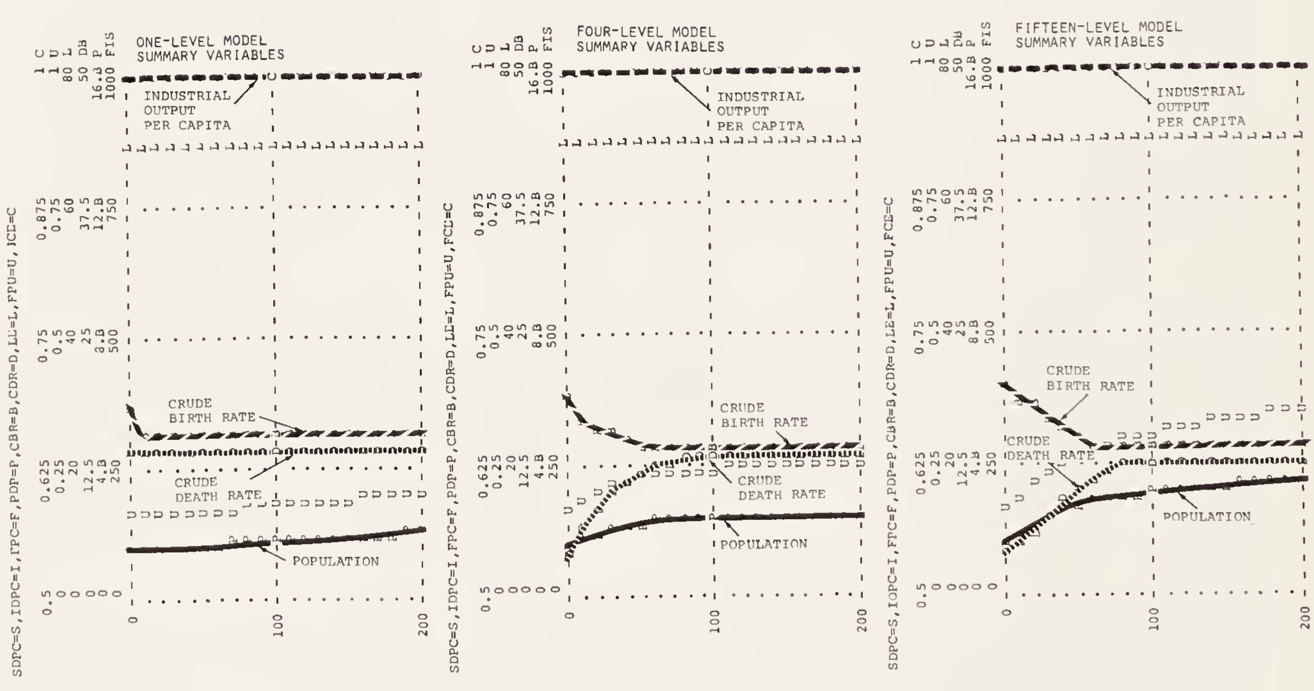

Figure 2-88 Run 2–5: constant high income

If the model run does not agree with our expectations, we must examine both the World3 assumptions and our own mental model assumptions to find the source of the discrepancy. In the process we can both improve the formal model and increase our own understanding of the real-world system.

Run 2–4 (Figure 2-87) shows the behavior of the model population under conditions of economic stagnation. The values of industrial, service, and food output

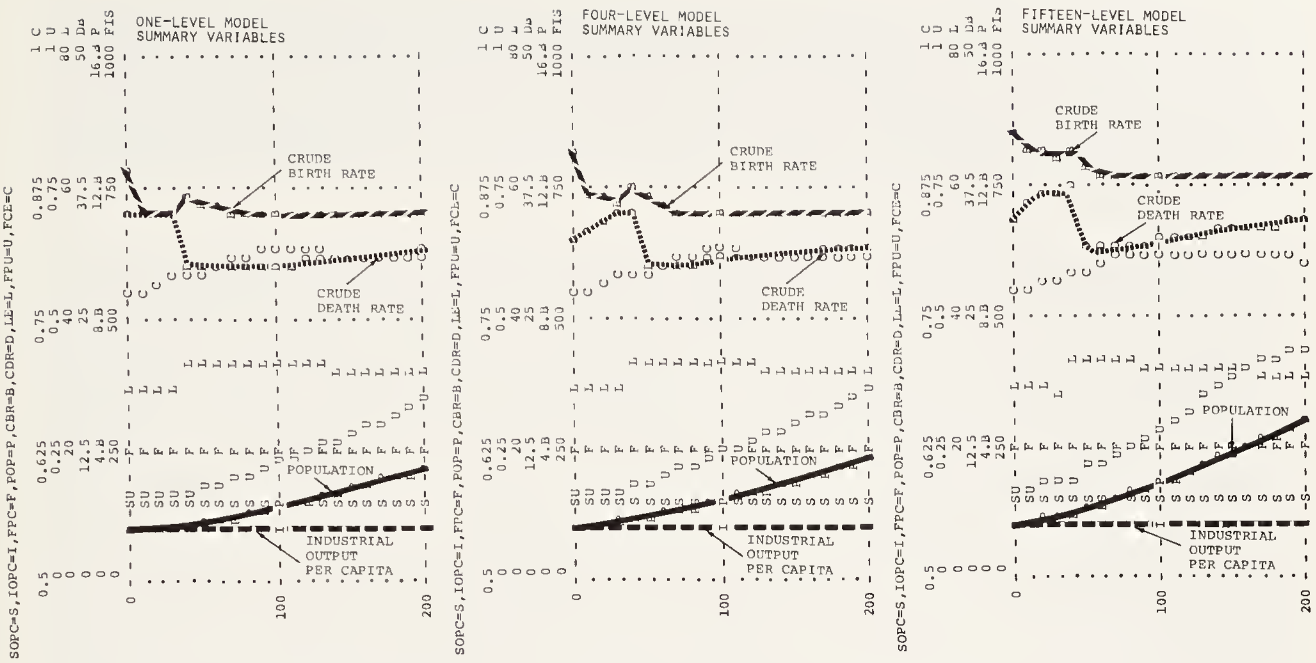

Figure 2-89 Run 2–6: constant low income, improved health care

per capita are held constant, all at low levels (industrial output per capita IOPC equals 100 dollars, service output per capita SOPC equals 150 dollars, and food per capita FPC equals 250 vegetable-equivalent kilograms per person-year). Thus this run represents a population living at a subsistence level, with no modern services.

Since the model assumes that social conditions are linked to economic conditions, nothing operates in Run 2–4 to change either the birth rate or the death rate. After an initial transient to achieve a stable age structure, birth and death rates are nearly equal at about 36 per thousand (higher in the fifteen-level model). The population grows only very slowly, if at all. The life expectancy is 28 years. This run might represent a traditional, nonindustrial society of the last century, with the typical fluctuations in the death rate smoothed out.

Another constant-income population is shown in Run 2–5 (Figure 2-88), but here the per capita values of industrial output, services, and food are fixed at high levels, characteristic of a fully industrialized economy such as the United States (IOPC=\$1,000, SOPC=\$1,500, and FPC=2,500 vegetable-equivalent kilograms per person-year). Birth and death rates are again constant (this time at about 14 per thousand), after a stable age structure has been attained. The age-structure transition takes about 50 years because the population is initialized with a developing-country age structure.

One more simulation under constant-income conditions is shown in Run 2–6 (Figure 2-89). In this case the per capita income is again held steady at a low value, but now the switch in the lifetime multiplier from health services is applied at year 40, with no other changes in the system. The slight increase in life expectancy from 30 to 35 years, when unaccompanied by any other model change, upsets the equilibrium between births and deaths and causes the population level to increase exponentially. The life expectancy decreases slightly over the course of the run, and the death rate rises again because of increased crowding under low-income health conditions. The population will continue to grow in this run until the death rate is raised again because of crowding—since food per capita is held constant, crowding is the only mechanism remaining to halt growth.

Exponential Economic Growth Run 2–7 (Figure 2-90) shows the behavior of the population sector under constant exponential growth in economic output. The initial values and growth rates are those used in the historical Run 2–1, but the growth in industrial, service, and food output is continued without limit for a 200-year period (pollution is still held constant). The behavior mode illustrated in Run 2–7 is essentially the demographic transition. Industrial output, services, and food per capita have all grown off the top of the graph by the year 150. Birth and death rates continue their decline and finally level off at values of about 18 and 13 per thousand, respectively, for a final net growth rate of 0.5 percent per year. Over the 200-year period the total population grows by a factor of 5 in the one-level model and by a factor of 10 in the fifteen-level model, the large difference being the result of accumulating a small differential in the net growth rate over a long period. The general behavior mode generated by all three models is the same. Fertility control effectiveness reaches 100 percent in the year 110, and world average life expectancy levels off at 65 years (slightly reduced because of crowding).

The variations in the age structure and the multipliers of life expectancy during this transition are shown in Run 2–8 (Figure 2-91). The lifetime multipliers from food and health services saturate at their maximum values. The lifetime multiplier from crowding increases as cities develop improved health services; it then decreases

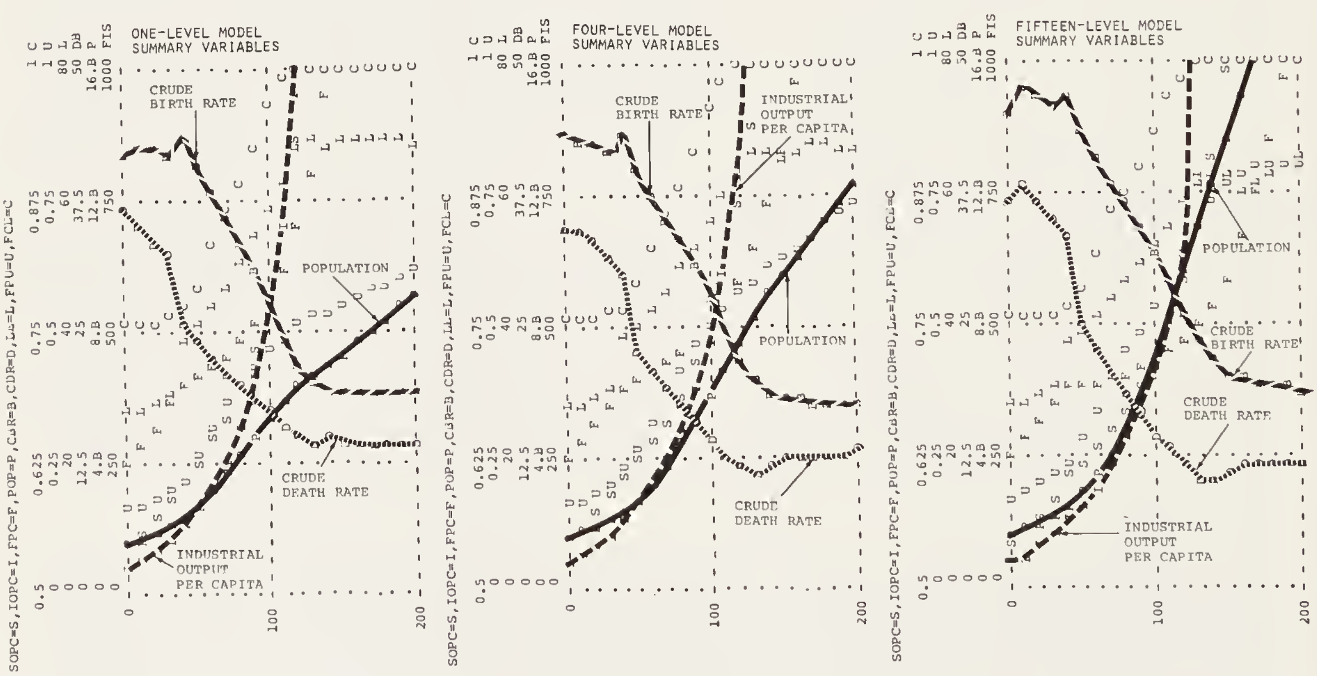

Figure 2-90 Run 2–7: exponential economic growth

as the cities become overcrowded and heavily industrialized. The age structure shifts from one that is characteristic of a high-birth-rate population. The fraction of the population under the age of 15 drops from 0.40 to 0.25. The age structure generated by the fifteen-level model at three different times in this transition is shown in Figure 2-92.

The behavior of the birth rate variables in this exponentially industrializing population is shown in Run 2–9 (Figure 2-93). With increasing health the maximum total fertility increases rapidly, but at the same time the desired total fertility falls because of an industrializing social structure and a perception of a lower child mortality. As fertility control effectiveness reaches 100 percent, actual total fertility becomes equal to desired total fertility. The multiplier from income expectations plays a minor role in this run, for per capita income grows at a nearly steady rate.

Under the assumption of exponentially increasing economic output, the model can be used to test the potential impact of various population policies. For example, in Run 2–10 (Figure 2-94) the fifteen-level model is used to test the policy of raising the marriage age (and thus the age-specific fertility schedule) as a way of minimizing the large population increase that occurs during the demographic transition. In this run the assumed age-specific fertilities are shifted as indicated in Figure 2-95. The resulting behavior in Run 2–10 can be compared directly with that of the fifteen-level model in Runs 2–7, 2–8, and 2–9. Total population in the year 200 decreases from 15 billion to 12 billion as a result of the policy, indicating that raising the marriage age has a small, quantitative effect on population size.

In Run 2–11 (Figure 2-96), an attempt is made to encourage a lowering of the birth rate by introducing 100 percent fertility control effectiveness in the model year

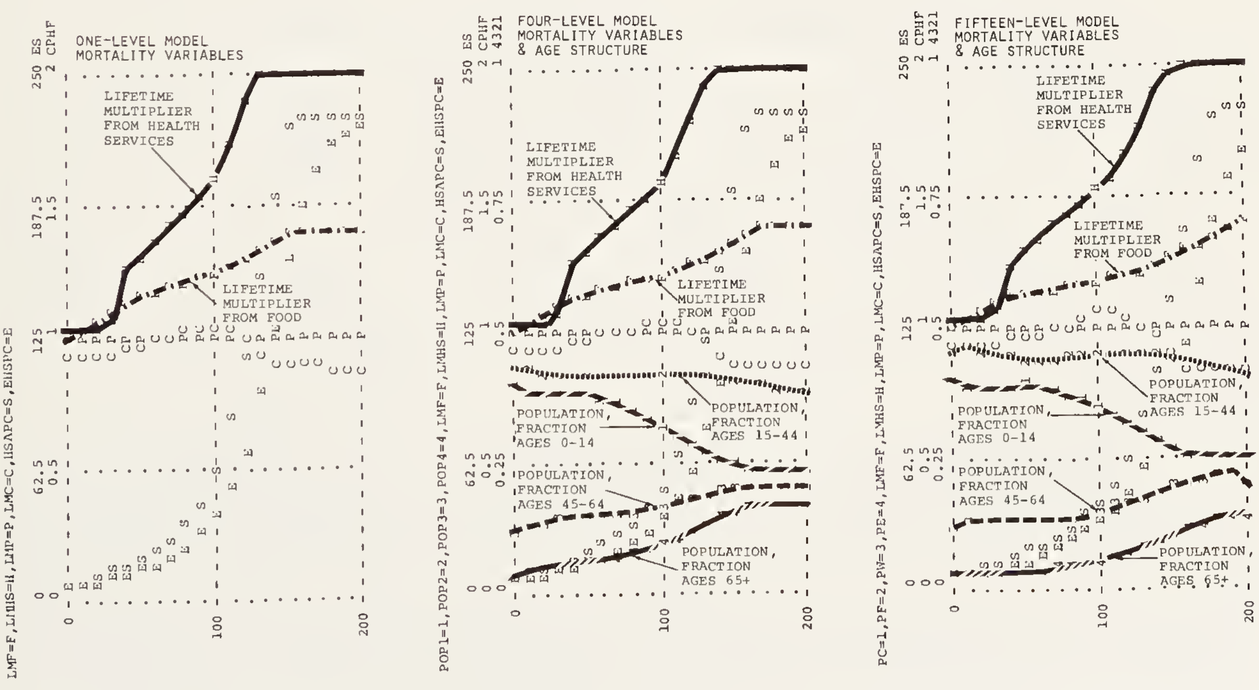

Figure 2-91 Run 2–8: exponential economic growth, mortality variables

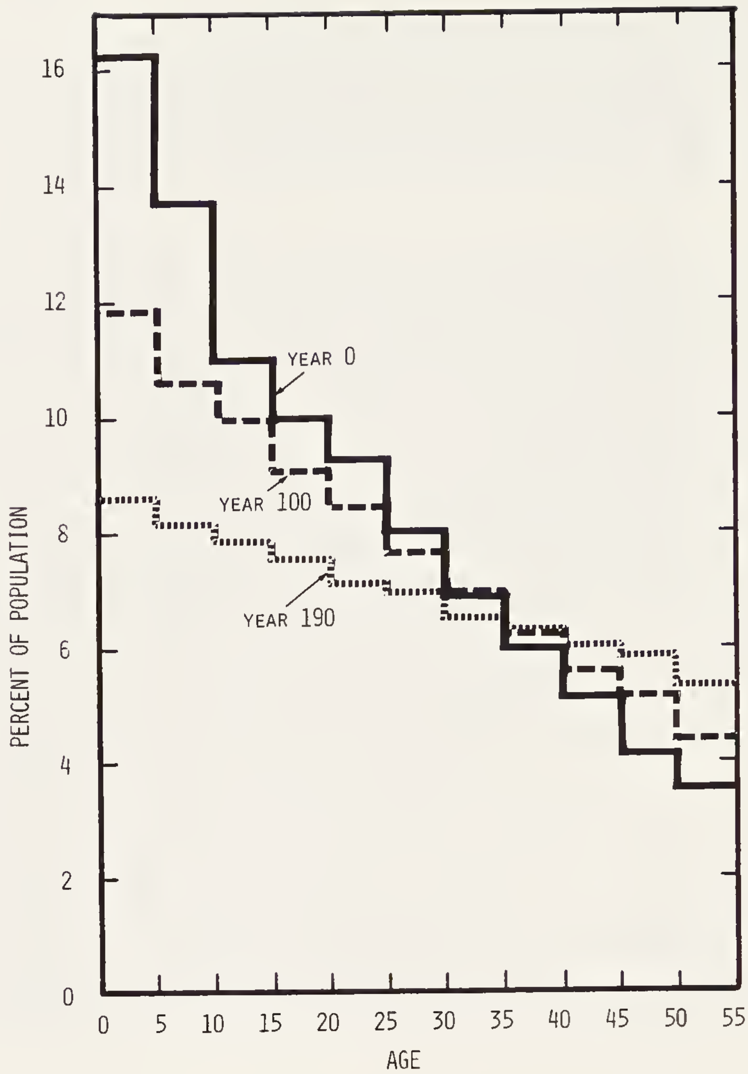

Figure 2-92 Changes in age structure during demographic transition (fifteen-level model)

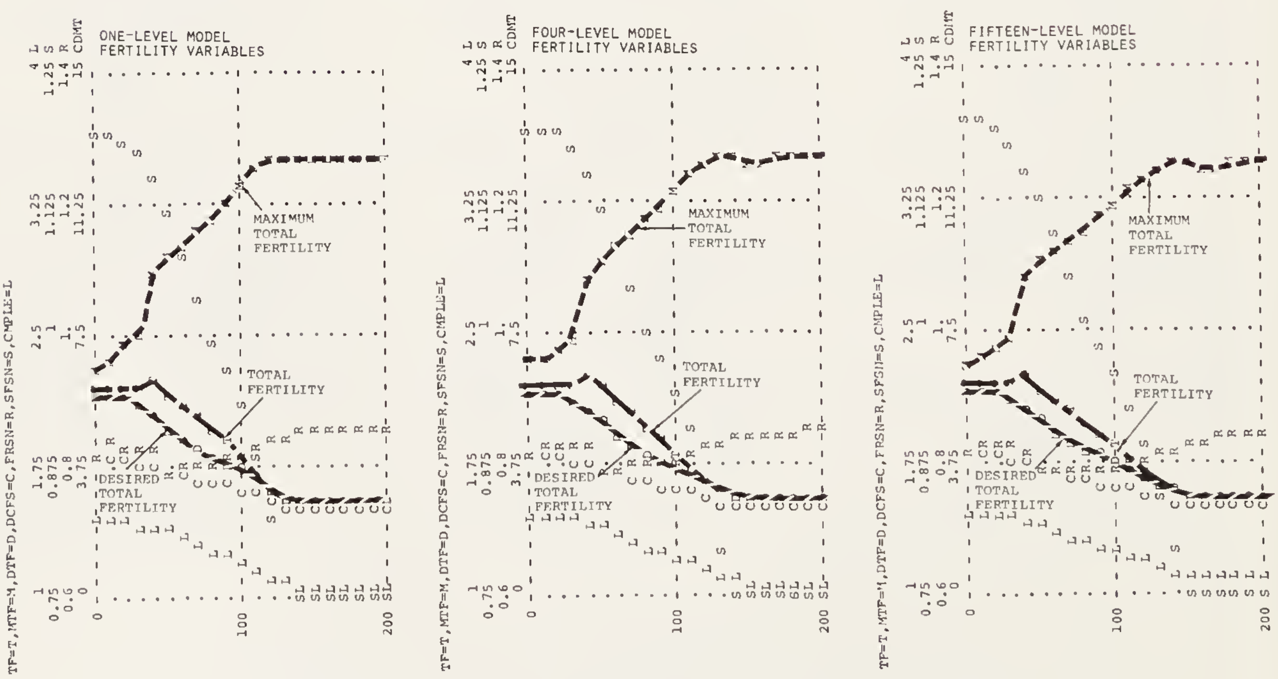

Figure 2-93: Run 2–9: exponential economic growth, fertility variables

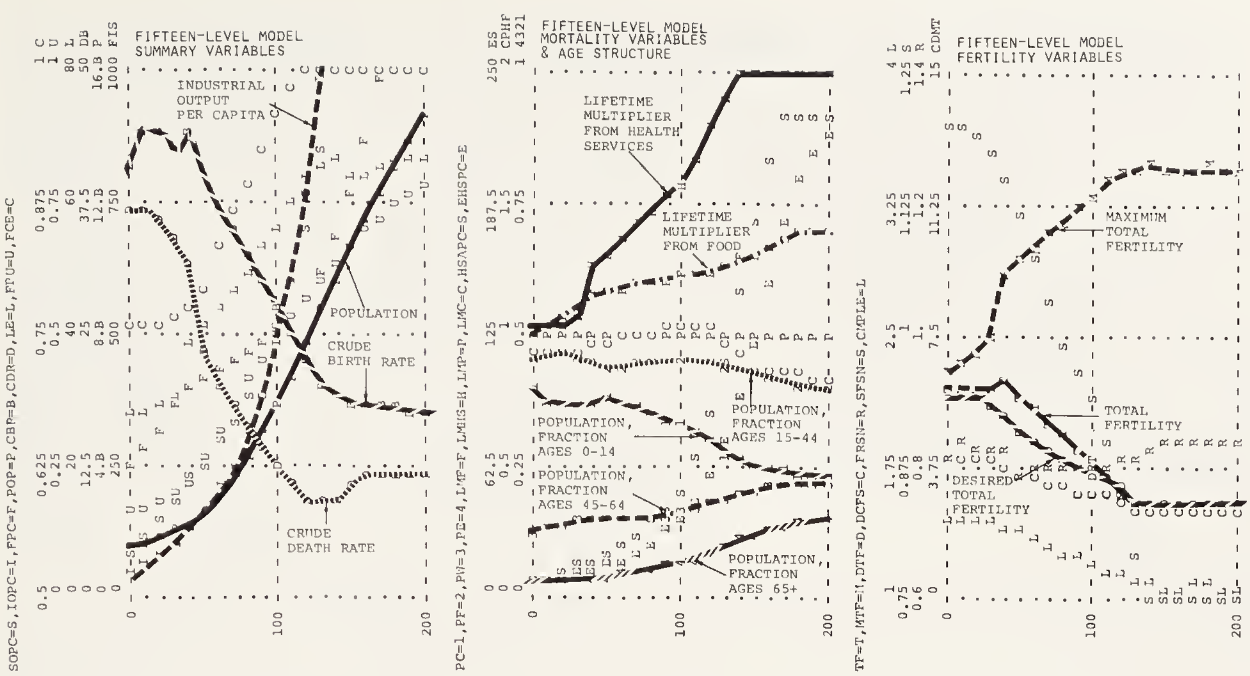

Figure 2-94 Run 2–10: exponential economic growth, higher childbearing age

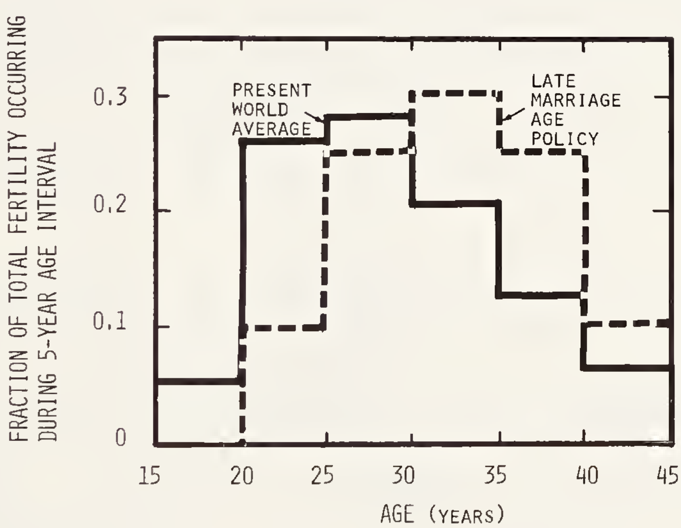

Figure 2-95 Alternate age-specific fertility assumptions

75. The resulting behavior is not qualitatively different from that of Run 2–7, but the population levels in the year 200 are somewhat smaller. The slight increase in the death rate in the fifteen-level model after the year 130 is due to stabilization of the age structure.

In Run 2–12 (Figure 2-97), the same economic driving functions are used again, but, in addition to the fertility control increase in the year 75, a CLIP function lowers the desired completed family size to two children, also in the year 75. This change greatly decreases the size of the population in the year 200 and brings the population

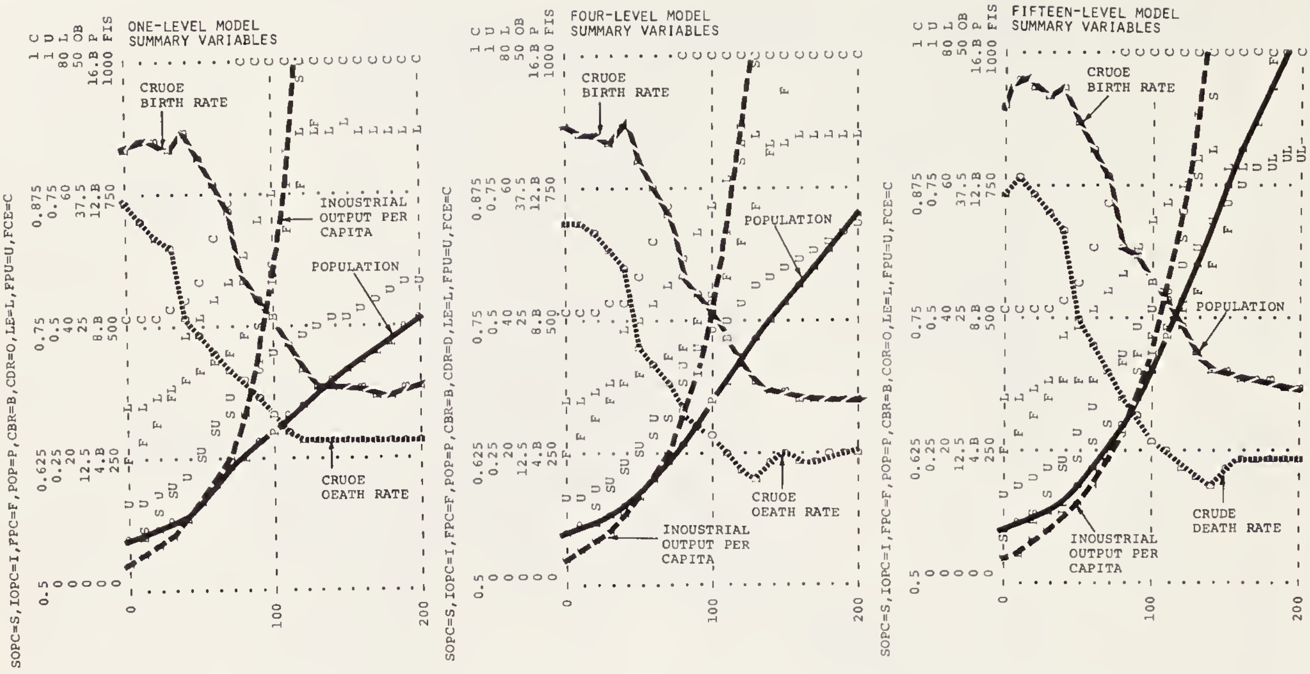

Figure 2-96 Run 2–11: exponential economic growth, perfect fertility control

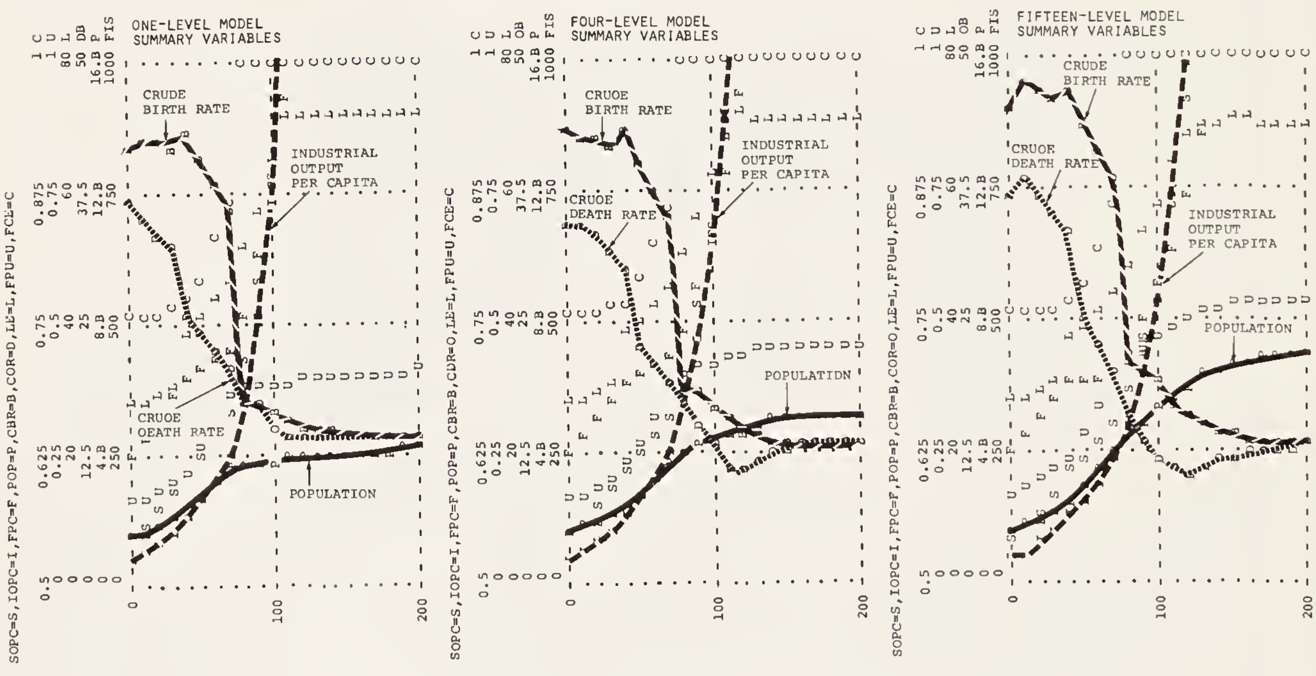

Figure 2-97 Run 2–12: exponential economic growth, perfect fertility control, reduced desired family size

to an eventual equilibrium, rather than the 0.5 percent growth rate of Run 2–7. In response to the rather radical changes in Run 2–12, all three age-structure representations show similar behavior, but the more accurate fifteen-level model shows pronounced short-term fluctuations and a slower approach to equilibrium.

Constant Total Output To investigate the behavior of the population model under a sudden change in economic conditions, we interrupted the driving exponential economic growth functions in the year 100 and held total output of industry, services, and food constant thereafter (per capita values were still free to change as the population size changes). The result is shown in Run 2–13 (Figure 2-98).

In this run, per capita income declines slowly after the year 100, since the population keeps growing while economic output is constant. The birth rate drops initially as the change in income expectation causes families to want fewer children. Eventually, the birth rate rises again, to compensate for the rising death rate. In the year 200 the population is approaching an equilibrium at intermediate birth and death rates, and the per capita income is beginning to stabilize. The delays in the population age structure cause a wider swing in the death rate calculated by the fifteen-level model.

In Run 2–14 (Figure 2-99) fertility control effectiveness was raised to 100 percent in the year 75, twenty-five years before the economic growth functions are held constant. This change decreases the growth of the population after the year 100 and hastens the equalization of birth and death rates. Again, the three models follow the same general behavior modes, with the fifteen-level model showing greater fluctuations in the death rate. The general behavior is similar to that shown in Run 2–13.

In Run 2–15 (Figure 2–100) a desired completed family size of two children is added to the birth control policy in the year 75. This change immediately causes a large decline in the birth rate, so that population equilibrium is nearly attained before industrial output growth is stopped in the year 100.

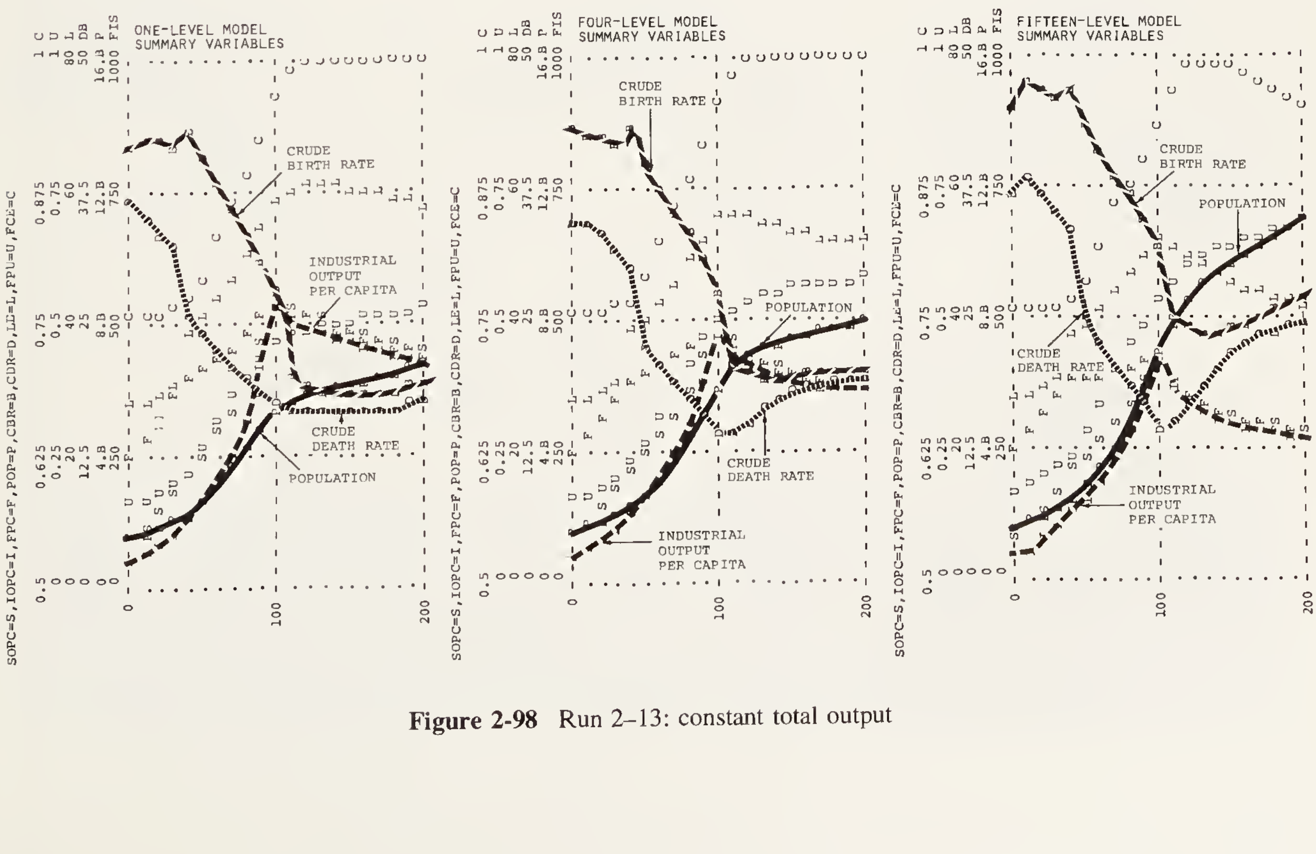

Figure 2-98 Run 2–13: constant total output

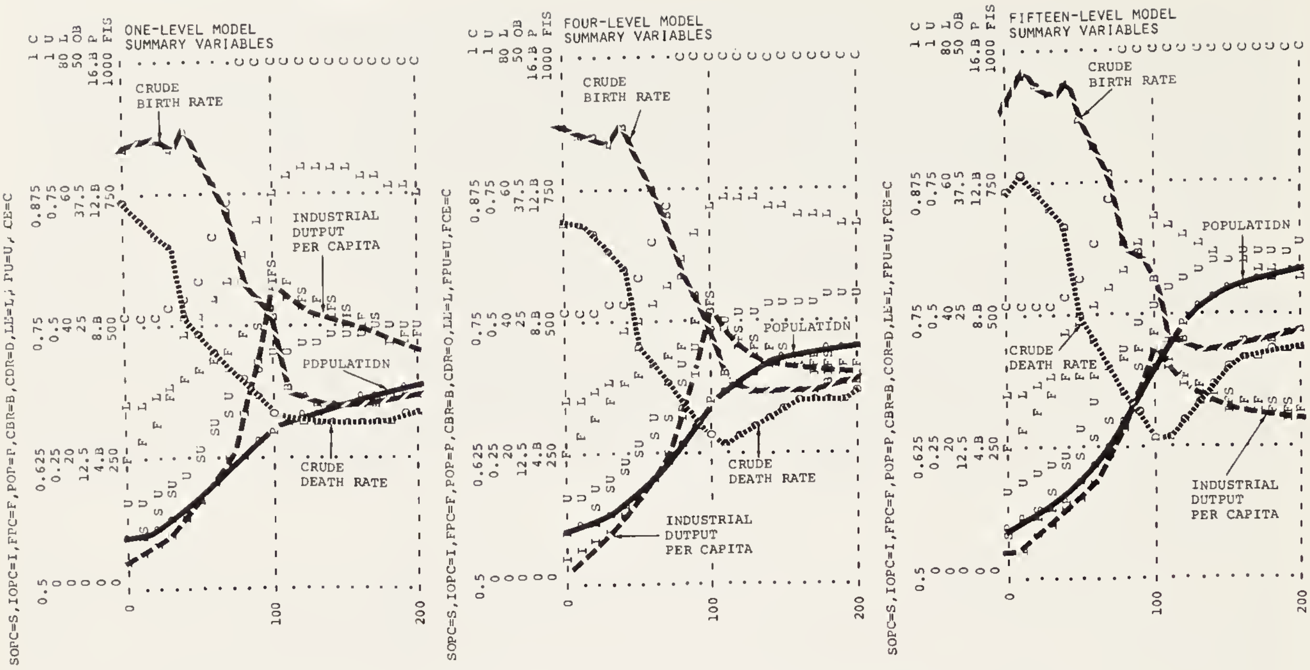

Figure 2-99 Run 2–14: constant total output, perfect fertility control

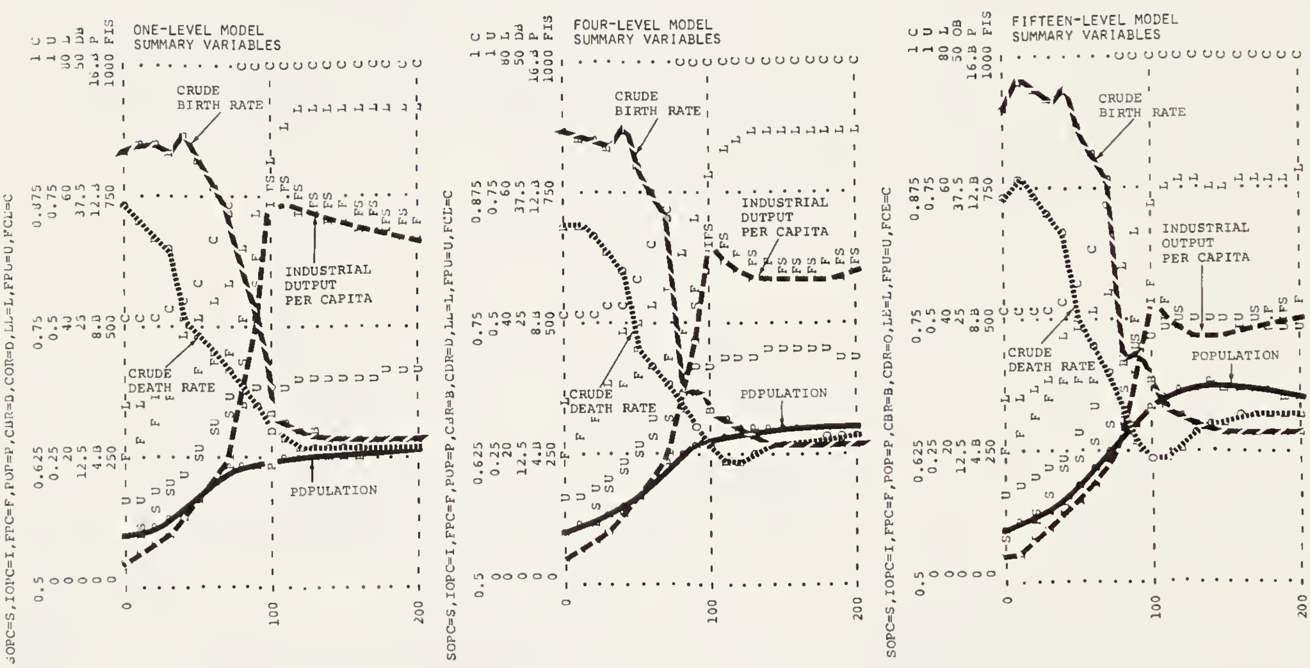

Figure 2-100 Run 2–15: constant total output, perfect fertility control, reduced desired family size

The model runs shown here indicate that from a long-term perspective the population age structure contributes little to the forces shaping the dynamic behavior of this population model. The delays inherent in the age structure cause small instabilities that are extremely important in the short term but of no concern for the sorts of long-term questions we are asking in World3. A more detailed model to be used for short-term decision making certainly must include at least a fifteen-level representation of the age structure for accuracy in planning. However, to save computational time and keep the level of aggregation consistent with the available data, we used the four-level age structure for the world model runs in Chapter 7 and in most of the following sensitivity analysis runs. This approximation of the population age structure tends to underestimate slightly the potential for growth and instability that a more accurate representation would demonstrate. The approximation is permissible only because the model is not intended for short-term point predictions.

Sensitivity Analysis

Are the behavior modes generated by the population sector equations sensitive to the numerical assumptions included in the equations? A thorough answer to this question would require the inclusion here of hundreds of sample model runs, varying every parameter over its entire reasonable range, with all possible combinations of other parameter variations. In this volume we can include only a fraction of the possible sensitivity analysis model runs, assuming that the interested reader will be able to test other variations for himself. The runs shown here were selected with a special emphasis on those parameters about which we have the least information and those which seem to be the most sensitive to quantitative changes.

The driving function used in all the following sensitivity runs is exponential growth to the year 100, followed by constant total output as shown in Run 2–13. This function was selected because it illustrates both the growth and the equilibrium modes of population dynamics. Unless otherwise indicated, the four-level age structure is used in all runs. For reference, Run 2–13 (Figure 2-98) is repeated in Run 2–16 (Figure 2–101), showing the behavior of all mortality and fertility variables. Run

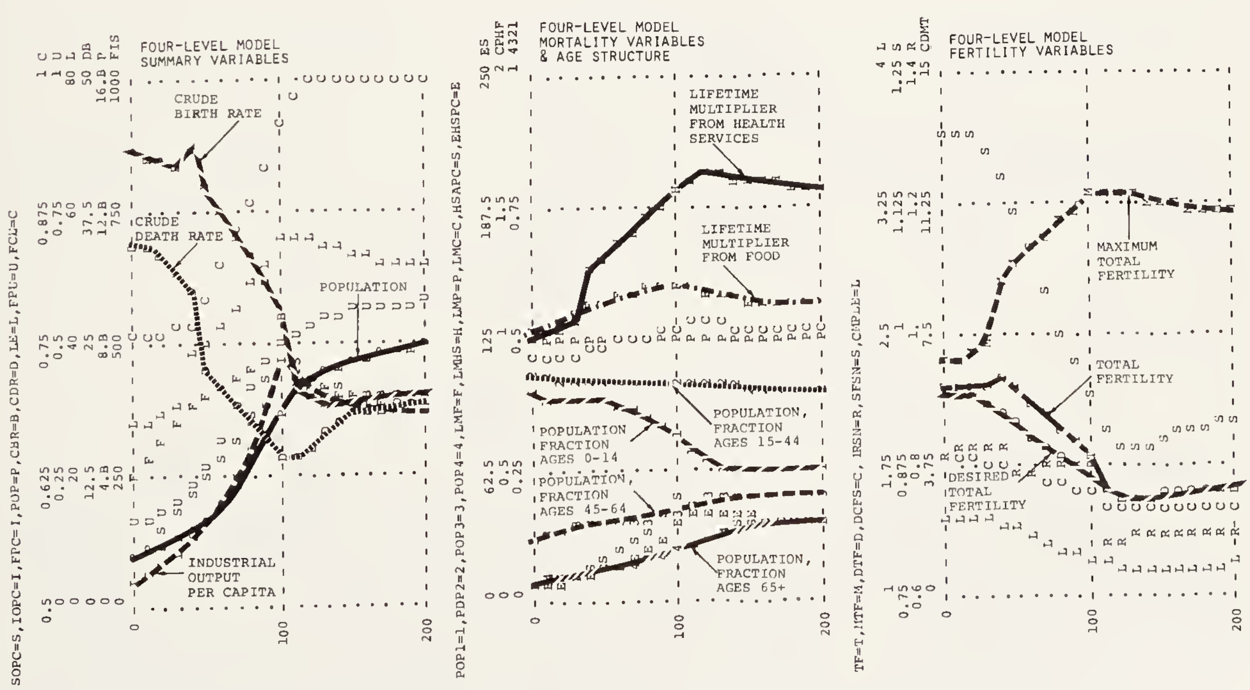

Figure 2-101 Run 2–16: constant total output, reference for sensitivity tests

2–16 shows the behavior of the system with all parameter values set to the same values used in the World3 "standard" run of Chapter 7. It represents our best guess at parameter values. The parameter changes introduced in the following sensitivity runs are purposely large, since we wanted to test each parameter at the extremes of its possible values.

Run 2–17 (Figure 2-102) shows the result of changing the lifetime multiplier from food LMF to reflect a nearly perfect utilization of available food supplies through more equitable distribution and better nutrition education. The changed values of the LMF table function are listed in Appendix B to this chapter. The effect of the change is to keep the lifetime multiplier from food constant at its maximum value throughout most of the run. Since the decreased death rate causes the population to grow more quickly, the model generates a consistently lower industrial output per capita. The general behavior mode is similar to that of Run 2–16.

Run 2–18 (Figure 2-103) incorporates a new table of lifetime multiplier from health services LMHS to show a hypothetical increase in medical technology that allows a maximum life expectancy of 100 years. To avoid the necessity of constructing a complete life table for a 100-year life expectancy, this run utilizes the one-level population model. The model output under these conditions is only slightly different from Run 2–16, the lower death rate generating a somewhat larger total population. In Runs 2–17 and 2–18, note that an increase in life expectancy from one cause brings about additional population growth, which tends to retard somewhat the expected lifetime increase from another cause. Raising the lifetime multiplier from food LMF in Run 2–17 causes LMHS to climb more slowly; in Run 2–18, raising LMHS slows the increase in LMF. A deliberate change in one part of the system is partially (but only partially in this case) offset by secondary changes induced in other parts of the system.

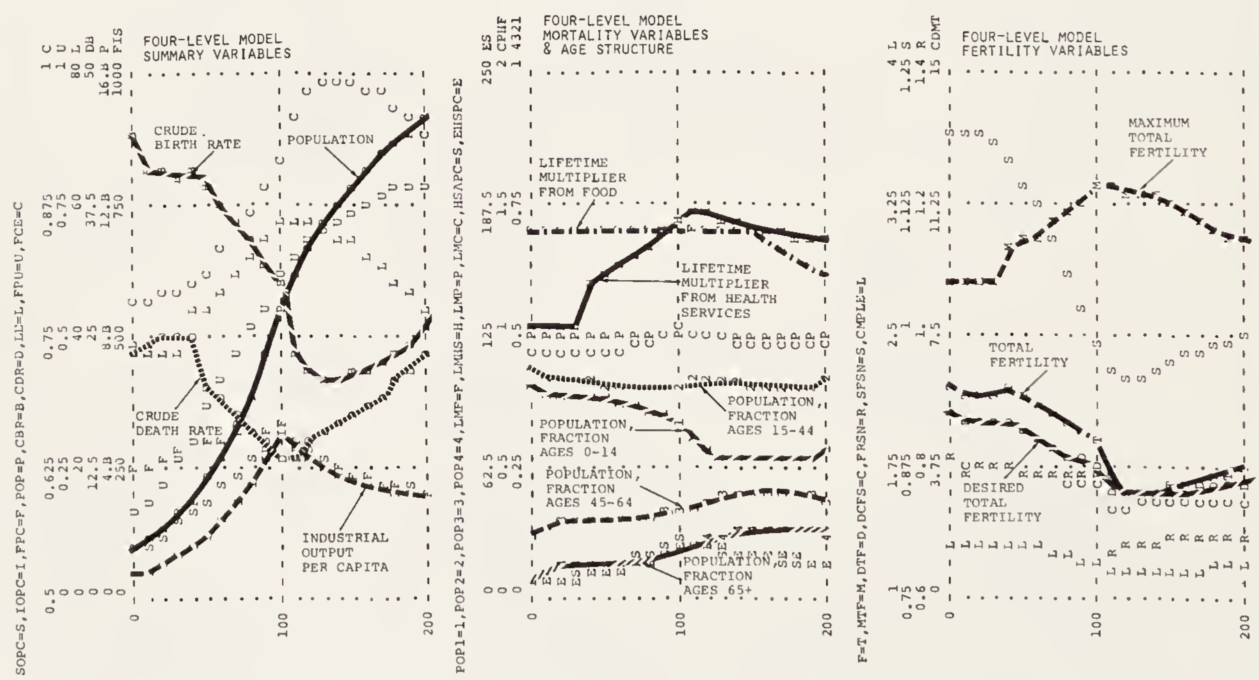

Figure 2-102 Run 2–17: equitable food distribution and nutrition education

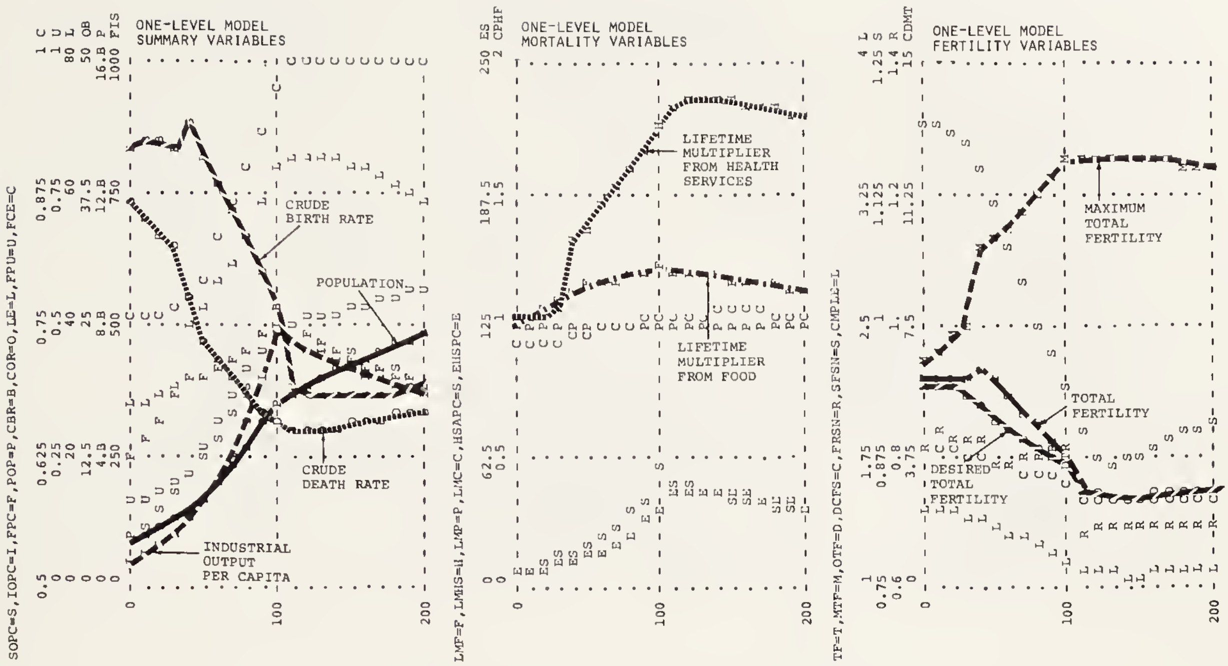

Figure 2-103 Run 2–18: maximum life expectancy of 100 years

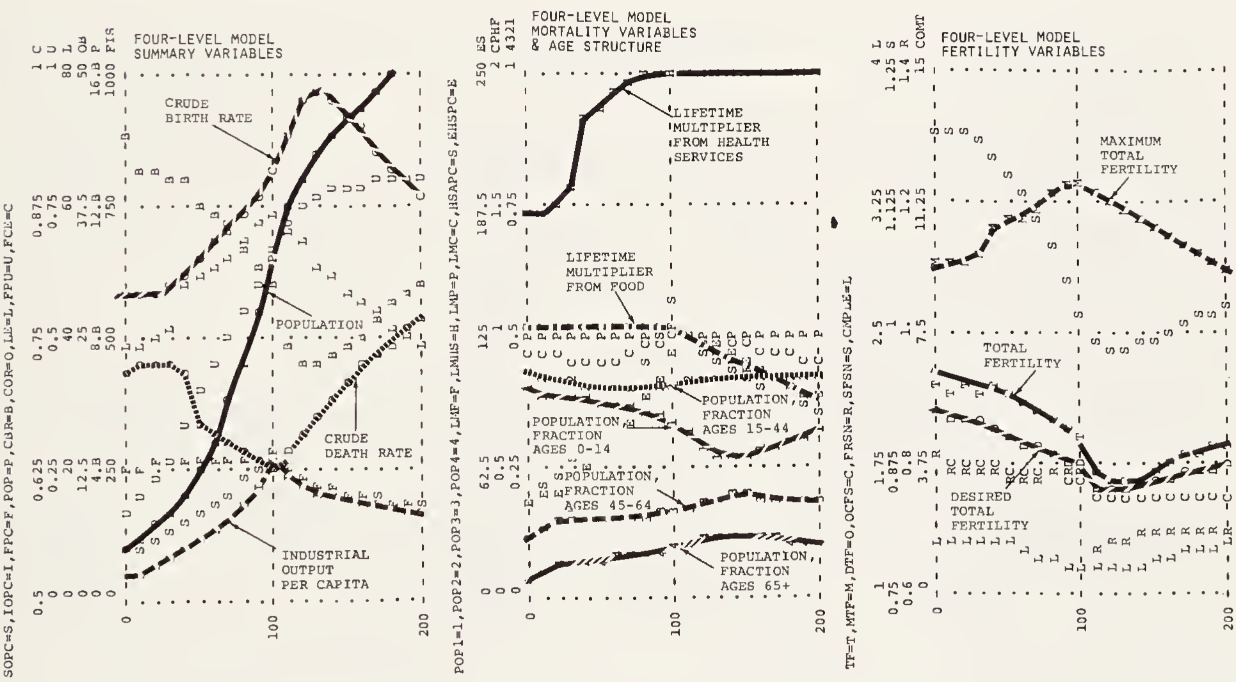

Figure 2-104 Run 2–19: greater allocations to health services

A similar result is obtained by changing the health services table HSAPCT to reflect a much greater allocation of total service output to health services, as shown in Run 2–19 (Figure 2–104). In this run the death rate is greatly reduced, producing a population increase so rapid that the lifetime multipliers from food and crowding eventually decrease more than enough to offset the high value of the lifetime multiplier from health services. Again, however, the general model behavior mode is unchanged.

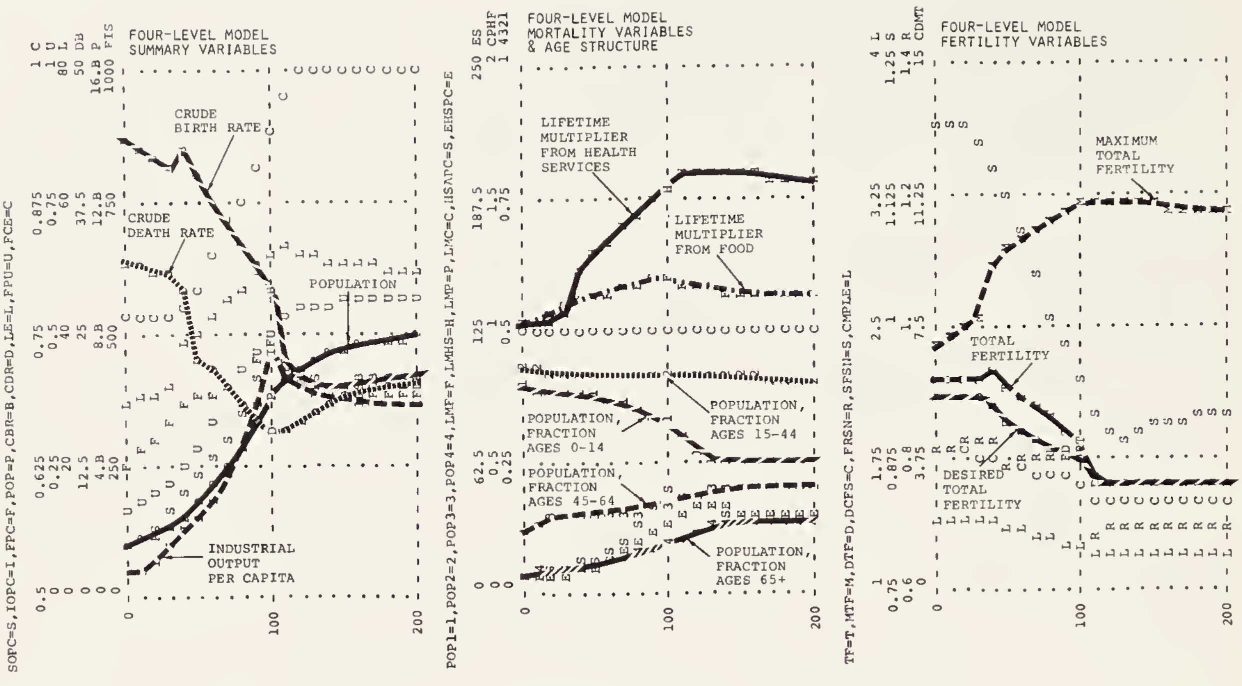

Figure 2-105 Run 2–20: no crowding effect

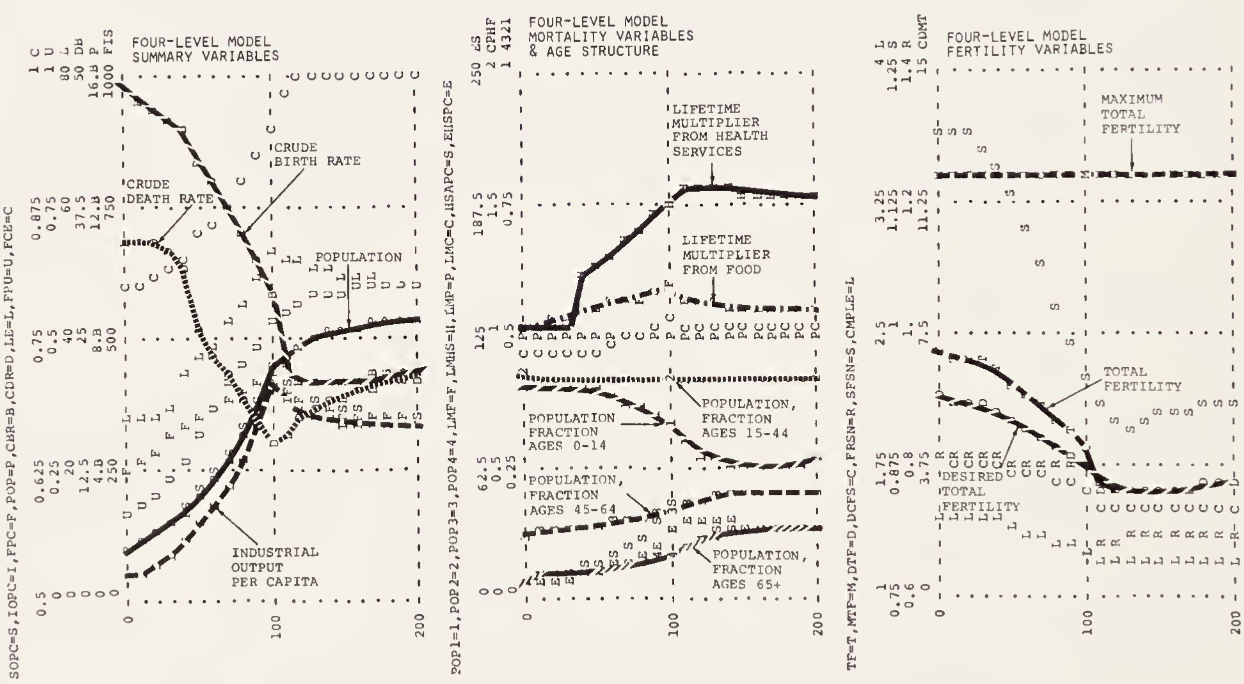

Figure 2-106 Run 2–21: constant maximum total fertility

In Run 2–20 (Figure 2-105), the lifetime multiplier from crowding is removed completely from the model by setting the crowding multiplier from industrialization to zero. A comparison of this run with Run 2–16 shows that the crowding loop has a very small quantitative effect on the model output. The only circumstance under which the crowding loop may become important is one of high urbanization and low

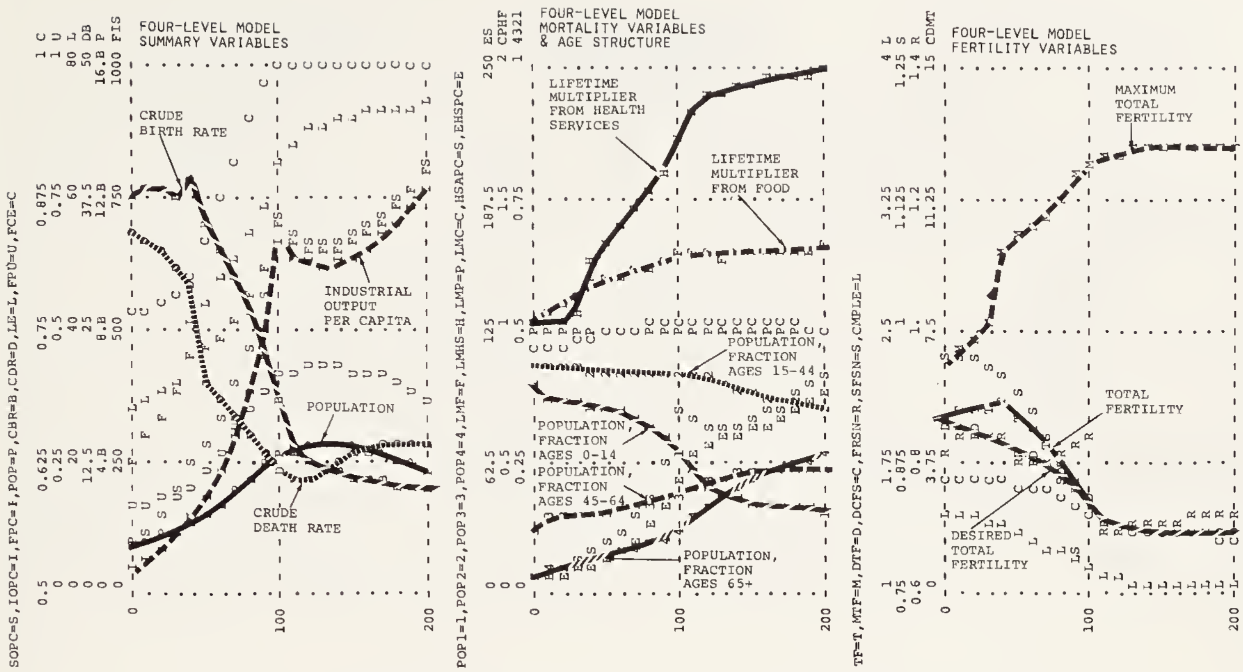

Figure 2-107 Run 2–22: lower family size norm

industrialization, a combination that can occur only during a complete economic collapse.

The sensitivity of the model to the assumption of varying fecundity is shown in Run 2–21 (Figure 2-106). Here the dependence of maximum total fertility on overall health conditions is removed, and fecundity is assumed to be constant at 12 children per woman. This change increases the birth rate somewhat and increases the gap between desired and actual fertility, but its effect on the overall behavior of the model is small.

The influence of family size norms is tested in Run 2–22 (Figure 2-107). The table representing the variation in social family size norm as a function of industrialization is shifted downward, so that it reflects a family norm ranging from 4 to 2 children rather than the standard assumed range of 5 to 3 children. This change brings about a significant decrease in the birth rate, even resulting in a population decline in the stagnant economy, where the family response to social norm FRSN also has a low value.

Another variation of this family norm function is shown in Run 2–23 (Figure 2-108). Here SFSN is held constant at 0.75, representing an unvarying social norm of 3 children. Again there is a marked change in the model behavior. The population begins and ends the run nearly in equilibrium; its slow growth rate results in an extremely high per capita income.

The social family size norm SFSN is unquestionably the most sensitive variable in the population sector. A shift in the socially approved family goal from 3 children to 2 children may be a small difference in absolute numbers, but it results in a large difference in system performance, since it reduces the relative strength of a major positive feedback loop. If it seems reasonable that this sensitivity is a property not

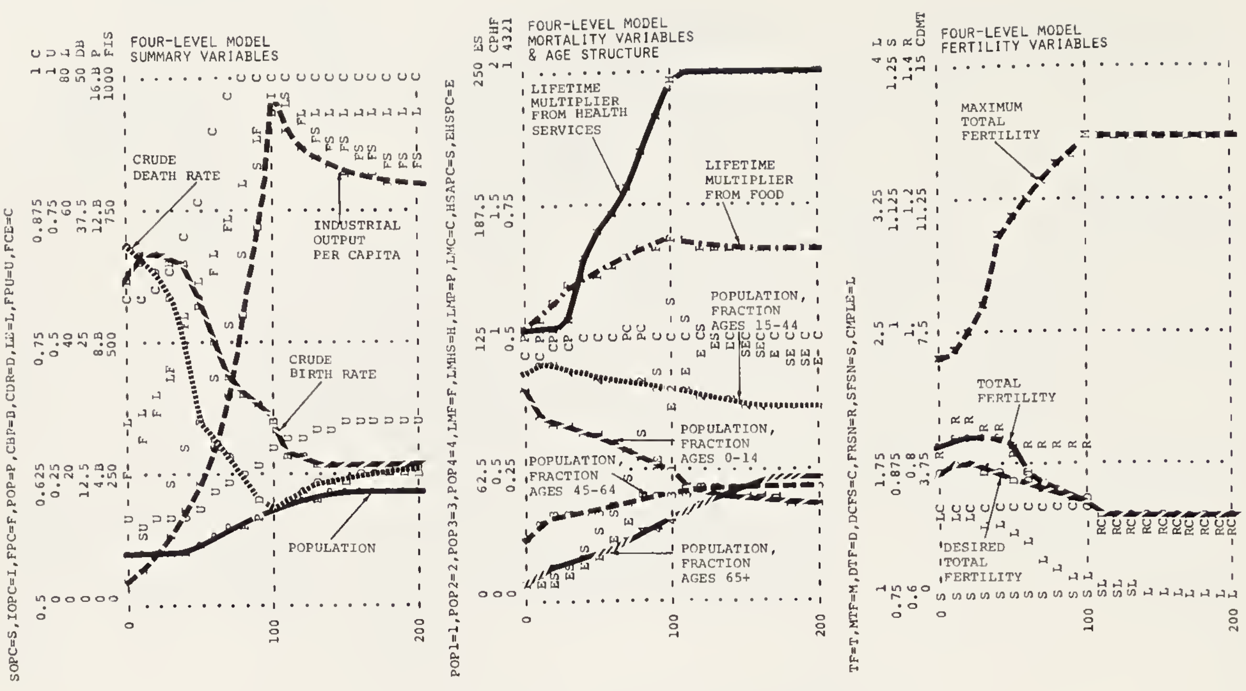

Figure 2-108 Run 2–23: constant family size norm of 3

only of the model but of the real system as well, then two conclusions can be drawn. First, further research should concentrate on the determinants of social family size norms because they may be more important than other variables in determining the accuracy of future models. Second, population policies will be most effective if they can be directed toward this sensitive variable. Even a small shift in the real social costs and benefits of raising children may produce a large (but delayed) response in population growth rates.

Run 2–24 (Figure 2-109) shows the effects of an increase in the delay time of the socially determined family size norm adjustment from 20 to 50 years. An increase of this magnitude has only a small quantitative effect on the model output; this run is very similar to Run 2–16.

In Run 2–25 (Figure 2-110) the effect of income expectation on desired family size is removed from the model by setting the family response to social norm FRSN to 1.0. The resulting birth rate is considerably higher, and it rebounds faster after the year 100 than it did in previous runs. This income expectation loop appears to be moderately important in determining the response of the population system to economic reversals, and it has a significant effect on the quantitative value of the population growth rate. However, the model behavior is not as sensitive to small changes in the FRSN table function as it is to the SFSN function.

In Run 2–26 (Figure 2-111), the compensatory multiplier from perceived life expectancy CMPLE is increased to represent the assumption that parents overcompensate for high child mortality by bearing more children than the actual mortality risk would necessitate. The birth rate is higher throughout the run, and the death rate is also somewhat higher because the faster population growth rate depresses the

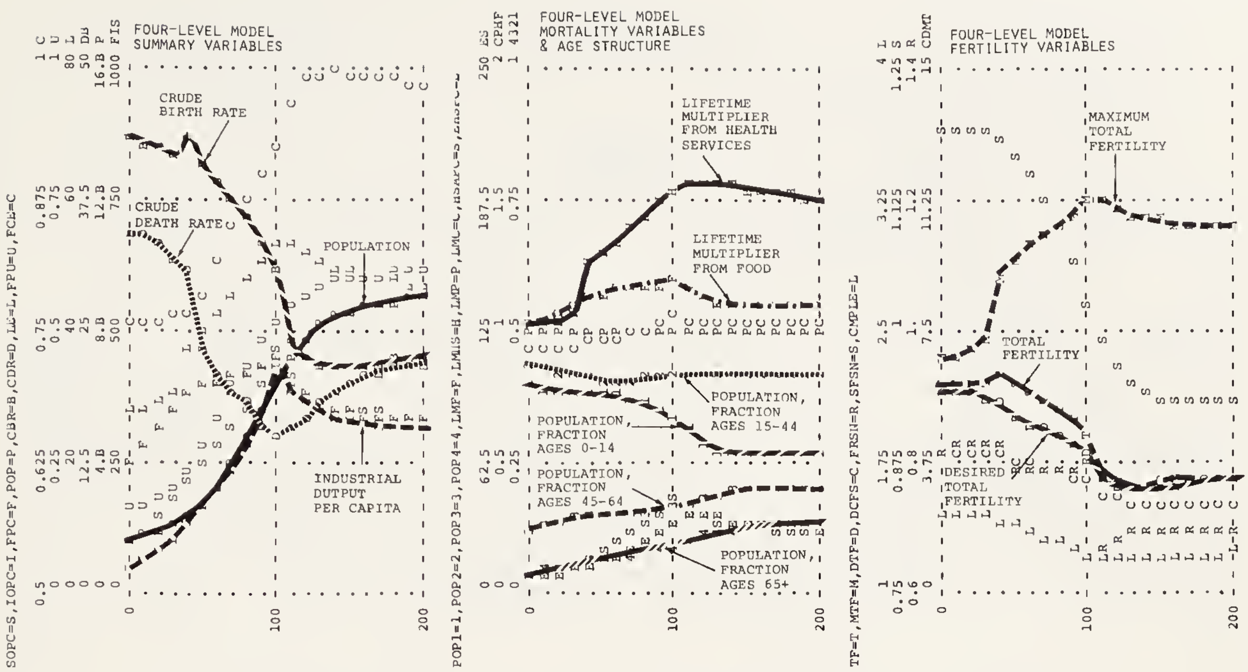

Figure 2-109 Run 2–24: increased social adjustment delay

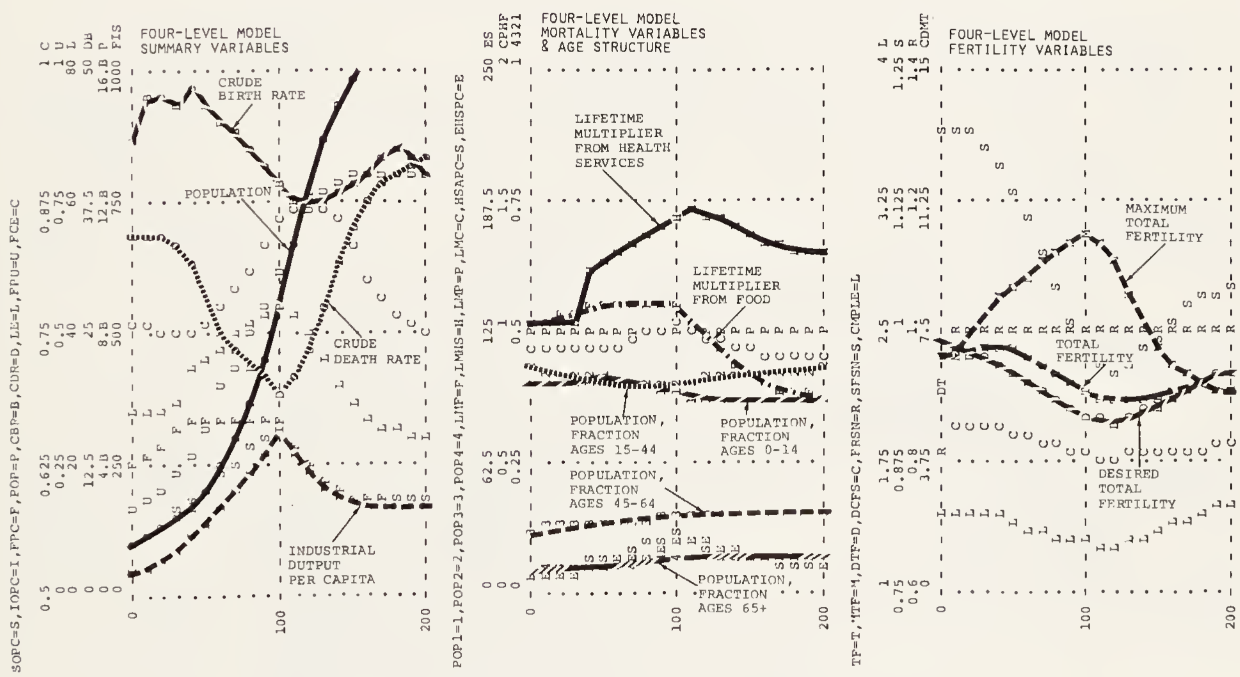

Figure 2-110 Run 2–25: no income expectation effect

increase of food and health services per capita. Again, the behavior mode is not greatly different from that of Run 2–16.

The delay in perception of changing mortality risks LPD is decreased in Run 2–27 (Figure 2-112) from 20 years to 10 years, allowing birth rates to be adjusted more rapidly to compensate for possible child mortality. The shorter delay time produces a slightly smaller population in the year 200; otherwise, it has very little effect on the model output.

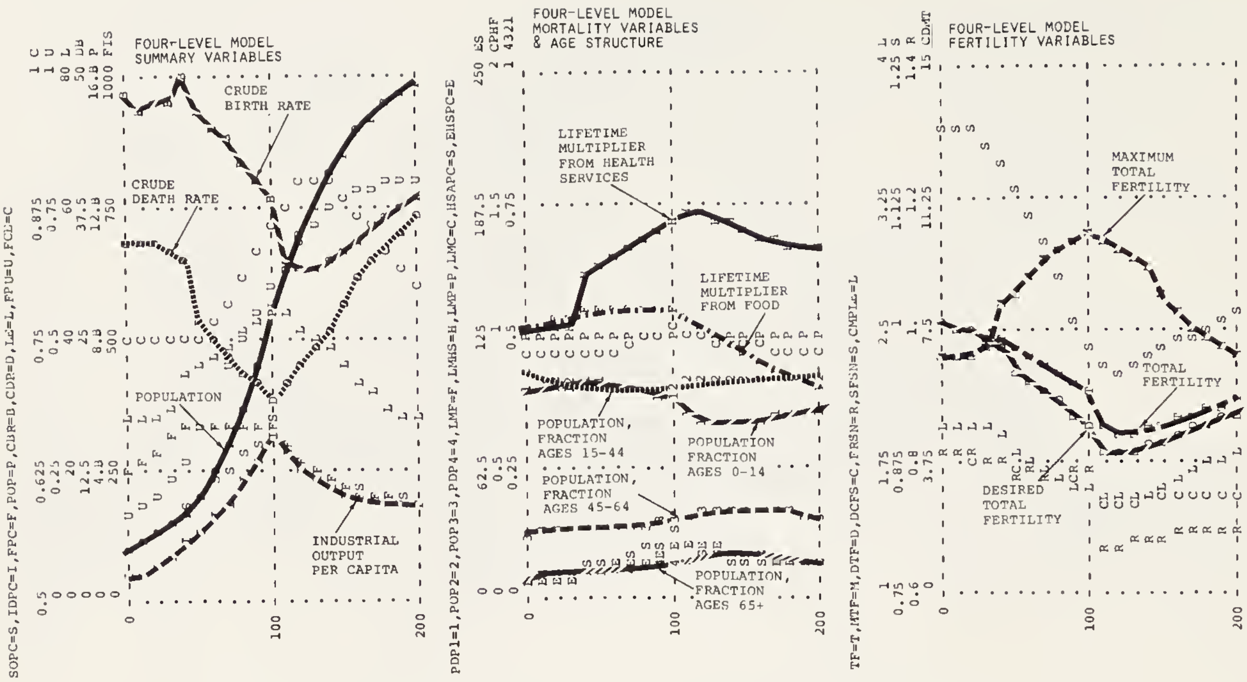

Figure 2-111 Run 2–26: increased compensation for perceived life expectancy

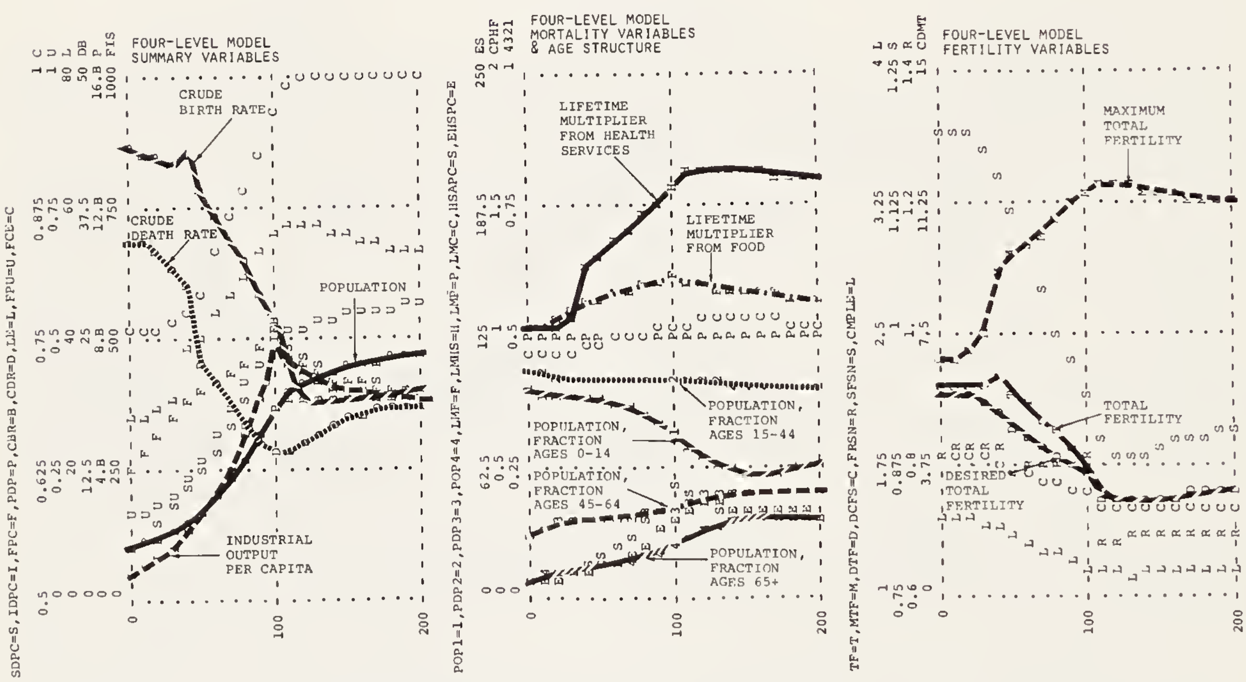

Figure 2-112 Run 2–27: decreased lifetime perception delay

Finally, Run 2–28 (Figure 2-113) shows the result of decreasing the assumed value of fertility control effectiveness FCE at any given value of family planning facilities per capita. The table used in Run 2–28 allows FCE to vary from 0.5 to 0.98 rather than from 0.7 to 1.0. This change causes a large gap between desired and actual total fertility, a higher birth rate, and a higher population. The general behavior mode is not altered.

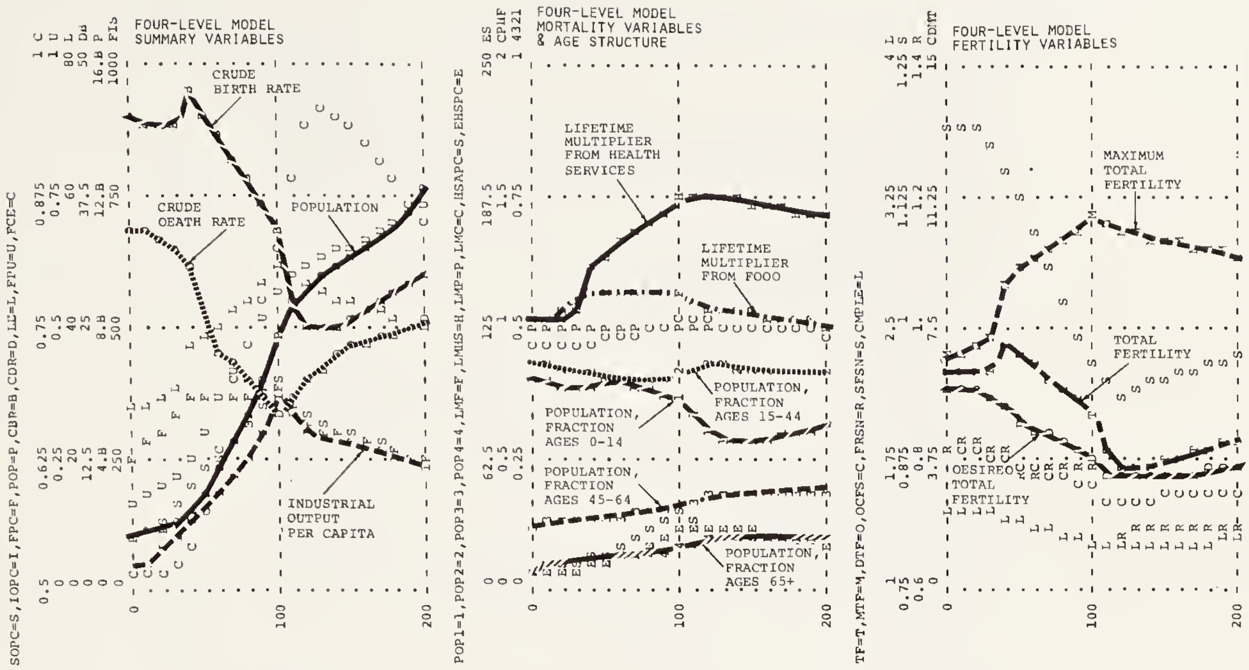

Figure 2-113 Run 2–28: decreased fertility control effectiveness

APPENDIX A: ONE-LEVEL POPULATION MODEL

```
POP1

*       ONE-LEVEL POPULATION SECTOR WITH EXOGENOUS INPUTS
NOTE
NOTE    POPULATION LEVEL EQUATIONS
NOTE
L       POP.K=POP.J+(DT)(B.JK-D.JK)
N       POP=POPI
C       POPI=1.61E9
NOTE
NOTE    DEATH RATE EQUATIONS
NOTE
R       D.KL=POP.K/LE.K
S       CDR.K=1000*D.JK/POP.K
A       LE.K=LEN*LMF.K*LMHS.K*LMP.K*LMC.K
C       LEN=28
A       LMF.K=TABHL(LMFT,FPC.K/SFPC,0,5,1)
T       LMFT=0/1/1.2/1.3/1.35/1.4
C       SFPC=230
A       HSAPC.K=TABHL(HSAPCT,SOPC.K,0,2000,250)
T       HSAPCT=0/20/50/95/140/175/200/220/230
A       EHSPC.K=SMOOTH(HSAPC.K,HSID)
C       HSID=20
A       LMHS.K=CLIP(LMHS2.K,LMHS1.K,TIME.K,IPHST)
C       IPHST=40
A       LMHS1.K=TABHL(LMHS1T,EHSPC.K,0,100,20)
T       LMHS1T=1/1.1/1.4/1.6/1.7/1.8
A       LMHS2.K=TABHL(LMHS2T,EHSPC.K,0,100,20)
T       LMHS2T=1/1.4/1.6/1.8/1.95/2.0
A       FPU.K=TABHL(FPUT,POP.K,0,16E9,2E9)
T       FPUT=0/.2/.4/.5/.58/.65/.72/.78/.80
A       CMI.K=TABHL(CMIT,IOPC.K,0,1600,200)
T       CMIT=.5/.05/-.1/-.08/-.02/.05/.1/.15/.2
A       LMC.K=1-(CMI.K*FPU.K)
A       LMP.K=TABHL(LMPT,PPOLX.K,0,100,10)
T       LMPT=1.0/.99/.97/.95/.90/.85/.75/.65/.55/.40/.20
NOTE
```

```
NOTE   BIRTH RATE EQUATIONS
NOTE
R      B.KL=CLIP(D.JK,(TF.K*POP.K*FFW/RLT),TIME.K,PET)
C      FFW=.21
C      RLT=30
C      PET=4000
S      CBR.K=1000*B.JK/POP.K
A      TF.K=MIN(MTF.K,(MTF.K*(1-FCE.K)+DTF.K*FCE.K))
A      MTF.K=MTFN*FM.K
C      MTFN=12
A      FM.K=TABHL(FMT,LE.K,0,80,10)
T      FMT=0/.2/.4/.6/.8/.9/1/1.05/1.1
A      DTF.K=DCFS.K*CMPLE.K
A      CMPLE.K=TABHL(CMPLET,PLE.K,0,80,10)
T      CMPLET=3/2.1/1.6/1.4/1.3/1.2/1.1/1.05/1
A      PLE.K=DLINF3(LE.K,LPD)
C      LPD=20
A      DCFS.K=CLIP(2,DCFSN*FRSN.K*SFSN.K,TIME.K,ZPGT)
C      ZPGT=4000
C      DCFSN=4
A      SFSN.K=TABHL(SFSNT,DIOPC.K,0,800,200)
T      SFSNT=1.25/1/.9/.8/.75
A      DIOPC.K=DLINF3(IOPC.K,SAD)
C      SAD=20
A      FRSN.K=TABHL(FRSNT,FIE.K,-.2,.2,.1)
T      FRSNT=.5/.6/.7/.85/1
N      FRSN=.82
A      FIE.K=(IOPC.K-AIOPC.K)/AIOPC.K
A      AIOPC.K=SMOOTH(IOPC.K,IEAT)
C      IEAT=3
A      NFC.K=(MTF.K/DTF.K)-1
A      FCE.K=CLIP(1.0,(TABHL(FCET,FCFPC.K,0,3,.5)),TIME.K,FCEST)
C      FCEST=4000
T      FCET=.75/.85/.9/.95/.98/.99/1
A      FCFPC.K=DLINF3(FCAPC.K,HSID)
A      FCAPC.K=FSAFC.K*SOPC.K
A      FSAFC.K=TABHL(FSAFCT,NFC.K,0,10,2)
T      FSAFCT=0/.005/.015/.025/.03/.035
NOTE
NOTE   EXOGENOUS INPUTS TO THE POPULATION SECTOR
NOTE
NOTE   INDUSTRIAL OUTPUT
NOTE
A      IO.K=CLIP(IO2.K,IO1.K,TIME.K,LT)
C      LT=500
A      IO1.K=CLIP(IO12.K,IO11.K,TIME.K,LT2)
C      LT2=500
A      IO11.K=.7E11*EXP(TIME.K*.037)
A      IO12.K=POP.K*CIO
C      CIO=100
A      IO2.K=.7E11*EXP(LT*.037)
A      IOPC.K=IO.K/POP.K
NOTE
NOTE   INDEX OF PERSISTENT POLLUTION
NOTE
A      PPOLX.K=1+RAMP(PS,PT)
C      PS=0
C      PT=10
NOTE
NOTE   SERVICE OUTPUT
NOTE
A      SO.K=CLIP(SO2.K,SO1.K,TIME.K,LT)
A      SO1.K=CLIP(SO12.K,SO11.K,TIME.K,LT2)
A      SO11.K=1.5E11*EXP(TIME.K*.030)
A      SO12.K=POP.K*CSO
C      CSO=150
A      SO2.K=1.5E11*EXP(LT*.030)
A      SOPC.K=SO.K/POP.K
NOTE
NOTE   FOOD
NOTE
A      F.K=CLIP(F2.K,F1.K,TIME.K,LT)
A      F1.K=CLIP(F12.K,F11.K,TIME.K,LT2)
A      F11.K=4E11*EXP(TIME.K*.020)
A      F12.K=POP.K*CFOOD
C      CFOOD=250
A      F2.K=4E11*EXP(LT*.020)
A      FPC.K=F.K/POP.K
NOTE
```

```
NOTE  CONTROL CARDS
NOTE
C     DT=1
C     LENGTH=200
C     PLTPER=10
C     PRTPER=0
PLOT  SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
X     CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
RUN   STANDARD
NOTE
NOTE  PARAMETER CHANGES FOR THE POPULATION SECTOR RUNS
NOTE
NOTE  HISTORICAL RUNS
NOTE
C     LENGTH=75
C     PLTPER=5
RUN   FIGURE 2-84: HISTORICAL BEHAVIOR, SUMMARY VARIABLES
C     LENGTH=75
C     PLTPER=5
PLOT  LMF=F,LMHS=H,LMP=P,LMC=C(0,2)/HSAPC=S,EHSPC=E(0,250)
RUN   FIGURE 2-85: HISTORICAL BEHAVIOR, MORTALITY VARIABLES
C     LENGTH=75
C     PLTPER=5
PLOT  TF=T,MTF=M,DTF=D,DCFS=C(0,15)/FRSN=R(.6,1.4)/
X     SFSN=S(.75,1.25)/CMPLE=L(1,4)
RUN   FIGURE 2-86: HISTORICAL BEHAVIOR, FERTILITY VARIABLES
NOTE
NOTE  CONSTANT INCOME PER CAPITA RUNS
NOTE
C     IPHST=4000
C     LT2=0
PLOT  SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
X     CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
RUN   FIGURE 2-87: CONSTANT LOW INCOME
C     IPHST=4000
C     LT2=0
C     CIO=1000
C     CSO=1500
C     CFOOD=2500
RUN   FIGURE 2-88: CONSTANT HIGH INCOME
C     LT2=0
RUN   FIGURE 2-89: CONSTANT LOW INCOME, IMPROVED HEALTH CARE
NOTE
NOTE  EXPONENTIAL ECONOMIC GROWTH RUNS
NOTE
RUN   FIGURE 2-90: EXPONENTIAL ECONOMIC GROWTH, SUMMARY VARIABLES
PLOT  LMF=F,LMHS=H,LMP=P,LMC=C(0,2)/HSAPC=S,EHSPC=E(0,250)
RUN   FIGURE 2-91: EXPONENTIAL ECONOMIC GROWTH, MORTALITY VARIABLES
PLOT  TF=T,MTF=M,DTF=D,DCFS=C(0,15)/FRSN=R(.6,1.4)/
X     SFSN=S(.75,1.25)/CMPLE=L(1,4)
RUN   FIGURE 2-93: EXPONENTIAL ECONOMIC GROWTH, FERTILITY VARIABLES
C     FCEST=75
PLOT  SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
X     CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
RUN   FIGURE 2-96: EXPONENTIAL GROWTH, PERFECT FERTILITY CONTROL
C     FCEST=75
C     ZPGT=75
RUN   FIGURE 2-97: EXPONENTIAL GROWTH, FERTILITY CONTROL, REDUCED DCFS
NOTE
NOTE  RUNS SIMULATING CONSTANT TOTAL OUTPUT
NOTE
C     LT=100
RUN   FIGURE 2-98: CONSTANT TOTAL OUTPUT
C     LT=100
C     FCEST=75
RUN   FIGURE 2-99: CONSTANT TOTAL OUTPUT, PERFECT FERTILITY CONTROL
C     LT=100
C     FCEST=75
C     ZPGT=75
RUN   FIGURE 2-100: CONSTANT OUTPUT, FERTILITY CONTROL, REDUCED DCFS
NOTE
NOTE  SENSITIVITY TESTS
NOTE
C     LT=100
T     LMHS2T=1/1.5/1.8/2/2.2/2.35
PLOT  SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
X     CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
PLOT  LMF=F,LMHS=H,LMP=P,LMC=C(0,2)/HSAPC=S,EHSPC=E(0,250)
PLOT  TF=T,MTF=M,DTF=D,DCFS=C(0,15)/FRSN=R(.6,1.4)/
X     SFSN=S(.75,1.25)/CMPLE=L(1,4)
RUN   FIGURE 2-103: LIFE EXPECTANCY OF 100 YEARS
```

APPENDIX B: FOUR-LEVEL POPULATION MODEL

```
          POP4

          *       FOUR-LEVEL POPULATION SECTOR WITH EXOGENOUS INPUTS
          NOTE    (THIS VERSION IS USED IN THE WORLD3 STANDARD MODEL)
          NOTE
          NOTE    POPULATION LEVEL EQUATIONS
          NOTE
 1        A       POP.K=P1.K+P2.K+P3.K+P4.K
 2        L       P1.K=P1.J+(DT)(B.JK-D1.JK-MAT1.JK)
          N       P1=P1I
          C       P1I=65E7
 3        R       D1.KL=P1.K*M1.K
 4        A       M1.K=TABHL(M1T,LE.K,20,80,10)
          T       M1T=.0567/.0366/.0243/.0155/.0082/.0023/.001
 5        R       MAT1.KL=(P1.K)(1-M1.K)/15
 6        L       P2.K=P2.J+(DT)(MAT1.JK-D2.JK-MAT2.JK)
          N       P2=P2I
          C       P2I=70E7
 7        R       D2.KL=P2.K*M2.K
 8        A       M2.K=TABHL(M2T,LE.K,20,80,10)
          T       M2T=.0266/.0171/.0110/.0065/.0040/.0016/.0008
 9        R       MAT2.KL=(P2.K)(1-M2.K)/30
10        L       P3.K=P3.J+(DT)(MAT2.JK-D3.JK-MAT3.JK)
          N       P3=P3I
          C       P3I=19E7
11        R       D3.KL=P3.K*M3.K
12        A       M3.K=TABHL(M3T,LE.K,20,80,10)
          T       M3T=.0562/.0373/.0252/.0171/.0118/.0083/.006
13        R       MAT3.KL=(P3.K)(1-M3.K)/20
14        L       P4.K=P4.J+(DT)(MAT3.JK-D4.JK)
          N       P4=P4I
          C       P4I=6E7
15        R       D4.KL=P4.K*M4.K
16        A       M4.K=TABHL(M4T,LE.K,20,80,10)
          T       M4T=.13/.11/.09/.07/.06/.05/.04
          NOTE
          NOTE    DEATH RATE SUBSECTOR
          NOTE
17        A       D.K=D1.JK+D2.JK+D3.JK+D4.JK
18        S       CDR.K=1000*D.K/POP.K
19        A       LE.K=LEN*LMF.K*LMHS.K*LMP.K*LMC.K
          C       LEN=28
20        A       LMF.K=TABHL(LMFT,FPC.K/SFPC,0,5,1)
          T       LMFT=0/1/1.2/1.3/1.35/1.4
21        A       HSAPC.K=TABHL(HSAPCT,SOPC.K,0,2000,250)
          T       HSAPCT=0/20/50/95/140/175/200/220/230
22        A       EHSPC.K=SMOOTH(HSAPC.K,HSID)
          C       HSID=20
          A       LMHS.K=CLIP(LMHS2.K,LMHS1.K,TIME.K,IPHST)
24        A       LMHS1.K=TABHL(LMHS1T,EHSPC.K,0,100,20)
          T       LMHS1T=1/1.1/1.4/1.6/1.7/1.8
25        A       LMHS2.K=TABHL(LMHS2T,EHSPC.K,0,100,20)
          T       LMHS2T=1/1.4/1.6/1.8/1.95/2.0
26        A       FPU.K=TABHL(FPUT,POP.K,0,16E9,2E9)
          T       FPUT=0/.2/.4/.5/.58/.65/.72/.78/.80
27        A       CMI.K=TABHL(CMIT,IOPC.K,0,1600,200)
          T       CMIT=.5/.05/-.1/-.08/-.02/.05/.1/.15/.2
28        A       LMC.K=1-(CMI.K*FPU.K)
29        A       LMP.K=TABHL(LMPT,PPOLX.K,0,100,10)
          T       LMPT=1.0/.99/.97/.95/.90/.85/.75/.65/.55/.40/.20
          NOTE
          NOTE    BIRTH RATE SUBSECTOR
          NOTE
30        R       B.KL=CLIP(D.K,(TF.K*P2.K*0.5/RLT),TIME.K,PET)
          C       RLT=30
          C       PET=4000
31        S       CBR.K=1000*B.JK/POP.K
32        A       TF.K=MIN(MTF.K,(MTF.K*(1-FCE.K)+DTF.K*FCE.K))
33        A       MTF.K=MTFN*FM.K
          C       MTFN=12
34        A       FM.K=TABHL(FMT,LE.K,0,80,10)
          T       FMT=0/.2/.4/.6/.8/.9/1/1.05/1.1
35        A       DTF.K=DCFS.K*CMPLE.K
36        A       CMPLE.K=TABHL(CMPLET,PLE.K,0,80,10)
          T       CMPLET=3/2.1/1.6/1.4/1.3/1.2/1.1/1.05/1
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```
37   A     PLE.K=DLINF3(LE.K,LPD)
     C     LPD=20
38   A     DCFS.K=CLIP(2.0,DCFSN*FRSN.K*SFSN.K,TIME.K,ZPGT)
     C     ZPGT=4000
     C     DCFSN=4
39   A     SFSN.K=TABHL(SFSNT,DIOPC.K,0,800,200)
     T     SFSNT=1.25/1/.9/.8/.75
40   A     DIOPC.K=DLINF3(IOPC.K,SAD)
     C     SAD=20
41   A     FRSN.K=TABHL(FRSNT,FIE.K,-.2,.2,.1)
     T     FRSNT=.5/.6/.7/.85/1
     N     FRSN=.82
42   A     FIE.K=(IOPC.K-AIOPC.K)/AIOPC.K
43   A     AIOPC.K=SMOOTH(IOPC.K,IEAT)
     C     IEAT=3
44   A     NFC.K=(MTF.K/DTF.K)-1
45   A     FCE.K=CLIP(1.0,(TABHL(FCET,FCFPC.K,0,3,.5)),TIME.K,FCEST)
     C     FCEST=4000
     T     FCET=.75/.85/.9/.95/.98/.99/1
46   A     FCFPC.K=DLINF3(FCAPC.K,HSID)
47   A     FCAPC.K=FSAFC.K*SOPC.K
48   A     FSAFC.K=TABHL(FSAFCT,NFC.K,0,10,2)
     T     FSAFCT=0/.005/.015/.025/.03/.035
     NOTE
     NOTE  EXOGENOUS INPUTS TO THE POPULATION SECTOR
     NOTE
     NOTE  INDUSTRIAL OUTPUT
     NOTE
     A     IO.K=CLIP(IO2.K,IO1.K,TIME.K,LT)
     C     LT=500
     A     IO1.K=CLIP(IO12.K,IO11.K,TIME.K,LT2)
     C     LT2=500
     A     IO11.K=.7E11*EXP(TIME.K*.037)
     A     IO12.K=POP.K*CIO
     C     CIO=100
     A     IO2.K=.7E11*EXP(LT*.037)
     A     IOPC.K=IO.K/POP.K
     NOTE
     NOTE  INDEX OF PERSISTENT POLLUTION
     NOTE
     A     PPOLX.K=1+RAMP(PS,PT)
     C     PS=0
     C     PT=10
     NOTE
     NOTE  SERVICE OUTPUT
     NOTE
     A     SO.K=CLIP(SO2.K,SO1.K,TIME.K,LT)
     A     SO1.K=CLIP(SO12.K,SO11.K,TIME.K,LT2)
     A     SO11.K=1.5E11*EXP(TIME.K*.030)
     A     SO12.K=POP.K*CSO
     C     CSO=150
     A     SO2.K=1.5E11*EXP(LT*.030)
     A     SOPC.K=SO.K/POP.K
     NOTE
     NOTE  FOOD
     NOTE
     A     F.K=CLIP(F2.K,F1.K,TIME.K,LT)
     A     F1.K=CLIP(F12.K,F11.K,TIME.K,LT2)
     A     F11.K=4E11*EXP(TIME.K*.020)
     A     F12.K=POP.K*CFOOD
     C     CFOOD=250
     A     F2.K=4E11*EXP(LT*.020)
     A     FPC.K=F.K/POP.K
     C     SFPC=230
     NOTE
     NOTE  CONTROL CARDS
     NOTE
     C     IPHST=40
     C     DT=1
     C     LENGTH=200
     C     PLTPER=10
     C     PRTPER=0
     A     POP1.K=P1.K/POP.K
     A     POP2.K=P2.K/POP.K
     A     POP3.K=P3.K/POP.K
     A     POP4.K=P4.K/POP.K
     PLOT  SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
     X     CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
     RUN   STANDARD
```

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NOTE
NOTE  PARAMETER CHANGES FOR THE POPULATION SECTOR RUNS
NOTE
NOTE  HISTORICAL RUNS
NOTE
C     LENGTH=75
C     PLTPER=5
RUN   FIGURE 2-84: HISTORICAL BEHAVIOR, SUMMARY VARIABLES
C     LENGTH=75
C     PLTPER=5
PLOT  POP1=1,POP2=2,POP3=3,POP4=4(0,1)/LMF=F,LMHS=H,
X     LMP=P,LMC=C(0,2)/HSAPC=S,EHSPC=E(0,250)
RUN   FIGURE 2-85: HISTORICAL BEHAVIOR, MORTALITY VARIABLES
C     LENGTH=75
C     PLTPER=5
PLOT  TF=T,MTF=M,DTF=D,DCFS=C(0,15)/FRSN=R(.6,1.4)/
X     SFSN=S(.75,1.25)/CMPLE=L(1,4)
RUN   FIGURE 2-86: HISTORICAL BEHAVIOR, FERTILITY VARIABLES
NOTE
NOTE  CONSTANT INCOME PER CAPITA RUNS
NOTE
C     IPHST=4000
C     LT2=0
PLOT  SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
X     CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
RUN   FIGURE 2-87: CONSTANT LOW INCOME
C     IPHST=4000
C     LT2=0
C     CIO=1000
C     CSO=1500
C     CFOOD=2500
RUN   FIGURE 2-88: CONSTANT HIGH INCOME
C     LT2=0
RUN   FIGURE 2-89: CONSTANT LOW INCOME, IMPROVED HEALTH CARE
NOTE
NOTE  EXPONENTIAL ECONOMIC GROWTH RUNS
NOTE
RUN   FIGURE 2-90: EXPONENTIAL ECONOMIC GROWTH, SUMMARY VARIABLES
PLOT  POP1=1,POP2=2,POP3=3,POP4=4(0,1)/LMF=F,LMHS=H,
X     LMP=P,LMC=C(0,2)/HSAPC=S,EHSPC=E(0,250)
RUN   FIGURE 2-91: EXPONENTIAL ECONOMIC GROWTH, MORTALITY VARIABLES
PLOT  TF=T,MTF=M,DTF=D,DCFS=C(0,15)/FRSN=R(.6,1.4)/
X     SFSN=S(.75,1.25)/CMPLE=L(1,4)
RUN   FIGURE 2-93: EXPONENTIAL ECONOMIC GROWTH, FERTILITY VARIABLES
C     FCEST=75
PLOT  SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
X     CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
RUN   FIGURE 2-96: EXPONENTIAL GROWTH, PERFECT FERTILITY CONTROL
C     FCEST=75
C     ZPGT=75
RUN   FIGURE 2-97: EXPONENTIAL GROWTH, FERTILITY CONTROL, REDUCED DCFS
NOTE
NOTE  RUNS SIMULATING CONSTANT TOTAL OUTPUT
NOTE
C     LT=100
RUN   FIGURE 2-98: CONSTANT TOTAL OUTPUT
C     LT=100
C     FCEST=75
RUN   FIGURE 2-99: CONSTANT TOTAL OUTPUT, PERFECT FERTILITY CONTROL
C     LT=100
C     FCEST=75
C     ZPGT=75
RUN   FIGURE 2-100: CONSTANT OUTPUT, FERTILITY CONTROL, REDUCED DCFS
NOTE
NOTE  SENSITIVITY TESTS
NOTE
C     LT=100
PLOT  SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
X     CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
PLOT  POP1=1,POP2=2,POP3=3,POP4=4(0,1)/LMF=F,LMHS=H,
X     LMP=P,LMC=C(0,2)/HSAPC=S,EHSPC=E(0,250)
PLOT  TF=T,MTF=M,DTF=D,DCFS=C(0,15)/FRSN=R(.6,1.4)/
X     SFSN=S(.75,1.25)/CMPLE=L(1,4)
RUN   FIGURE 2-101: CONSTANT TOTAL OUTPUT
C     LT=100
T     LMFT=0/1.4/1.4/1.4/1.4/1.4
RUN   FIGURE 2-102: EQUITABLE FOOD DISTRIBUTION
C     LT=100
T     HSAPCT=0/125/250/375/500/625/750/875/1000
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RUN    FIGURE 2-104: GREATER ALLOCATIONS TO HEALTH SERVICES
C      LT=100
T      CMIT=0/0/0/0/0/0/0/0/0
RUN    FIGURE 2-105: NO CROWDING EFFECT
C      LT=100
T      FMT=1/1/1/1/1/1/1/1/1
RUN    FIGURE 2-106: CONSTANT MAXIMUM TOTAL FERTILITY
C      LT=100
T      SFSNT=1/.9/.7/.6/.5
RUN    FIGURE 2-107: LOWER FAMILY SIZE NORM
C      LT=100
T      SFSNT=.75/.75/.75/.75/.75
RUN    FIGURE 2-108: CONSTANT FAMILY SIZE NORM OF 3
C      LT=100
C      SAD=50
RUN    FIGURE 2-109: INCREASED SOCIAL ADJUSTMENT DELAY
C      LT=100
T      FRSNT=1/1/1/1/1
RUN    FIGURE 2-110: NO INCOME EXPECTATION EFFECT
C      LT=100
T      CMPLET=5/4/2.5/1.8/1.6/1.4/1.3/1.15/1.1
RUN    FIGURE 2-111: INCREASED CMPLE
C      LT=100
C      LPD=10
RUN    FIGURE 2-112: DECREASED LIFETIME PERCEPTION DELAY
C      LT=100
T      FCET=.5/.7/.8/.9/.95/.98/.98
RUN    FIGURE 2-113: DECREASED FCE
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APPENDIX C: FIFTEEN-LEVEL POPULATION MODEL

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POP15

*      FIFTEEN-LEVEL POPULATION SECTOR WITH EXOGENOUS INPUTS
NOTE
NOTE   POPULATION LEVEL EQUATIONS
NOTE
NOTE   AGE 0-1
L      P1.K=P1.J+(DT)(B.JK-D1.JK-MAT1.JK)
N      P1=P1I
C      P1I=5.3E7
A      D1A.K=P1.K*M1.K
A      M1.K=TABHL(M1T,LE.K,20,70,10)
T      M1T=.40/.28/.20/.14/.07/.02
R      D1.KL=D1A.K
R      MAT1.KL=P1.K-D1A.K
NOTE   AGE 1-4
L      P2.K=P2.J+(DT)(MAT1.JK-D2.JK-MAT2.JK)
N      P2=P2I
C      P2I=2.1E8
A      D2A.K=P2.K*M2.K
A      M2.K=TABHL(M2T,LE.K,20,70,10)
T      M2T=.08/.05/.03/.02/.008/.002
R      D2.KL=D2A.K
R      MAT2.KL=(P2.K-D2A.K)/4
NOTE   AGE 5-9
L      P3.K=P3.J+(DT)(MAT2.JK-D3.JK-MAT3.JK)
N      P3=P3I
C      P3I=2.2E8
A      D3A.K=P3.K*M3.K
A      M3.K=TABHL(M3T,LE.K,20,70,10)
T      M3T=.02/.01/.007/.004/.002/.001
R      D3.KL=D3A.K
R      MAT3.KL=(P3.K-D3A.K)/5
NOTE   AGE 10-14
L      P4.K=P4.J+(DT)(MAT3.JK-D4.JK-MAT4.JK)
N      P4=P4I
C      P4I=1.8E8
A      D4A.K=P4.K*M4.K
A      M4.K=TABHL(M4T,LE.K,20,70,10)
T      M4T=.01/.008/.005/.003/.001/.0005
R      D4.KL=D4A.K
R      MAT4.KL=(P4.K-D4A.K)/5
NOTE   AGE 15-19
L      P5.K=P5.J+(DT)(MAT4.JK-D5.JK-MAT5.JK)
N      P5=P5I
C      P5I=1.6E8
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A       D5A.K=P5.K*M5.K
A       M5.K=TABHL(M5T,LE.K,20,70,10)
T       M5T=.02/.01/.007/.004/.002/.0008
R       D5.KL=D5A.K
R       MAT5.KL=(P5.K-D5A.K)/5
NOTE    AGE 20-24
L       P6.K=P6.J+(DT)(MAT5.JK-D6.JK-MAT6.JK)
N       P6=P6I
C       P6I=1.5E8
A       D6A.K=P6.K*M6.K
A       M6.K=TABHL(M6T,LE.K,20,70,10)
T       M6T=.02/.01/.01/.006/.003/.001
R       D6.KL=D6A.K
R       MAT6.KL=(P6.K-D6A.K)/5
NOTE    AGE 25-29
L       P7.K=P7.J+(DT)(MAT6.JK-D7.JK-MAT7.JK)
N       P7=P7I
C       P7I=1.3E8
A       D7A.K=P7.K*M7.K
A       M7.K=TABHL(M7T,LE.K,20,70,10)
T       M7T=.02/.02/.01/.006/.003/.001
R       D7.KL=D7A.K
R       MAT7.KL=(P7.K-D7A.K)/5
NOTE    AGE30-34
L       P8.K=P8.J+(DT)(MAT7.JK-D8.JK-MAT8.JK)
N       P8=P8I
C       P8I=1.1E8
A       D8A.K=P8.K*M8.K
A       M8.K=TABHL(M8T,LE.K,20,70,10)
T       M8T=.03/.02/.01/.007/.004/.002
R       D8.KL=D8A.K
R       MAT8.KL=(P8.K-D8A.K)/5
NOTE    AGE35-39
L       P9.K=P9.J+(DT)(MAT8.JK-D9.JK-MAT9.JK)
N       P9=P9I
C       P9I=9.6E7
A       D9A.K=P9.K*M9.K
A       M9.K=TABHL(M9T,LE.K,20,70,10)
T       M9T=.03/.02/.01/.007/.004/.002
R       D9.KL=D9A.K
R       MAT9.KL=(P9.K-D9A.K)/5
NOTE    AGE 40-44
L       P10.K=P10.J+(DT)(MAT9.JK-D10.JK-MAT10.JK)
N       P10=P10I
C       P10I=8.3E7
A       D10A.K=P10.K*M10.K
A       M10.K=TABHL(M10T,LE.K,20,70,10)
T       M10T=.04/.02/.01/.008/.005/.003
R       D10.KL=D10A.K
R       MAT10.KL=(P10.K-D10A.K)/5
NOTE    AGE 45-49
L       P11.K=P11.J+(DT)(MAT10.JK-D11.JK-MAT11.JK)
N       P11=P11I
C       P11I=6.8E7
A       D11A.K=P11.K*M11.K
A       M11.K=TABHL(M11T,LE.K,20,70,10)
T       M11T=.04/.03/.02/.01/.006/.004
R       D11.KL=D11A.K
R       MAT11.KL=(P11.K/5)-D11A.K
NOTE    AGE 50-54
L       P12.K=P12.J+(DT)(MAT11.JK-D12.JK-MAT12.JK)
N       P12=P12I
C       P12I=5.6E7
A       D12A.K=P12.K*M12.K
A       M12.K=TABHL(M12T,LE.K,20,70,10)
T       M12T=.05/.03/.02/.01/.009/.006
R       D12.KL=D12A.K
R       MAT12.KL=(P12.K-D12A.K)/5
NOTE    AGE 55-59
L       P13.K=P13.J+(DT)(MAT12.JK-D13.JK-MAT13.JK)
N       P13=P13I
C       P13I=4.5E7
A       D13A.K=P13.K*M13.K
A       M13.K=TABHL(M13T,LE.K,20,70,10)
T       M13T=.06/.04/.03/.02/.01/.009
R       D13.KL=D13A.K
R       MAT13.KL=(P13.K-D13A.K)/5
NOTE    AGE 60-64
L       P14.K=P14.J+(DT)(MAT13.JK-D14.JK-MAT14.JK)
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N       P14=P14I
C       P14I=3.3E7
A       D14A.K=P14.K*M14.K
A       M14.K=TABHL(M14T,LE.K,20,70,10)
T       M14T=.07/.05/.04/.03/.02/.01
R       D14.KL=D14A.K
R       MAT14.KL=(P14.K-D14A.K)/5
NOTE    AGE 65+
L       P15.K=P15.J+(DT)(MAT14.JK-D15.JK)
N       P15=P15I
C       P15I=4.8E7
R       D15.KL=P15.K*M15.K
A       M15.K=TABHL(M15T,LE.K,20,70,10)
T       M15T=.13/.11/.09/.07/.06/.05
NOTE
NOTE    AUXILLARY EQUATIONS
NOTE
A       D.K=D1.JK+D2.JK+D3.JK+D4.JK+D5.JK+D6.JK+D7.JK+D8.JK+D9.JK+D10.JK+
X       D11.JK+D12.JK+D13.JK+D14.JK+D15.JK
A       POP.K=P1.K+P2.K+P3.K+P4.K+P5.K+P6.K+P7.K+P8.K+P9.K+P10.K+P11.K+
X       P12.K+P13.K+P14.K+P15.K
A       PC.K=(P1.K+P2.K+P3.K+P4.K)/POP.K
A       PF.K=(P5.K+P6.K+P7.K+P8.K+P9.K+P10.K)/POP.K
A       PW.K=(P11.K+P12.K+P13.K+P14.K)/POP.K
A       PE.K=P15.K/POP.K
NOTE
NOTE    DEATH RATE EQUATIONS
NOTE
S       CDR.K=1000*D.K/POP.K
A       LE.K=LEN*LMF.K*LMHS.K*LMP.K*LMC.K
C       LEN=28
A       LMF.K=TABHL(LMFT,FPC.K/SFPC,0,5,1)
T       LMFT=0/1/1.2/1.3/1.35/1.4
C       SFPC=230
A       HSAPC.K=TABHL(HSAPCT,SOPC.K,0,2000,250)
T       HSAPCT=0/20/50/95/140/175/200/220/230
A       EHSPC.K=SMOOTH(HSAPC.K,HSID)
C       HSID=20
A       LMHS.K=CLIP(LMHS2.K,LMHS1.K,TIME.K,IPHST)
C       IPHST=40
A       LMHS1.K=TABHL(LMHS1T,EHSPC.K,0,100,20)
T       LMHS1T=1/1.1/1.4/1.6/1.7/1.8
A       LMHS2.K=TABHL(LMHS2T,EHSPC.K,0,100,20)
T       LMHS2T=1/1.4/1.6/1.8/1.95/2.0
A       FPU.K=TABHL(FPUT,POP.K,0,16E9,2E9)
T       FPUT=0/.2/.4/.5/.58/.65/.72/.78/.80
A       CMI.K=TABHL(CMIT,IOPC.K,0,1600,200)
T       CMIT=.5/.05/-.1/-.08/-.02/.05/.1/.15/.2
A       LMC.K=1-(CMI.K*FPU.K)
A       LMP.K=TABHL(LMPT,PPOLX.K,0,100,10)
T       LMPT=1.0/.99/.97/.95/.90/.85/.75/.65/.55/.40/.20
NOTE
NOTE    BIRTH RATE EQUATIONS
NOTE
A       EXTRA.K=P5.K*.06+P6.K*.25+P7.K*.28+P8.K*.21+P9.K*.13+P10.K*.07
R       B.KL=CLIP(D.K,((TF.K/10)*EXTRA.K),TIME.K,PET)
C       PET=4000
S       CBR.K=1000*B.JK/POP.K
A       TF.K=MIN(MTF.K,(MTF.K*(1-FCE.K)+DTF.K*FCE.K))
A       MTF.K=MTFN*FM.K
C       MTFN=12
A       FM.K=TABHL(FMT,LE.K,0,80,10)
T       FMT=0/.2/.4/.6/.8/.9/1/1.05/1.1
A       DTF.K=DCFS.K*CMPLE.K
A       CMPLE.K=TABHL(CMPLET,PLE.K,0,80,10)
T       CMPLET=3/2.1/1.6/1.4/1.3/1.2/1.1/1.05/1
A       PLE.K=DLINF3(LE.K,LPD)
C       LPD=20
A       DCFS.K=CLIP(2,DCFSN*FRSN.K*SFSN.K,TIME.K,ZPGT)
C       ZPGT=4000
C       DCFSN=4
A       SFSN.K=TABHL(SFSNT,DIOPC.K,0,800,200)
T       SFSNT=1.25/1/.9/.8/.75
A       DIOPC.K=DLINF3(IOPC.K,SAD)
C       SAD=20
A       FRSN.K=TABHL(FRSNT,FIE.K,-.2,.2,.1)
T       FRSNT=.5/.6/.7/.85/1
N       FRSN=.82
A       FIE.K=(IOPC.K-AIOPC.K)/AIOPC.K
A       AIOPC.K=SMOOTH(IOPC.K,IEAT)
```

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C       IEAT=3
A       NFC.K=(MTF.K/DTF.K)-1
A       FCE.K=CLIP(1.0,(TABHL(FCET,FCFPC.K,0,3,.5)),TIME.K,FCEST)
C       FCEST=4000
T       FCET=.75/.85/.9/.95/.98/.99/1
A       FCFPC.K=DLINF3(FCAPC.K,HSID)
A       FCAPC.K=FSAFC.K*SOPC.K
A       FSAFC.K=TABHL(FSAFCT,NFC.K,0,10,2)
T       FSAFCT=0/.005/.015/.025/.03/.035
NOTE
NOTE    EXOGENOUS INPUTS TO THE POPULATION SECTOR
NOTE
NOTE    INDUSTRIAL OUTPUT
NOTE
A       IO.K=CLIP(IO2.K,IO1.K,TIME.K,LT)
C       LT=500
A       IO1.K=CLIP(IO12.K,IO11.K,TIME.K,LT2)
C       LT2=500
A       IO11.K=.7E11*EXP(TIME.K*.037)
A       IO12.K=POP.K*CIO
C       CIO=100
A       IO2.K=.7E11*EXP(LT*.037)
A       IOPC.K=IO.K/POP.K
NOTE
NOTE    INDEX OF PERSISTENT POLLUTION
NOTE
A       PPOLX.K=1+RAMP(PS,PT)
C       PS=0
C       PT=10
NOTE
NOTE    SERVICE OUTPUT
NOTE
A       SO.K=CLIP(SO2.K,SO1.K,TIME.K,LT)
A       SO1.K=CLIP(SO12.K,SO11.K,TIME.K,LT2)
A       SO11.K=1.5E11*EXP(TIME.K*.030)
A       SO12.K=POP.K*CSO
C       CSO=150
A       SO2.K=1.5E11*EXP(LT*.030)
A       SOPC.K=SO.K/POP.K
NOTE
NOTE    FOOD
NOTE
A       F.K=CLIP(F2.K,F1.K,TIME.K,LT)
A       F1.K=CLIP(F12.K,F11.K,TIME.K,LT2)
A       F11.K=4E11*EXP(TIME.K*.020)
A       F12.K=POP.K*CFOOD
C       CFOOD=250
A       F2.K=4E11*EXP(LT*.020)
A       FPC.K=F.K/POP.K
NOTE
NOTE    CONTROL CARDS
NOTE
C       DT=1
C       LENGTH=200
C       PLTPER=10
C       PRTPER=0
PLOT    SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
X       CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
RUN     STANDARD
NOTE
NOTE    PARAMETER CHANGES FOR THE POPULATION SECTOR RUNS
NOTE
NOTE    HISTORICAL RUNS
NOTE
C       LENGTH=75
C       PLTPER=5
RUN     FIGURE 2-84: HISTORICAL BEHAVIOR, SUMMARY VARIABLES
C       LENGTH=75
C       PLTPER=5
PLOT    PC=1,PF=2,PW=3,PE=4(0,1)/LMF=F,LMHS=H,
X       LMP=P,LMC=C(0,2)/HSAPC=S,EHSPC=E(0,250)
RUN     FIGURE 2-85: HISTORICAL BEHAVIOR, MORTALITY VARIABLES
C       LENGTH=75
C       PLTPER=5
PLOT    TF=T,MTF=M,DTF=D,DCFS=C(0,15)/FRSN=R(.6,1.4)/
X       SFSN=S(.75,1.25)/CMPLE=L(1,4)
RUN     FIGURE 2-86: HISTORICAL BEHAVIOR, FERTILITY VARIABLES
NOTE
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NOTE    CONSTANT INCOME PER CAPITA RUNS
NOTE
C       IPHST=4000
C       LT2=0
PLOT    SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
X       CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
RUN     FIGURE 2-87: CONSTANT LOW INCOME
C       IPHST=4000
C       LT2=0
C       CIO=1000
C       CSO=1500
C       CFOOD=2500
RUN     FIGURE 2-88: CONSTANT HIGH INCOME
C       LT2=0
RUN     FIGURE 2-89: CONSTANT LOW INCOME, IMPROVED HEALTH CARE
NOTE
NOTE    EXPONENTIAL ECONOMIC GROWTH RUNS
NOTE
RUN     FIGURE 2-90: EXPONENTIAL ECONOMIC GROWTH, SUMMARY VARIABLES
PLOT    PC=1,PF=2,PE=4(0,1)/LMF=F,LMHS=H,
X       LMP=P,LMC=C(0,2)/HSAPC=S,EHSPC=E(0,250)
RUN     FIGURE 2-91: EXPONENTIAL ECONOMIC GROWTH, MORTALITY VARIABLES
PLOT    TF=T,MTF=M,DTF=D,DCFS=C(0,15)/FRSN=R(.6,1.4)/
X       SFSN=S(.75,1.25)/CMPLE=L(1,4)
RUN     FIGURE 2-93: EXPONENTIAL ECONOMIC GROWTH, FERTILITY VARIABLES
NOTE    ** THE FOLLOWING CHANGE MUST BE MADE IN EDIT MODE:
NOTE    ** A EXTRA.K=P6.K*.1+P7.K*.25+P8.K*.3+P9.K*.25+P10.K*.1
PLOT    SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
X       CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
PLOT    PC=1,PF=2,PW=3,PE=4(0,1)/LMF=F,LMHS=H,
X       LMP=P,LMC=C(0,2)/HSAPC=S,EHSPC=E(0,250)
PLOT    TF=T,MTF=M,DTF=D,DCFS=C(0,15)/FRSN=R(.6,1.4)/
X       SFSN=S(.75,1.25)/CMPLE=L(1,4)
RUN     FIGURE 2-94: EXPONENTIAL GROWTH, HIGHER CHILDBEARING AGE
C       FCEST=75
PLOT    SOPC=S,IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/
X       CBR=B,CDR=D(0,50)/LE=L(0,80)/FPU=U(0,1)/FCE=C(.5,1)
RUN     FIGURE 2-96: EXPONENTIAL GROWTH, PERFECT FERTILITY CONTROL
C       FCEST=75
C       ZPGT=75
RUN     FIGURE 2-97: EXPONENTIAL GROWTH, FERTILITY CONTROL, REDUCED DCFS
NOTE
NOTE    RUNS SIMULATING CONSTANT TOTAL OUTPUT
NOTE
C       LT=100
RUN     FIGURE 2-98: CONSTANT TOTAL OUTPUT
C       LT=100
C       FCEST=75
RUN     FIGURE 2-99: CONSTANT TOTAL OUTPUT, PERFECT FERTILITY CONTROL
C       LT=100
C       FCEST=75
C       ZPGT=75
RUN     FIGURE 2-100: CONSTANT OUTPUT, FERTILITY CONTROL, REDUCED DCFS
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APPENDIX D: NATIONAL POPULATION STATISTICS

	1	2	3	4	5	6
	Population, Mid-1972[a] (thousands)	**Crude Birth Rate**[a] (annual births per 1,000 population)	**Crude Death Rate**[a] (annual deaths per 1,000 population)	**Annual Net Rate of Population Growth**[a,b] (percent)	**Life Expectancy**[c,d] (average of male and female at birth, years)	**GNP per Capita**[a,e] (1969 dollars)
Africa	**364,000**	**47**	**21**	**2.6**		**184**
Algeria	15,000	50	17	3.3	(1965–1970) 50.7	260
Angola	5,900	50	30	2.1	(1965–1970) 33.5	210
Burundi	3,800	48	25	2.3	(1965) 36.75	<100
Cameroon	6,000	43	23	2.0	(1965–1970) 41.0	150
Central African Republic	1,600	46	25	2.1	(1966) 36.3	130
Chad	3,900	48	25	2.3	(1963–1964) 32.0	<100
Congo-Kinshasa (Zaire)	18,300	44	23	2.1	(1950–1952) 38.87	<100
Dahomey	2,800	51	26	2.6	(1965–1970) 38.5	<100
Ethiopia	26,200	46	25	2.1	(1965–1970) 38.5	<100
Ghana	9,600	47	18	2.9	(1965–1970) 46.0	190
Guinea	4,100	47	25	2.3	(1955) 25.8	<100
Ivory Coast	4,500	46	23	2.4	(1965–1970) 41	240
Kenya	11,600	48	18	3.0	(1965–1970) 47.5	130
Liberia	1,200	50	23	2.7	(1962) 37.35	200
Libya	2,000	46	16	2.8	(1965–1970) 52.7	1,510
Malagasy Republic	7,300	46	25	2.1	(1966) 37.9	110
Malawi	4,700	49	25	2.5	(1965–1970) 38.5	<100
Mali	5,300	50	27	2.3	(1965–1970) 37.2	<100
Mauritania	1,200	44	23	2.1	(1965–1970) 41.0	140
Morocco	16,800	50	16	3.4	(1965–1970) 50.5	190
Mozambique	8,100	43	23	2.1	(1965–1970) 47.0	210
Niger	4,100	50	25	2.6	(1965–1970) 41.0	<100
Nigeria	58,000	52	23	2.9	(1965–1966) 36.95	140
Rwanda	3,800	52	23	2.9	(1965–1970) 41.0	<100
Senegal	4,100	46	22	2.4	(1965–1970) 41.0	200
Sierra Leone	2,800	45	22	2.3	(1965–1970) 41.0	170
Somali Republic	2,900	46	24	2.2	(1965–1970) 38.5	<100
Republic of South Africa	21,000	41	17	2.4	(1965–1970) 49.0	710
Southern Rhodesia	5,400	48	14	3.4	(1965–1970) 51.4	240
Sudan	16,800	49	18	3.1	(1965–1970) 47.6	110
Tanzania	14,000	47	22	2.6	(1967) 40–41	<100
Togo	2,000	51	26	2.5	(1961) 36.9	100
Tunisia	5,400	42	16	2.6	(1965–1970) 51.7	230
Uganda	9,100	43	18	2.6	(1965–1970) 47.5	110
Upper Volta	5,600	49	29	2.0	(1960–1961) 31.6	<100
Zambia	4,600	50	21	2.9	(1965–1970) 43.5	290
Asia	**2,154,000**	**37**	**14**	**2.3**		
Afghanistan	17,900	51	17	2.4	(1965–1970) 37.5	<100
Burma	29,100	40	17	2.3	(1965–1970) 47.5	<100
Cambodia (Khmer Republic)	7,600	45	16	3.0	(1958–1959) 42.75	130
Ceylon (Sri Lanka)	13,200	31	8	2.3	(1967) 65.9	190
China, People's Republic of	786,100	30	13	1.7	(1965–1970) 50.0	<100
China, Taiwan	14,700	28	5	2.3	(1966) 67.5	300
Hong Kong	4,400	20	5	2.4	(1968) 70.0	850
India	584,800	42	17	2.5	(1961) 45.0	110
Indonesia	128,700	47	19	2.9	(1961) 45.8	100
Iran	30,200	45	17	2.8	(1965–1970) 50.0	350
Iraq	10,400	49	15	3.4	(1965–1970) 51.6	310
Israel	3,000	27	7	2.4	(1969) 71.33	1,570
Japan	106,000	19	7	1.2	(1968) 71.68	1,430
Jordan	2,500	48	16	3.3	(1959–1963) 52.3	280
Lebanon	3,000					580

7 Average Annual Rate of GNP Growth[e] per Capita (1961–1968)	8 Literacy[f] (percent)	9 Infant Deaths per 1,000 Live Births[f]	10 Urban Population[f] (percent)	11 Labor in Agriculture[f] (percent)	12 Food per Capita[g] (vegetable calories per person per day)	13 Health Expenditures, Public and Private (dollars per person-year)	14 Doctors per 100,000 Population[g]	15 Population Density 1970[g] (persons/km²)
	20	136	20	76				
−3.5	25–30	86	43	50	(1964–1966) 2,570		(1969) 12	6
2.1	10–15	192	14	82	(1964–1966) 2,710		(1966) 10	5
0	10	161	3	95	(1964–1966) 2,360		(1970) 2	127
1.1	10–15	110	20	84	(1964–1966) 2,900		(1970) 4	12
−0.6	5–10	129	8	92	(1964–1966) 3,080		(1970) 3	3
−1.5	5–10	129	8	92	(1964–1966) 3,310		(1970) 2	3
−0.3	35–45	115	16	69	(1964–1966) 2,530		(1969) 14	3
1.1	20	149	17	84	(1964–1966) 2,690		(1970) 3	24
2.6	5	162	8	88	(1964–1966) 3,180		(1969) 1	20
−0.7	25	122	37	56	(1966–1968) 2,450	5.90	(1969) 7	38
2.7	5–10	216	11	85	(1964–1966) 2,430		(1969) 2	16
4.8	20	154	21	86	(1964–1966) 2,310		(1969) 5	13
1.4	20–25	126	10	88	(1964–1966) 3,450		(1969) 11	19
0.7	9	143	9	80	(1964–1966) 2,800		(1966) 11	11
19.4	27		27	35	(1969) 4,214		(1970) 38	1
−0.2	39	102	13	84	(1964–1966) 3,540		(1969) 10	11
2.2	15	119	5	81	(1964–1966) 2,400		(1967) 2	37
1.3	5	190	12	90	(1964–1966) 3,280		(1969) 2	4
11.3	1–5	137	2	90	(1964–1966) 5,310		(1969) 4	1
0.4	14	145	35	54	(1964–1966) 3,280		(1969) 8	35
3.6	7		5	69	(1964–1966) 2,640		(1967) 6	10
−1.6	5	148	3	96	(1964–1966) 3,380		(1969) 2	3
−0.3	25	157	23	80	(1964–1966) 2,550		(1968) 4	60
1.5	10	124	0	95	(1964–1966) 2,240		(1970) 2	136
−1.4	5–10	156	24	74	(1964–1966) 3,680		(1970) 7	20
1.5	10	136	14	75	(1964–1966) 2,632		(1969) 6	39
0.2	5	190	11	89	(1964–1966) 3,890		(1967) 3	4
3.7	35		51	29	(1964–1966) 5,830		(1967) 67	16
−0.1	25–30	65	22	73	(1964–1966) 4,080		(1970) 16	13
−0.4	10–15	121	10	78	(1964–1966) 3,974		(1967) 5	6
1.2	15–20	165	7	95	(1964–1966) 3,770		(1969) 4	14
0.5	5–10	163	16	79	(1964–1966) 2,610		(1968) 4	33
2.7	30	120	44	41	(1964–1966) 3,260		(1967) 14	31
1.1	20	124	8	89	(1964–1966) 3,320		(1969) 12	41
0.1	5–10	181	5	87	(1964–1966) 2,550		(1970) 1	20
3.6	15–20	159	22	81	(1964–1966) 3,060		(1967) 6	6
−0.3	8	190	8	87	(1964–1966) 2,925		(1969) 5	26
1.6	60	139	19	62	(1964–1966) 2,740		(1966) 10	41
0.6	41	159	12	80	(1964–1966) 3,170	5.45	(1970) 7	41
2.3	70–80	50	20	49	(1969) 2,740	5.20	(1968) 27	191
0.3	25	122		63	(1964–1966) 3,750			79
6.5	85	19	64	39	(1969) 4,980	11.00	(1969) 32	390
8.1	71	20	80	5	(1964–1966) 5,180		(1970) 55	3,829
−0.3	8	190	8	87	(1968–1969) 2,640		(1967) 22	164
0.8	43	140	17	70	(1964–1966) 2,070		(1967) 4	81
5.0	35	160	41	42	(1964–1966) 3,128		(1970) 44	18
2.9	20	104	44	48	(1964–1966) 3,470		(1969) 19	22
4.7	90	19	80	10	(1968–1969) 6,450	87.00	(1970) 250	141
9.9	98	14	72	17	(1969) 4,510		(1969) 111	280
4.8	35–40	115	44	35	(1964–66) 3,510	3.65	(1970) 25	24
2.4	86		41	55	(1964–1966) 4,480		(1969) 68	268

	1	2	3	4	5	6
	Population, Mid-1972[a] (thousands)	**Crude Birth Rate**[a] (annual births per 1,000 population)	**Crude Death Rate**[a] (annual deaths per 1,000 population)	**Annual Net Rate of Population Growth**[a, b] (percent)	**Life Expectancy**[c, d] (average of male and female at birth, years)	**GNP per Capita**[a, e] (1969 dollars)
North Korea	14,700	39	11	2.8	(1965–1970) 57.7	280
South Korea	18,700	31	11	2.0	(1955–1960) 52.43	210
Laos	3,700	42	17	2.5	(1965–1970) 47.5	110
Malaysia	11,400	37	8	2.8	(1966) 65.2	340
Mongolia	1,400	42	11	3.1	(1965–1970) 57.7	460
Nepal	11,800	45	23	2.2	(1965–1970) 40.6	<100
Pakistan	146,600	51	18	3.3	(1962) 51.26	110
Philippines	40,800	45	12	3.3	(1960) 57.0	210
Saudi Arabia	8,200	50	23	2.8	(1965–1970) 42.3	380
Singapore	2,200	23	5	2.2	(1965–1970) 68.2	800
Thailand	38,600	43	10	3.3	(1960) 56.15	160
Turkey	37,600	40	15	2.5	(1965–1970) 54.5	350
United Arab Republic	35,900	44	16	2.8	(1968) 52.7	160
North Vietnam	22,000				(1965–1970) 50.0	<100
South Vietnam	18,700				(1965–1970) 50.0	140
Yemen Arab Republic	6,100	50	23	2.8	(1965–1970) 42.3	<100
Europe	**469,000**	**16**	**10**	**0.7**		**1,831**
Albania	2,300	35.3	7.5	2.8	(1965–1970) 65.95	430
Austria	7,500	15.2	13.4	0.2	(1969) 69.9	1,470
Belgium	9,800	14.7	12.3	0.2	(1966) 70.8	2,010
Bulgaria	8,700	16.3	9.1	0.7	(1966–1968) 70.9	860
Czechslovakia	14,900	15.8	11.4	0.5	(1967) 70.6	1,370
Denmark	5,000	14.4	9.8	0.5	(1966) 72.8	2,310
Finland	4,800	13.7	9.5	0.4	(1966) 69.6	1,980
France	51,900	16.7	10.6	0.7	(1968) 71.75	2,460
West Germany	59,200	13.3	11.7	0.2	(1967) 70.8	2,190
East Germany	16,300	13.9	14.1	0.0	(1966) 70.9	1,570
Greece	9,000	16.3	8.3	0.8	(1966–1968) 72.6	840
Hungary	10,400	14.7	11.7	0.3	(1967) 69.5	1,100
Ireland	3,000	21.8	11.5	0.7	(1967) 71.3	1,110
Italy	54,500	16.8	9.7	0.7	(1964) 70.5	1,400
Netherlands	13,300	18.4	8.4	1.0	(1968) 73.7	1,760
Norway	4,000	16.6	9.8	0.7	(1967) 74.1	2,160
Poland	33,700	16.8	8.2	0.9	(1965–1966) 69.84	940
Portugal	9,700	18.0	9.7	0.8	(1966–1968) 66.9	510
Romania	20,800	21.1	9.5	1.2	(1964–1967) 68.48	860
Spain	33,900	19.6	8.5	1.0	(1967) 71.9	820
Sweden	8,200	13.7	9.9	0.4	(1967) 74.2	2,920
Switzerland	6,400	15.8	9.1	1.0	(1967) 72.8	2,700
USSR	248,000	17.4	8.2	0.9	(1967–1968) 70	1,200
United Kingdom	56,600	16.2	11.7	0.5	(1967–1969) 71.6	1,890
Yugoslavia	21,000	17.8	9.0	0.9	(1966–1967) 68.37	580
Latin America	**300,000**	**38**	**10**	**2.8**		**471**
Argentina	25,000	22	9	1.5	(1965–1970) 67.2	1,060
Bolivia	4,900	44	19	2.4	(1968) 51[f]	160
Brazil	98,400	38	10	2.8	(1965–1970) 60.7	270
Chile	10,200	28	9	1.9	(1967) 62.7	510
Colombia	22,900	44	11	3.4	(1965) 59.9	290
Costa Rica	1,900	34	7	2.7	(1966) 66.3	510
Cuba	8,700	27	8	1.9	(1965–1970) 66.8	280
Dominican Republic	4,600	49	15	3.4	(1966) 64.8	280
Ecuador	6,500	45	11	3.4	(1965) 58.7	240
El Salvador	3,700	40	10	3.0	(1961) 58.5	290

7 Average Annual Rate of GNP Growth[e] per Capita (1961–1968)	8 Literacy[f] (percent)	9 Infant Deaths per 1,000 Live Births[f]	10 Urban Population[f] (percent)	11 Labor in Agriculture[f] (percent)	12 Food per Capita[g] (vegetable calories per person per day)	13 Health Expenditures, Public and Private (dollars per person-year)	14 Doctors per 100,000 Population[g]	15 Population Density 1970[g] (persons/km²)
5.9		144			(1964–1966) 2,820			115
5.6	71	41	38	50	(1968) 3,130	5.80	(1970) 93	323
0.2	15	137	13	81	(1964–1966) 2,650		(1970) 6	13
4.3	43	79	40	55	(1964–1966) 4,530	9.25	(1970) 26	70
0.8		86			(1964–1966) 8,780		(1970) 170	1
0.3	5–10	162	5	92	(1964–1966) 2,760		(1969) 2	67
3.1	20	136	14	68	(1968–1969) 4,050		(1969) 19	121
0.8	72	82	34	53	(1969) 2,420		(1969) 10	123
7.2	5–15	157	25	72	(1964–1966) 3,080		(1968) 9	4
3.8	75	21	100	7	(1964–1966) 4,770	22.00	(1970) 66	3,527
4.6	68	68	15	78	(1964–1966) 3,290		(1969) 12	70
3.5	35	98	44	62	(1964–1966) 4,416		(1970) 45	45
1.5	30	120	43	57	(1966–1967) 4,200		(1969) 50	33
3.3					(1964–1966) 3,080			133
1.9	60–65		24	65	(1964–1966) 2,320		(1970) 8	105
2.0	10	160	6	89	(1964–1966) 2,170		(1966) 2	29
	95		**61**	**29**				
4.9	72	86.8	38	67	(1964–1966) 4,350		(1967) 59	75
3.6	98	25	54	20	(1969–1970) 9,370	96.00	(1970) 540	88
3.2	97	22	69	5	(1969–1969) 10,710	127.00	(1969) 156	317
6.7	87	37	51	38	(1964–1966) 7,270		(1970) 186	77
3.7		22.1	52	19	(1964–1966) 7,950		(1969) 200	113
3.3	99	15	80	15	(1969–1970) 11,320		(1968) 145	114
3.2	99	13	61	32	(1969–1970) 10,760	84.00	(1970) 102	14
3.7	96	16	67	15	(1969–1970) 11,120		(1970) 134	93
3.4	99	23	81	10	(1969–1970) 9,660	157.00	(1969) 176	240
4.0		18.8	81	14	(1964–1966) 9,820		(1970) 168	150
5.9	82	32	49	54	(1967) 6,380	29.00	(1969) 155	67
5.2	84	36	43	29	(1969) 9,840		(1969) 192	111
3.1	99	21	47	31	(1968) 11,730		(1966) 104	42
4.6	92	30	53	21	(1968–1969) 6,310	63.00	(1970) 181	178
3.0	98	13	71	9	(1968–1969) 4,240	137.00	(1970) 120	319
4.1	99	14	53	18	(1968–1969) 10,400		(1970) 138	12
5.5	96	33.4	53	37	(1964—1966) 8,790		(1970) 150	104
5.0	62	57	37	40	(1969) 5,350		(1970) 85	105
7.8	90	49.5	42	52	(1964–1966) 6,370		(1968) 141	85
6.5	87	30	61	34	(1969–1970) 6,050		(1969) 132	67
6.5	87	30	61	34	(1969–1970) 9,530	177.00	(1969) 130	18
2.4	98	15	58	10	(1967–1968) 9,470	163.00	(1970) 159	152
5.8	98	25	57	31	(1964–1966) 7,110		(1969) 230	11
2.0	98–99	18	81	3	(1968–1969) 11,812	82.00	(1970) (England and Wales) 117	228
4.2	80	55.1	37	48	(1968) 6,890		(1970) 100	80
	69	**78**	**56**	**45**				
1.0	91	56	79	18	(1967) 9,650		(1969) 199	9
1.8	40	108	34	48	(1964–1966) 4,940		(1970) 43	4
1.6	61	94	52	52	(1966–1968) 4,970		(1969) 51	11
1.8	84	92	74	24	(1964–1966) 8,565		(1969) 47	13
1.4	84	60	37	49	(1964–1966) 5,160		(1967) 45	19
2.1	84	60	37	49	(1964–1966) 4,092		(1969) 55	34
	94	41	60	37	(1964–1966) 4,900		(1968) 87	73
0.5	65	72	40	61	(1964–1966) 3,830		(1969) 15	89
1.2	68	80	39	53	(1964–1968) 3,840		(1967) 36	21
2.1	49	63	41	60	(1964–1966) 3,140	10.80	(1969) 26	165

	1 Population, Mid-1972[a] (thousands)	2 Crude Birth Rate[a] (annual births per 1,000 population)	3 Crude Death Rate[a] (annual deaths per 1,000 population)	4 Annual Net Rate of Population Growth[a, b] (percent)	5 Life Expectancy[c, d] (average of male and female at birth, years)	6 GNP per Capita[d, e] (1969 dollars)
Guatemala	5,400	43	17	2.6	(1963–1965) 50.1	350
Haiti	5,500	44	20	2.4	(1965–1970) 44.5	<100
Honduras	2,900	49	17	3.2	(1965–1970) 49.0	260
Jamaica	2,700	33	8	2.1	(1963) 65.0	550
Mexico	54,300	43	10	3.3	(1965–1970) 62.38	580
Nicaragua	2,200	46	17	2.9	(1965–1970) 49.9	380
Panama	1,600	38	9	2.9	(1966) 66.1	660
Paraguay	2,600	45	11	3.4	(1965–1970) 59.4	240
Peru	14,500	42	11	3.1	(1960–1965) 54.04	330
Trinidad and Tobago	1,100	23	7	1.1	(1967) 66.3	890
Uruguay	3,000	21	9	1.2	(1963) 64.8	560
Venezuela	11,500	41	8	3.4	(1965–1970) 63.8	1,000
North America	**231,000**	**17**	**9**	**1.1**		
Canada	22,200	17.5	7.3	1.7	(1966–1968) 72.2	2,650
United States	209,200	17.3	9.3	1.0	(1968) 70.3	2,650
Puerto Rico	2,900	25	7	1.4	(1965) 70.9	1,410
Oceania	**20,000**	**25**	**10**	**2.0**		
Australia	13,000	20.5	9.0	1.9	(1966) 70.9	2,300
New Guinea	2,500					210
New Zealand	3,000	22.1	8.8	1.7	(1966–1968) 71.6	2,230

[a]Population Reference Bureau, Inc., *World Population Data Sheet* (Washington, D.C., 1972).

[b]"Annual rate of population growth (composed of the rate of natural increase modified by the net rate of in- or out-migration) is derived from the latest available published estimates by the United Nations, except where substantiated changes have occurred in birth rates, death rates, or migration streams" (ibid.).

[c]United Nations, *Demographic Yearbook, 1970* (New York, 1971), Table 3, pp. 119–125.

[d]N. Keyfitz and W. Flieger, *Population* (San Francisco: W. H. Freeman and Company, 1971).

[e]Data supplied by International Bank for Reconstruction and Development, *World Bank Atlas* (Washington, D.C., 1970).

7 Average Annual Rate of GNP Growth[e] per Capita (1961–1968)	8 Literacy[f] (percent)	9 Infant Deaths per 1,000 Live Births[f]	10 Urban Population[f] (percent)	11 Labor in Agriculture[f] (percent)	12 Food per Capita[g] (vegetable calories per person per day)	13 Health Expenditures, Public and Private (dollars per person-year)	14 Doctors per 100,000 Population[g]	15 Population Density 1970[g] (persons/km²)
1.7	38	92	31	65	(1964–1966) 3,000		(1969) 25	48
−3.3	10	130	17	83	(1964–1966) 2,450		(1969) 8	175
1.2	45	135	26	67	(1964–1966) 3,190	7.50	(1968) 27	23
0.8	82	39	38	36	(1964–1966) 4,520		(1970) 36	171
3.4	76	68	60	46	(1964–1966) 4,360		(1968) 54	25
3.8	50	121	42	60	(1964–1966) 4,010		(1969) 60	15
4.6	78	58	47	40		36.00	(1969) 56	19
1.3	74	67	39	54	(1964–1966) 6,070		(1958) 62	6
3.5	61	62	51	45	(1967) 4,050		(1969) 52	11
4.4	89	37	50	21	(1964–1966) 5,060		(1968) 43	184
−1.4	91	54	78	21	(1964–1966) 10,080		(1967) 96	16
1.4	76	46	72	25	(1966) 4,590		(1970) 91	11
2.8		21	75	6	(1969) 11,850		(1969) 143	2
3.4	98	20	74	6	(1969) 13,570		(1969) 150	22
5.9	87	28	48	10	(1964–1966) 7,545		(1969) 114	306
3.1	98	17.9	65	8	(1966–1967) 10,800	149.00	(1969) 117	2
2.5			0	64			(1969) 4	7
1.7	98	17	66	12	(1969) 13,480		(1968) 158	10

[f]United States, Agency for International Development, *Population Program Assistance* (Washington, D.C.: Government Printing Office, 1971), pp. 270–274.

[g]United Nations, Department of Economic and Social Affairs, *Statistical Yearbook, 1971* (New York, 1972), Table 160, pp. 504–509.

[h]World Health Organization, *Fourth Report on the World Health Situation, 1965–1968*, Official Reports no. 192 (Geneva, 1971).

[i]Anthony Picardi; personal communication.

REFERENCES

Adelman 1963	Adelman, I. "An Econometric Analysis of Population Growth." *American Economic Review* 3:314.
Adelman and Morris 1966	Adelman, I., and C. J. Morris. "A Quantitative Study of Social and Political Determinants of Fertility." *Economic Development and Cultural Change,* January 1966, p. 129.
Arriaga 1967	Arriaga, E. E. "Rural-Urban Mortality in Developing Countries: An Index for Detecting Underregistration." *Demography* 4:98.
Arriaga and Davis 1969	Arriaga, E. E., and K. Davis. "The Pattern of Mortality Change in Latin America." *Demography* 6:223.
Backman 1948	Backman, G. "Die Beschleunigte Entwicklung der Jugend." *Acta Anatomica Scandinavica* 4:420.
Bazell 1971	Bazell, R. J. "Lead Poisoning: Combating the Threat from the Air." *Science* 174:574.
Berelson 1966	Berelson, B. "KAP Studies on Fertility." In *Family Planning and Population Programs,* edited by B. Berelson et al., p. 655. Chicago: University of Chicago Press, 1966.
Biraben 1968	Biraben, J-N. "Certain Demographic Characteristics of the Plague Epidemic in France, 1720–1722." *Daedalus,* Spring 1968, p. 536.
Blake 1965	Blake, J. "Demographic Science and the Redirection of Population Policy." *Journal of Chronic Diseases* 18:1181.
Blake 1967	Blake, J. "Income and Reproductive Motivation." *Population Studies* 21:185.
Blake 1971	Blake, J. "Abortion and Public Opinion: The 1960–1970 decade." *Science* 171:540.
Boffey 1970	Boffey, P. M. "Japan: A Crowded Nation Wants to Boost Its Birthrate." *Science* 167:960.
Bogue 1969	Bogue, D. J. *Principles of Demography.* New York: John Wiley, 1969.
Borgstrom 1965	Borgstrom, Georg. *The Hungry Planet.* New York: Macmillan, 1965; reprinted in paperback by Collier-Macmillan, London, 1970.
Bourgeois-Pichat 1965	Bourgeois-Pichat, J. "Les facteurs de la fécondité non dirigée." *Population* 20:383.
Bremer, Singer, and Luterbacher 1971	Bremer, S., J. D. Singer, and U. Luterbacher. "Crowding and Combat in Animal and Human Societies: The European Nations, 1816–1965." Working paper. University of Michigan, 1971.
Brown 1970	Brown, L. R. *Seeds of Change: The Green Revolution and Development in the 1970's.* New York: Praeger Publishers, 1970.
Bumpass and Westoff 1970	Bumpass, L., and C. F. Westoff. "The 'Perfect Contraceptive' Population." *Science* 169:1177.
Calhoun 1962	Calhoun, J. B. "Population Density and Social Pathology." *Scientific American* 206:139.
Calhoun 1970	Calhoun, J. B. "Population." In *Population Control,* edited by A. Allison, p. 110. Harmondsworth, Eng.: Penguin Books, 1970.

Carr-Saunders 1936	Carr-Saunders, A. M. *World Population: Past Growth and Present Trends*. Oxford: Clarendon Press, 1936.
Cassel 1971	Cassel, J. "Health Consequences of Population Density and Crowding." In *Rapid Population Growth*, p. 462. Baltimore: Johns Hopkins University Press for the National Academy of Sciences, 1971.
Cépède, Houtart, and Grond 1964	Cépède, M., F. Houtart, and L. Grond. *Population and Food*. New York: Sheed and Ward, 1964.
Chisholm 1971	Chisholm, J. J. "Lead Poisoning." *Scientific American* 224:15.
Cho 1964	Cho, L. J. "Estimated Refined Measures of Fertility for All Major Countries of the World." *Demography* 1:359.
Choucri and North 1972	Choucri, N., and R. C. North. "Dynamics of International Conflict: Some Policy Implications of Population, Resources, and Technology." *World Politics* 24:80.
Coale and Demeny 1966	Coale, A. J., and P. Demeny. *Regional Model Life Tables and Stable Populations*. Princeton: Princeton University Press, 1966.
Corsa and Oakley 1971	Corsa, L., and D. Oakley. "Consequences of Population Growth for Health Services in Less Developed Countries—An Initial Appraisal." In *Rapid Population Growth*. Baltimore: Johns Hopkins University Press for the National Academy of Sciences, 1971.
David and Wright 1971	David, H. P., and N. H. Wright. "Abortion Legislation: The Romanian Experience." *Studies in Family Planning* 2, no. 10 (October 1971), pp. 205–210.
Davis 1965	Davis, K. "The Urbanization of the Human Population." *Scientific American* 213:41.
Davis and Blake 1956	Davis, K., and J. Blake. "Social Structure and Fertility: An Analytic Framework." *Economic Development and Cultural Change* 4:211.
Deevey 1960	Deevey, E. S. "The Human Population." *Scientific American* 203:195.
Dickson and Patterson et al. 1972	Dickson, E. M., C. C. Patterson, et al. "Mercury and Lead in the Greenland Ice Sheet: A Reexamination of the Data." *Science* 177:536.
Djerassi 1970	Djerassi, C. "Birth Control after 1984." *Science* 169:941.
Dodge and Martin 1970	Dodge, D. L., and W. T. Martin. *Social Stress and Chronic Illness*. Notre Dame, Ind.: University of Notre Dame Press, 1970.
Driver 1963	Driver, E. D. *Differential Fertility in Central India*. Princeton: Princeton University Press, 1963.
Dubos 1965	Dubos, R. *Man Adapting*. New Haven: Yale University Press, 1965.
Easterlin 1962	Easterlin, R. A. *The American Baby Boom in Historical Perspective*. National Bureau of Economic Research, Occasional Paper no. 79. New York, 1962.
Easterlin 1966	Easterlin, R. A. "On the Relation of Economic Factors to Recent and Projected Fertility Changes." *Demography* 3:131.
Eaton and Mayer 1953	Eaton, J., and A. J. Mayer. "The Social Biology of Very High Fertility amongst the Hutterites: The Demography of a Unique Population." *Human Biology* 25:206.

Ehrlich and Ehrlich 1970	Ehrlich, P. R., and A. H. Ehrlich. *Population, Resources, Environment*. San Francisco: W. H. Freeman, 1970.
Espenshade 1971	Espenshade, T. J. "A New Method for Estimating the Level of Natural Fertility in Populations Practicing Birth Control." *Demography* 8:525.
FAO 1970	United Nations. Food and Agriculture Organization. *Provisional Indicative World Plan for Agricultural Development*. Rome, 1970.
Fisher and Potter	Fisher, J. L., and N. Potter. "The Effects of Population Growth on Resource Adequacy and Quality." In *Rapid Population Growth*. Baltimore: Johns Hopkins University Press for the National Academy of Sciences, 1971.
Forbes 1967	Forbes, W. H. *New England Journal of Medicine* 277:71.
Forrester 1961	Forrester, J. W. *Industrial Dynamics*. Cambridge, Mass.: The M.I.T. Press, 1961.
Forrester 1971	Forrester, J. W. *World Dynamics*. Cambridge, Mass.: Wright-Allen Press, 1971.
Frederiksen 1969	Frederiksen, H. "Feedbacks in Economic and Demographic Transition." *Science* 166:837.
Freedman 1963	Freedman, R. "Norms for Family Size in Underdeveloped Areas." *Proceedings of the Royal Society* 159:220.
Freedman, Baumert, and Bolte 1959	Freedman, R., G. Baumert, and M. Bolte. "Expected Family Size and Family Size Values in West Germany." *Population Studies* 13:145.
Freedman, Goldberg, and Sharp 1955	Freedman, R., D. Goldberg, and H. Sharp. "Ideals about Family Size in the Detroit Metropolitan Area: 1954." *Milbank Memorial Fund Quarterly* 23:187.
Frejka 1968	Frejka, T. "Reflections on the Demographic Conditions Needed to Establish a United States Stationary Population Growth." *Population Studies* 22, no. 3 (November 1968).
Friedlander and Silver 1967	Friedlander, S., and M. Silver. "A Quantitative Study of the Determinants of Fertility Behavior." *Demography* 4:30.
Frisch and Revelle 1967	Frisch, R., and R. Revelle. "Variations in Body Weights among Different Populations." In PSAC 1967, vol. 2, p. 1.
Galle, Gove, and McPherson 1972	Galle, O. R., W. R. Gove, and J. M. McPherson. "Population Density and Pathology: What Are the Relations for Man?" *Science* 176:23.
Glass 1964	Glass, D. V. "Some Indicators of Differences between Urban and Rural Mortality in England, Wales, and Scotland." *Population Studies* 17:263.
Gordon 1969	Gordon, J. E. "Social Implications of Nutrition and Disease." *Archives of Environmental Health* 18:216.
Gordon, Wyon, and Ascoli 1967	Gordon, J. E., J. B. Wyon, and W. Ascoli. "The Second Year Death Rate in Less Developed Countries." *American Journal of the Medical Sciences* 254:121.
Greenburg et al. 1967	Greenburg, L., F. Field, C. L. Erhardt, M. Glasser, and J. T. Reed. "Air Pollution, Influenza, and Mortality in New York City." *Archives of Environmental Health* 15:430.
Hammond 1971	Hammond, A. L. "Mercury in the Environment: Natural and Human Factors." *Science* 171:789.

Hauser 1969 — Hauser, P. M. "World Population Growth." In *The Population Dilemma,* edited by P. M. Hauser, p. 14. Englewood Cliffs, N.J.: Prentice-Hall, 1969.

Hawley and Prachuabmoh 1966 — Hawley, A. H., and V. Prachuabmoh. "Family Growth and Planning in a Rural District of Thailand." In *Family Planning and Population Programs,* edited by B. Berelson et al., p. 523. Chicago: University of Chicago Press, 1966.

Hawthorn 1970 — Hawthorn, G. *The Sociology of Fertility.* London: Collier-Macmillan, 1970.

Hayes 1966 — Hayes, W. J. In National Academy of Sciences, National Research Council, *Scientific Aspects of Pest Control.* Publication 1402. Washington, D.C., 1967.

Hayes, Dale, and Pirkle 1971 — Hayes, W. J., W. E. Dale, and C. I. Pirkle. "Evidence of Safety of Long-Term, High, Oral Doses of DDT for Man." *Archives of Environmental Health* 22:119.

Heer 1966 — Heer, D. M. "Economic Development and Fertility." *Demography* 3:423.

Heer 1968 — Heer, D. M. *Society and Population.* Englewood Cliffs, N.J.: Prentice-Hall, 1968.

Heer and Boynton 1971 — Heer, D M., and J. W. Boynton. "A Multivariate Regression Analysis of Differences in Fertility of United States Counties." *Social Biology* 17:180.

Heer and Smith 1968 — Heer, D. M., and D. O. Smith. "Mortality Level, Desired Family Size, and Population Increase." *Demography* 5:104.

Henry 1961 — Henry, L. "Some Data on Natural Fertility." *Eugenics Quarterly* 8:81.

Himes 1936 — Himes, N. E. *Medical History of Contraception.* Reprint ed. New York: Gamut Press, 1963.

Howell-Lee 1971 — Howell-Lee, N. "The Feasibility of Demographic Studies in Small and Remote Populations." Princeton: Princeton University, Office of Population Research, working paper, 1971.

Jaszmann, Van Lith, and Zaat 1969 — Jaszmann, L., N. D. Van Lith, and J. C. A. Zaat. "The Duration of the Reproductive Stage and the Age at Final Pregnancy of Women in their Forties and Fifties." *Medical Gynaecologist Society* 4, no. 10.

Jensen 1972 — Jensen, S. "The PCB Story." *Ambio* 1:123.

Johansson 1960 — Johansson, O. *The Gross Domestic Product of Sweden.* Stockholm: Almquist and Wiksell, 1960.

Keyfitz 1971*a* — Keyfitz, N. "Models." *Demography* 8:571.

Keyfitz 1971*b* — Keyfitz, N. "Changes of Birth and Death Rates and Their Demographic Effects." In *Rapid Population Growth.* Baltimore: Johns Hopkins University Press for the National Academy of Sciences, 1971.

Keyfitz and Flieger 1971 — Keyfitz, N., and W. Flieger. *Population.* San Francisco: W. H. Freeman, 1971.

Keys et al. 1950 — Keys, A., J. Brozek, A. Henschel, O. Mickelson, and H. L. Taylor. *The Biology of Human Starvation.* Minneapolis: University of Minnesota Press, 1950.

Kiser, Grabill, and Campbell 1968 — Kiser, C. V., W. H. Grabill, and A. A. Campbell. *Trends and Variations in Fertility in the United States.* Cambridge, Mass.: Harvard University Press, 1968.

Kormandy 1969 — Kormandy, E. J. *Concepts of Ecology*. Englewood Cliffs, N.J.: Prentice-Hall, 1969.

Kusukawa 1967 — Kusukawa, A. "Social and Economic Factors in Mortality in Developing Countries." In United Nations, Department of Economic and Social Affairs, *Proceedings of the World Population Conference* 2:337. New York, 1967.

Lave and Seskin 1970 — Lave, L. B., and E. P. Seskin. "Air Pollution and Human Health." *Science* 169:723.

Légaré 1967 — Légaré, J. "Mortality at Age 45 and Over: Recent Trends in Norway and Other Countries with Low Mortality Levels." In United Nations, Department of Economic and Social Affairs, *Proceedings of the World Population Conference* 2:414. New York, 1967.

Leibenstein 1957 — Leibenstein, H. *Economic Backwardness and Economic Growth*. New York: John Wiley, 1957.

Lorimer 1967 — Lorimer, F. "The Economics of Family Formation under Different Conditions." In United Nations, Department of Economic and Social Affairs, Proceedings of the *World Population Conference* 2:92. New York, 1967.

MacMahon and Worcester 1966 — MacMahon, B., and G. Worcester. "Age at Menopause: United States—1960–1962." In U.S. Department of Health, Education, and Welfare, *Vital and Health Statistics*, ser. 11, no. 19. Washington, D.C.: Government Printing Office, 1966.

Mason et al. 1971 — Mason, K. O., A. S. David, E. K. Gerstel, Q. W. Lindsey, and M. v.E. Rulison. *Social and Economic Correlates of Family Fertility: A Survey of the Evidence*. Research Park, N.C.: Research Triangle Institute, 1971. Project SU-518.

Maugh 1972 — Maugh, T. H. "Polychlorinated Biphenyls: Still Prevalent but Less of a Problem." *Science* 178:338.

Mauldin 1965 — Mauldin, W. P. "Fertility Studies: Knowledge, Attitude, and Practice." *Studies in Family Planning*, 1, no. 7, pp. 1–10.

May and Heer 1968 — May, D. A., and D. M. Heer. "Son Survivorship Motivation and Family Size in India: A Computer Simulation." *Population Studies* 22:199.

Morgan and Roan 1971 — Morgan, D. P., and C. C. Roan. "Absorption, Storage, and Metabolic Conversion of Ingested DDT and DDT Metabolites in Man." *Archives of Environmental Health* 22:301.

Morsa 1966 — Morsa, J. "The Tunisia Survey: A Preliminary Analysis." In *Family Planning and Population Programs*, edited by B. Berelson et al., p. 581. Chicago: University of Chicago Press, 1966.

Myrdal 1941 — Myrdal, A. *Nation and Family*. Reprinted. Cambridge, Mass.: The M.I.T. Press, 1968.

Nag 1968 — Nag, M. *Factors Affecting Human Fertility in Nonindustrial Societies: A Cross-Cultural Study*. Yale University Publications in Anthropology no. 66. New Haven, 1968.

Neel 1970 — Neel, J. V. "Lessons from a Primitive People." *Science* 170:815.

Nortman 1972 — Nortman, D. *Population and Family Planning Programs: A Factbook*. Reports on Population/Family Planning, no. 2, (September 1972), pp. 1–87.

Notestein 1945 — Notestein, F. W. "Population—The Long View." In *Food for the World*, edited by T. W. Schultz, p. 36. Chicago: University of Chicago Press, 1945.

Omran 1971	Omran, A. R. "Abortion in the Demographic Transition." In *Rapid Population Growth*. Baltimore: Johns Hopkins University Press for the National Academy of Sciences, 1971.
Patterson 1965	Patterson, C. C. "Contaminated and Natural Lead Environments of Man." *Archives of Environmental Health* 2:344.
Pearl 1939	Pearl, R. *The Natural History of Population*. London: Oxford University Press, 1939.
Peters, Israel, and Purshottam 1958	Peters, H., S. Israel, and S. Purshottam. "Lactation Period in Indian Women." *Fertility and Sterility* 9:134.
Population Index 1971	Office of Population Research, Princeton University, and Population Association of America. *Population Index* 37 (April–June 1971).
Population Reference Bureau 1968	Population Reference Bureau, Inc. *World Population Data Sheet*. Washington, D.C., 1968
Population Reference Bureau 1970	Population Reference Bureau, Inc. "India, Ready or Not, Here They Come." *Population Bulletin*, November 1970.
Potter 1966	Potter, R. G. "Application of Life Table Techniques to Measurement of Contraceptive Effectiveness." *Demography* 3:297.
PSAC 1967	United States. President's Science Advisory Committee. *The World Food Problem*. Report of the Panel on the World's Food Supply. Vols. 1–3. Washington, D.C.: Government Printing Office, 1967.
Rainwater 1960	Rainwater, L. *And the Poor Get Children*. Chicago: Quadrangle Books, 1960.
Rainwater 1965	Rainwater, L. *Family Design: Marital Sexuality, Family Size, and Contraception*. Chicago: Aldine Press, 1965.
Repetto 1972	Repetto, R. "Son Preference and Fertility Behavior in Developing Countries." *Studies in Family Planning* 3, no. 4.
Ryder and Westoff 1971	Ryder, N. B., and C. F. Westoff. *Reproduction in the United States 1965*. Princeton: Princeton University Press, 1971.
Sarhan 1967	Sarhan, A. E. In United Nations, Department of Economic and Social Affairs. *Proceedings of the World Population Conference* 2: 359–360. New York, 1967.
Sauvy 1961	Sauvy, Alfred. *Fertility and Survival*. New York: Criterion Books, 1961.
Sauvy 1969	Sauvy, Alfred. *General Theory of Population*. Translated from the French by Christophe Campos. New York: Basic Books; London: Weidenfeld and Nicolson, 1969.
Schroeder 1970	Schroeder, H. A. "A Sensible Look at Air Pollution by Metals." *Archives of Environmental Health* 21: 798.
Sen 1967	Sen, S. R. In United Nations, Department of Economic and Social Affairs, *Proceedings of the World Population Conference* 2:410. New York, 1967.
Södergren and Ulfstrand 1972	Södergren, A., and S. Ulfstrand. "DDT and PCB Relocate When Caged Robins Use Fat Reserves." *Ambio* 1:36.
Southam 1966	Southam, A. L. "Contraceptive Methods: Use, Safety, and Effectiveness." In *Family Planning and Population Programs*, edited by B. Berelson et al., p. 375. Chicago: University of Chicago Press, 1966
Spengler 1966	Spengler, J. J. "Values and Fertility Analysis." *Demography* 3:109.

Stoetzel 1955	Stoetzel, J. "Les attitudes et la conjuncture demographique: La dimension ideale de la famille." In United Nations, Department of Economic and Social Affairs, *Proceedings of the World Population Conference* 6:1019. New York, 1955.
Stycos 1968	Stycos, J. M. *Human Fertility in Latin America*. Ithaca, N.Y.: Cornell University Press, 1968.
Sweden 1972	Sweden. Royal Ministry for Foreign Affairs, Royal Ministry of Agriculture. "Air Pollution across International Boundaries: The Impact on the Environment of Sulfur in Air and Precipitation." Sweden's case study for the United Nations Conference on Human Environment, 1972.
Taylor and Berelson 1971	Taylor, H. C., and B. Berelson. "Comprehensive Family Planning Based on Maternal/Child Health Services: A Feasibility Study for a World Program." *Studies in Family Planning* 2, no. 2 (February 1971), pp. 22–54.
Taylor and Knowelden 1957	Taylor, I., and J. Knowelden. *Principles of Epidemiology*. Boston: Little, Brown, 1957.
Thomlinson 1965	Thomlinson, R. *Population Dynamics*. New York: Random House, 1965.
Thompson 1953	Thompson, Warren S. *Population Problems*. New York: McGraw-Hill, 1953.
Tietze 1957	Tietze, C. "Reproductive Span and Rate of Reproduction among Hutterite Women." *Fertility and Sterility* 8:89.
U.N. *DY*	United Nations. *Demographic Yearbook*. 1951–1970. eds. New York.
U.N. 1953	United Nations. Department of Social Affairs. Population Division. *The Determinants and Consequences of Population Trends*. New York, 1953.
U.N. 1956	United Nations. Department of Economic and Social Affairs. *Methods for Population Projections by Sex and Age*. Population Studies, no. 25. New York, 1956.
U.N. 1962	United Nations. Department of Economic and Social Affairs. *Population Bulletin of the United Nations*, no. 6. New York, 1962.
U.N. 1965	United Nations. Department of Economic and Social Affairs. *Population Bulletin of the United Nations*, no. 7. New York, 1965.
U.N. 1966	United Nations. Department of Economic and Social Affairs. *World Population Prospects as Assessed in 1963*. Population Studies, no. 41.
U.N. 1970	United Nations. Department of Economic and Social Affairs. *The World Population Situation in 1970*. Population Studies, no. 48. New York, 1971.
U.N. 1972*a*	United Nations. Department of Economic and Social Affairs. *Statistical Yearbook, 1971*. New York, 1972.
U.N. 1972*b*	United Nations. Population Division. "The World's Million Cities, 1950–1985." Working paper, ESA/P/WP, 45. New York, 1972.
U.S. 1960	United States. Department of Commerce. Bureau of the Census. *Historical Statistics of the United States*. Washington, D.C.: Government Printing Office, 1960.

U.S. 1964	United States. Department of Commerce. Bureau of the Census. *Projections of Population of the USSR, by Age and Sex: 1964–1985.* Washington, D.C.: Government Printing Office, 1964.
USAID 1971	United States. Agency for International Development. Bureau for Technical Assistance. Office of Population. *Population Program Assistance.* Washington, D.C.: Government Printing Office, 1971.
USAID 1972	United States. Agency for International Development. Bureau for Technical Assistance. Office of Population. *Population Program Assistance.* Washington, D.C.: Government Printing Office, 1972.
Vallois 1961	Vallois, H. V. In *Social Life of Early Man,* edited by S. J. Washburn. Chicago: Aldine, 1961.
Wallich 1970	Wallich, H. C. "Population Growth." *Newsweek,* June 29, 1970.
Watt 1971	Watt, K. E. F. *Principles of Environmental Systems.* New York: Macmillan, 1971.
Wattenberg 1970	Wattenberg, B. "The Nonsense Explosion." *New Republic,* April 4 and 11, 1970.
Weintraub 1962	Weintraub, R. "The Birth Rate and Economic Development: An Empirical Study." *Econometrica* 40:812.
Weiss, Koide, and Goldberg 1971	Weiss, H. V., M. Koide, and E. D. Goldberg. "Mercury in a Greenland Ice Sheet: Evidence of Recent Input by Man." *Science* 174:692.
Welch 1964	Welch, B. L. "Psychophysiological Response to the Mean Level of Environmental Integration." *Symposium on Medical Aspects of Stress in the Military Climate.* Washington, D.C.: Walter Reed Army Institute of Research, 1964.
Westoff 1962	Westoff, C. F. In *Research in Family Planning,* edited by C. V. Kiser. Princeton: Princeton University Press, 1962.
Whelpton, Campbell, and Patterson 1966	Whelpton, P. K., A. A. Campbell, and J. E. Patterson. *Fertility and Family Planning in the United States.* Princeton: Princeton University Press, 1966.
WHO 1967	World Health Organization. *Third Report on the World Health Situation, 1961–1964.* Official Reports, no. 155. Geneva, 1967.
WHO 1971	World Health Organization. *Fourth Report on the World Health Situation, 1965–1968.* Official Reports, no. 192. Geneva, 1971.
Winkelstein 1967	Winkelstein, W. "The Relationship of Air Pollution and Economic Status to Total Mortality and Selected Respiratory System Mortality in Man." *Archives of Environmental Health* 14:162.
Wiser and Wiser 1963	Wiser, W. H., and C. V. Wiser. *Behind Mud Walls.* Berkeley and Los Angeles: University of California Press, 1963.
Wyon and Gordon 1971	Wyon, J. B., and J. E. Gordon. *The Khanna Study.* Cambridge, Mass.: Harvard University Press, 1971.
Zacharias, Wurtman, and Schatzoff 1970	Zacharias, L., R. J. Wurtman, and M. Schatzoff. "Sexual Maturation in Contemporary American Girls." *American Journal of Obstetrics and Gynecology* 108:833.

3
Capital Sector

William W. Behrens III and Peter M. Milling

3.1 INTRODUCTION

The quantities and the types of goods, services, and food available to an individual strongly influence his education, values, health, family size, and life style. Each of these personal characteristics in turn influences the mix of goods, services, and investments he is likely to prefer in the future. Our objective in the capital sector was to provide the basic components of a causal model that would project long-term patterns in the global population's access to material goods, services, and food. We were not concerned with interest rates during the next quarter year nor with the level of unemployment next year, but with shifts in productive capability and personal consumption over the next hundred years.

Economists have surpassed all other social scientists in the production and analysis of formal theories, but their attention has been almost exclusively on short-term problems. For example, in response to a survey of U.S. government forecasting activities, members of the Council of Economic Advisers to the U.S. president stated that the council makes no forecasts beyond the next five years (CEQ 1972). Since World3 involves economic phenomena that evolve over periods of thirty to one hundred years or more, most current economic models were of little use in constructing the capital sector. However, there are common patterns in the aggregated relationships among service output, industrial production, food consumption, investment, and material consumption in different economies around the world and over time. Our purpose in Chapter 3 is to depict those patterns and to describe the set of causal relationships that reproduce them in World3.

In the next section of this chapter we present data on the composition of the GNP of various economies over several decades. The data will illustrate the general behavior patterns we captured in the capital sector of World3. Following the description of those patterns, we discuss the concepts and definitions that were employed to formulate the capital sector (section 3.3). This conceptual discussion is followed by a description of the sector's causal feedback-loop structure (section 3.4), and finally by the precise DYNAMO equations used in the model (section 3.5). The chapter closes with a set of simulation runs of the capital sector driven by exogenous values for population, capital allocated to obtaining resources, unemployment, and food per capita.

3.2 HISTORICAL BEHAVIOR MODES

Measures of historical global productive activity must be derived from indices of the productive activities of individual countries. The most widely used national economic index is gross national product (GNP), a monetary valuation of all the material goods, food, and services produced by a country in a year. The ratio of a nation's GNP to its population, its per capita GNP (measured in dollars per person-year), is for many purposes a convenient index for a comparison of the living standards of different countries. Analyses of time-series and cross-sectional data on the magnitude and composition of GNP per capita for many different countries yield the two behavior patterns discussed in this section: exponential growth in total output, and shifting composition of that output.

Growth in GNP and GNP per Capita

In economic data compiled by the World Bank (IBRD 1970), only one country with a population greater than one million people—Yemen—reported a declining gross national product over the period from 1960 to 1968. Fifteen other countries exhibited a declining GNP per capita because their populations were growing faster than their GNPs. The populations of these sixteen countries totaled about 170 million people, less than 6 percent of the total world population. The other 106 countries for which World Bank data are available were at the same time exhibiting growth in GNP per capita at rates up to 19 percent per year. Although there are numerous problems in deriving these statistics, particularly in evaluating output that is not traded for any currency, the overall pattern in the world today appears to be growth in both per capita and total GNP. Figure 3-1 illustrates the recorded growth in GNP per capita for seven nations that may be considered typical.*

Common Evolution in the Composition of GNP

For purposes of international accounting, national GNP statistics are subdivided into mutually exclusive, collectively exhaustive categories. The most commonly used scheme for subdivision is that based on the International Standard Industrial Classification (ISIC) scheme. The nine major ISIC categories are listed in Figure 3-2, along with the nine major subdivisions of the third ISIC category, manufacturing.

By aggregating national data from the ISIC categories in various ways, economists have found similarities in the way the economies of different countries evolve over time. One study divided GNP into three sectors: primary production, industry, and services (Chenery and Taylor 1968). In their study Chenery and Taylor defined the primary sector to include agriculture, mining, forestry, and fishing products; the industry category to include manufacturing, construction, and other material products; and the service category to include all banking, health care, insurance, and other intangible products. When the fraction of GNP in each of these three sectors was related to the total GNP per capita of the country at several points in time during the growth of the economy, a common pattern of evolution was found for all the countries studied: as the total GNP per capita of a country increases, the fraction of the GNP derived from the primary sector declines, the fraction of product from the service sector rises slowly, and the fraction from the industrial sector rises rapidly.

When a country's GNP per capita is between 50 and 100 dollars per year, 50–60 percent of the total GNP is derived from the production of raw materials and food, 10–15 percent arises from industrial production, and the remaining 25–40 percent is

*The wide disparity among growth rates as exhibited in Figure 3-1 indicates that the absolute gap in GNP per capita between the currently industrialized countries and the currently nonindustrialized countries is widening. It has been estimated that the gap in average incomes between the rich and the poor countries was about 1,900 dollars in 1964 and 2,400 dollars in 1970 (Benoit 1972). While the existence of this widening gap does influence international relations, World3 employs globally aggregated data and does not explicitly address this important characteristic of international development.

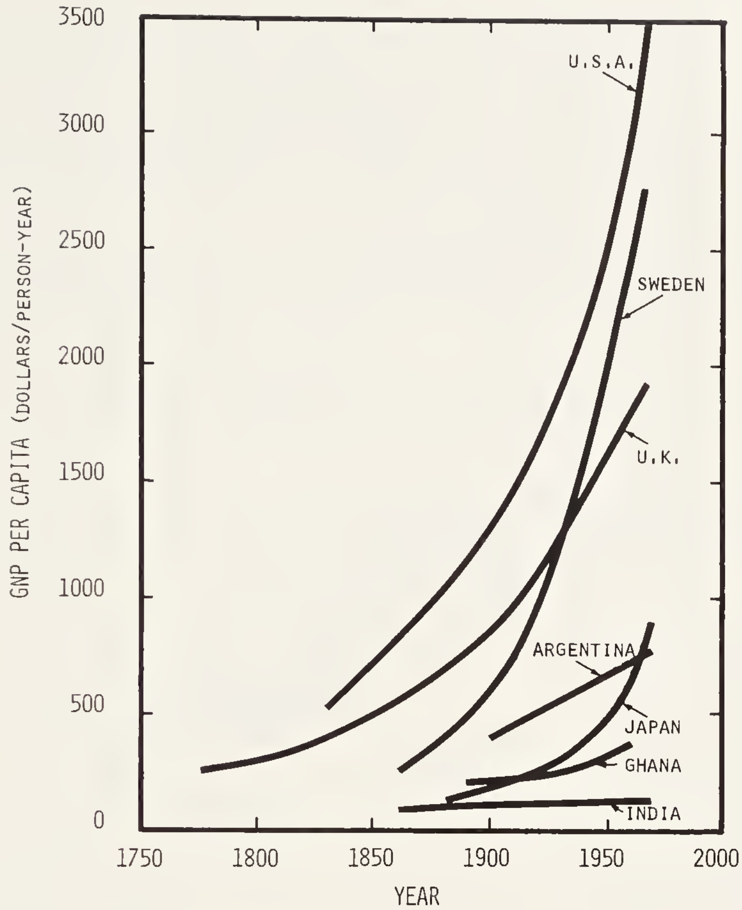

Figure 3-1 Growth in GNP per capita for seven nations
Source: Kuznets 1971.

Code	Classification and Description
1	Agriculture, hunting, forestry, and fishing
2	Mining and quarrying
3	Manufacturing
31	Manufacture of food, beverages, and tobacco
32	Textile, wearing apparel, and leather industries
33	Manufacture of wood and wood products, including furniture
34	Manufacture of paper and paper products, printing, and publishing
35	Manufacture of chemicals and chemical, petroleum, coal, rubber, and plastic products
36	Manufacture of nonmetallic mineral products, except petroleum and coal
37	Basic metal industries
38	Manufacture of fabricated metal products, machinery, and equipment
39	Other manufacturing industries
4	Electricity, gas, and water
5	Construction
6	Wholesale and retail trade, restaurants, and hotels
7	Transport, storage, and communication
8	Financing, insurance, real estate, and business services
9	Community, social, and personal services

Figure 3-2 International Standard Industrial Classification
Source: ISIC 1968.

in the form of services. When a country's GNP per capita is 2,000 dollars per year, only 10 percent of that amount is from the production of raw materials and food, while 40–50 percent is composed of industrial production and 40–50 percent is in the form of services. Although the relative share of the primary sector declines from 60 percent to 10 percent during industrialization, the absolute value of the primary sector's product actually rises with increasing GNP.

Two striking facts about this general pattern are that it has been exhibited by industrialized countries as disparate as the United States, Italy, and Japan and that it seems to characterize both countries that industrialized early in this century and countries that are just now beginning to industrialize. In Figure 3-3A the primary

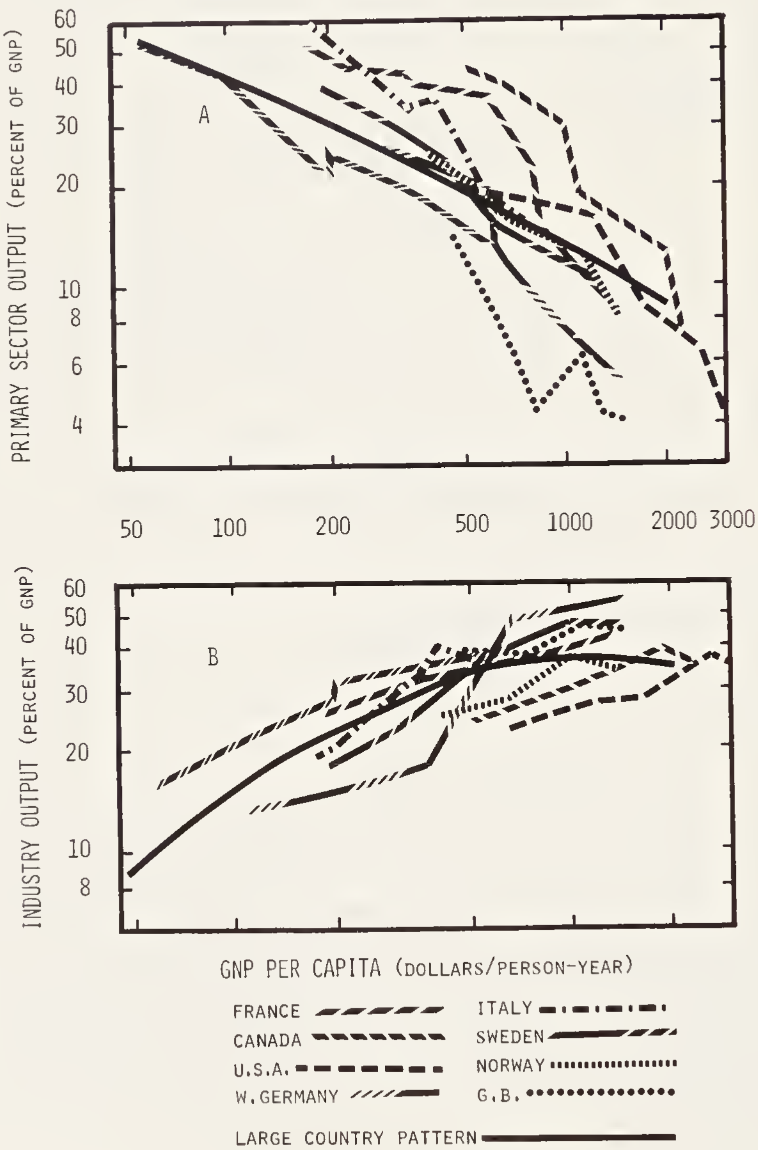

Figure 3-3 GNP per capita versus the contribution of primary and industrial production to total output during the development of nine countries, 1860–1960 (time-series data)

A. Primary share versus GNP per capita

B. Industry share versus GNP per capita

Source: Chenery and Taylor 1968, p. 401.

sector's share of total GNP is plotted against GNP per capita for nine industrialized countries over the period of their industrialization. Primary production falls from 60 percent of GNP to 10 percent or less in each case. Figure 3-3B summarizes the growth in industry's share of total GNP for the same countries. During the period of development, industry's share of each national economy rises from about 15 percent to about 40 percent. Figures 3-4A and 3-4B confirm the generality of this development pattern, showing cross-sectional data relating the primary and industry sector shares of GNP to total GNP per capita at one point in time for nineteen large countries.

In another study, Temin (1967) describes patterns in the sector composition of nine national economies over time. Although Temin included mining products in the industry sector rather than in the primary sector, his data, summarized in Figure 3-5, suggest an evolution pattern similar to that identified by Chenery and Taylor (1968).

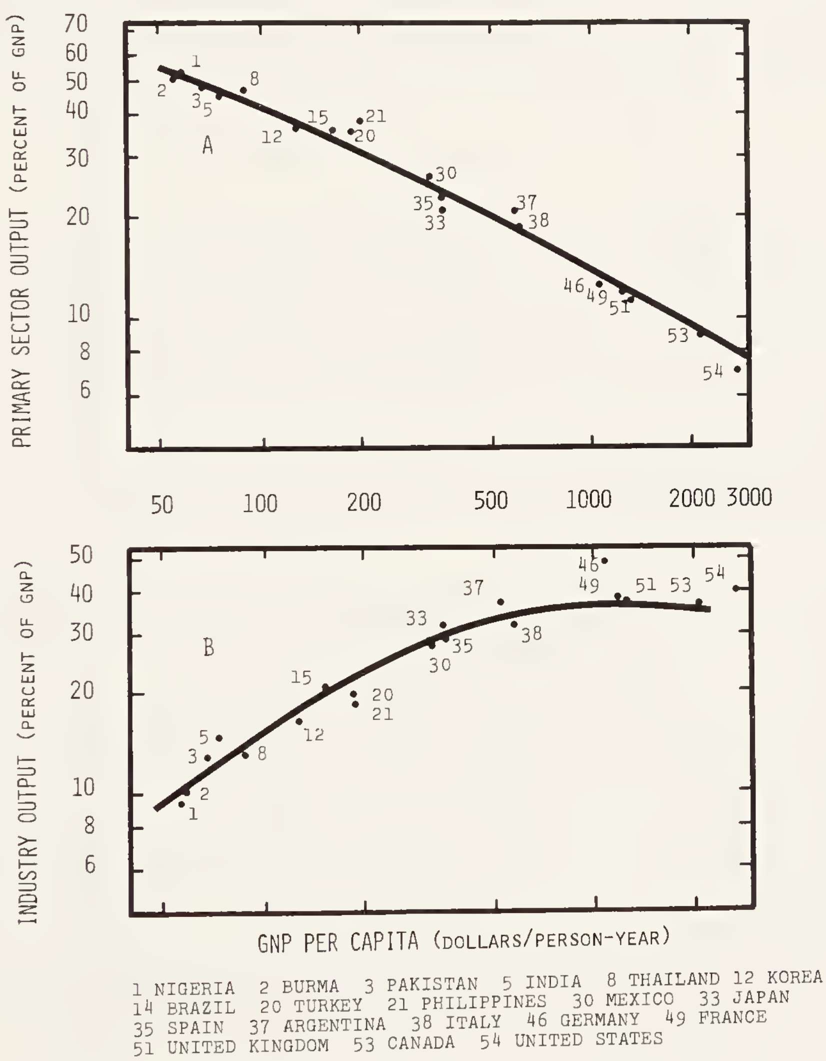

Figure 3-4 GNP per capita versus the contributions of primary and industry production to total output at one point in time for nineteen large countries (cross-sectional data)

A. Primary share versus GNP

B. Industry share versus GNP

Source: Chenery and Taylor 1968, p. 394.

The time trends for the growth in total product and the shifts over time in product composition for a single country can be obtained by combining the data from Figures 3-1 and 3-5. Working with data on Sweden from both sources, it is possible to determine the evolution of that country's economy over the period 1890–1950 (Figure 3-6). Production in the primary sector rose slightly during this period to about 200 dollars per capita, while the industry and service sector products grew from 125 dollars and 200 dollars, respectively, in 1890 to 925 dollars and 875 dollars in 1950. Over different time spans, other industrialized countries have exhibited similar patterns. The regularity of these compositional patterns, despite regional differences in resource endowment, climate, culture, technologies, and other characteristics, points to a set of common changes underlying the development of a country from an agrarian to an industrial and service economy.

The general development patterns just described are quite understandable and are to be expected, so long as most individuals in a society have some influence over the allocation of investments either through free market mechanisms or through political processes. Most human societies share a common set of priorities: first, physiological

Country	1870	1890	1910	1930	1950
Australia	25.5	22.8	26.9	22.5	18.3
Canada	44.0	35.2	27.6	13.1	14.0
France	34.8	30.2	28.4	22.4	16.0
Germany	25.5	21.4	18.2	13.4	10.9
Italy	57.6	50.4	45.0	33.8	35.5
Sweden	39.4	32.0	23.6	14.4	10.4
United Kingdom	14.2	8.6	6.0	4.1	6.2
Japan	—	53.4	41.7	21.2	24.6
United States	—	16.6	17.0	8.7	7.9

A. The relative share of agriculture, forestry, and fishing in national product in current prices (percentages)

Country	1870	1890	1910	1930	1950
Australia	27.1	28.4	26.6	25.4	39.1
Canada	22.9	29.5	30.4	31.7	40.2
France	34.1	36.7	40.1	36.5	33.0
Germany	26.3	27.4	39.2	42.0	47.9
Italy	19.3	20.1	24.8	31.4	39.8
Sweden	17.7	22.6	33.2	38.7	46.3
United Kingdom	38.1	38.4	37.0	39.0	44.9
Japan	—	15.9	21.2	27.0	32.2
United States	—	24.9	26.5	25.7	36.7

B. The relative share of manufacturing, mining, and construction in national product in current prices (percentages)

Figure 3-5 Shifts in the composition of national product in nine nations, 1870–1950
Source: Temin 1967.

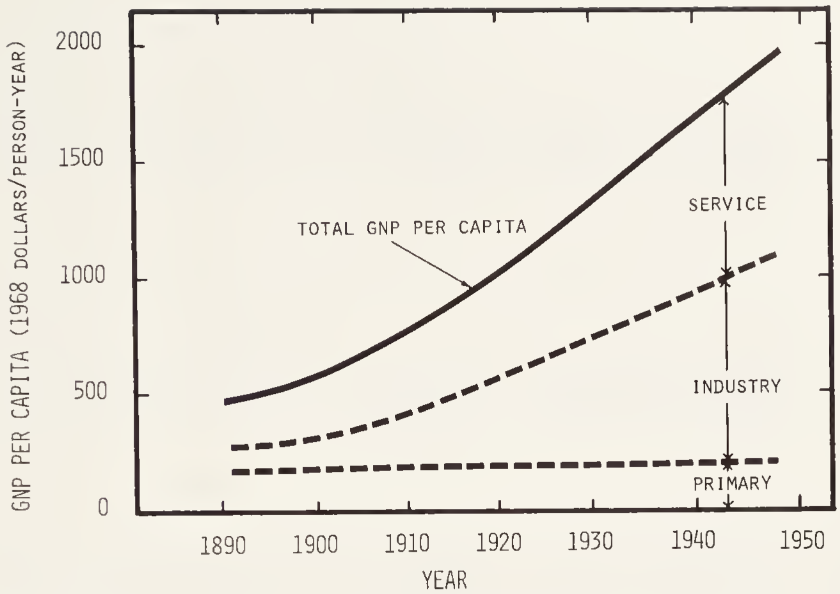

Figure 3-6 Growth in total product and shifts in product composition, Sweden, 1890–1950

Sources: Figures 3-1 and 3-5.

sustenance; then physical comfort; and finally, intellectual or spiritual fulfillment. Until nutrition is raised to survival levels there is little interest in housing or education. Once the agriculture sector has grown sufficiently to provide basic food needs, more attention can be placed on housing, clothing, and other necessities for physical comfort. With the physical needs met through the expansion of the industrial sector, emphasis may shift to increasing services. This hierarchy of needs, which has been recognized by social scientists (for example, Maslow 1954), would suggest that the development patterns found by Chenery and Taylor (1968) and Temin (1967) are fundamental to man's economic systems.

There is nothing immutable about the precise sectoral ratios observed on the average in the past. Societies with political dictatorships or centrally planned economies could conceivably shift the ratio of industrial production to food or service output typically observed at any level of GNP per capita. For example, it appears that Japan and the USSR have increased the relative emphasis on industrial production. China appears to have higher service levels than would be implied by historical relationships in other countries. Nevertheless, given the fundamental nature of the hierarchy of man's needs, it seems that large deviations from the general growth patterns described by Chenery and Taylor (1968) and Temin (1967) would be possible only after a significant change in social values.

3.3 BASIC CONCEPTS

Because we wished to develop a model from causal rather than correlational relationships, it was not sufficient merely to observe historical patterns in the magnitude and composition of national products. We had also to understand the functioning of the

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		1967					
Country	GNP per Capita (1968 dollars)	GNP (national currency)	Depreciation (national currency)	Percentage of Output in Agriculture	Percentage of Output in Industry	Percentage of Output in Services	Consumption as a Percentage of GNP
Algeria	220						
Argentina	820	4,650		16	38	46	80
Australia	2,070	21,600	2,158	9	39	52	77
Austria	1,320	241	31	9	47	44	74
Belgium	1,810	848	92	5	39	56	77
Bolivia	150	8,707	488	20	35	45	91
Burma	70	8,586	407	34	12	54	85
Brazil	250	282					86
Cambodia	120						
Canada	2,460	54,200	6,962				76
Ceylon	180	8,368	473	38	17	45	87
Chile	480	29,500	2,933	9	39	52	86
Colombia	310	77,400	7,111	31	24	45	83
Congo	90	460					
Costa Rica	450	4,166	270	26	22	52	86
Denmark	2,070	82,600	6,784	9	38	53	80
Ecuador	220	22,800	1,150	33	24	43	90
El Salvador	280	2,053	110	28	21	51	88
Finland	1,720	26,700	2,750	17	36	47	73*
France	2,130	571	62	7	46	47	73
West Germany	1,970	486	55	4	48	48	75
Greece	740	178	13	24	24	52	85
Guatemala	320	1,453	68				90
Haiti	70						
Honduras	260	1,096	46	39	21	40	86
India	100						
Iraq	260	883	45				

Israel	1,360						79
Italy	1,230	38,500	3,615	13	36	51	82
Jamaica	460	341	26	11	35	54	
Japan	1,190		5,603				63
Kenya	130	407		58	17	25	82
Korea (Republic of)	180	1,120	74	35	24	51	91
Malaysia	330						
Mexico	530						84
Netherlands	1,620	74,100	7,210	7	40	53	74
Nigeria	70						87
Norway	2,000	54,400	7,646	7	35	58	70
Pakistan	100	61,600	4,202	47	16	37	87
Paraguay	230	62,020	4,382	33	20	47	87
Peru	380						83
Philippines	180	21,800	2,290	33	23	45	87*
Portugal	460	120	7	20	40	40	83
Puerto Rico	1,340	3,537	267	6	33	61	92
Rhodesia	220	372		26	30	44	84*
Spain	730	1,514	108	16	33	51	80
Taiwan	270	124	9	24	28	48	77
Thailand	150	106	9	30	21	49	75
Tunisia	220	454	24	25	29	46	90*
Turkey	310	927	5	34	25	41	85*
United Kingdom	1,790	34,400	3,148	3	42	55	81*
United States	3,980	803	79	3	34	63	82*
Uruguay	520	149	6	12	30	56	87
Venezuela	950	39,500	3,819				77

*For countries where foreign trade is a significant fraction of GNP, GDP was used to calculate the fraction allocated to consumption.

Figure 3-7 Economic statistics for fifty-four countries
Source: U.N. 1969.

productive system underlying those patterns. This section describes the fundamental concepts and definitions we found useful in modeling the operation of the global productive system in the capital sector of World3.

Classification of Capital and Output

For our study it was important to divide the constituents of GNP into groups of economic activities that have similar effects on the other sectors of World3—pollution, resources, and population. In World3 the criteria used to disaggregate GNP were the degrees to which an economic activity depletes nonrenewable resources and generates persistent pollution (as defined in Chapters 5 and 6). Specifically, we identified four categories of output:

1. Service output, the intangible component of GNP, is composed of activities that promote the population's health, education, culture, and so on. The utilization of service capital to produce service output does not deplete resources or generate persistent pollution.*
2. Agricultural output is the portion of GNP composed of those activities required to produce, process, and distribute food. The utilization of agricultural capital to produce agricultural output does not deplete nonrenewable resources but may generate persistent pollution.†
3. Production of nonrenewable resources is the component of GNP composed of activities needed to locate, extract, process, and distribute minerals and fuels. The capital required to obtain resources is considered a part of industrial capital.
4. Industrial output is composed of the total global stream of manufactured goods. The utilization of industrial capital to produce industrial output both depletes resources and generates persistent pollution.

The four categories are not perfectly distinct from each other. For example, any item of capital stock constituting social infrastructure, like a road, contributes to each of the four categories. However, most productive stocks and most activities can be related to one of the three capital categories. For example, in the year it is produced, an airplane intended for civilian transport appears as a component of industrial output. The airplane's manufacture causes some pollution generation and resource consumption, part of the total pollution generation and resource depletion caused by that year's industrial output. After construction the airplane is added to the service capital stock, where its use contributes to service output during its lifetime. The mere existence of the airplane does not cause pollution; only if the airplane consumes fuel (or spare parts or tires) does it generate pollution and consume resources. The fuel consumed by the airplane is produced by a fuel oil refinery whose

*The manufacture of service capital is an industrial process and does therefore cause both resource depletion and pollution.

†The production of agricultural chemicals and equipment does deplete resources and cause pollution. This production is included in World3 as a component of industrial output. Thus fertilizer factories are part of industrial capital, but the fertilizer they produce is invested in the agriculture sector as a part of agricultural capital. The use of capital in the agriculture sector may cause significant deterioration in the globe's air, water, and soil resources.

output may be consumed by homes, factories, airplanes, and other users. The oil refinery is considered part of industrial capital, and its oil production is part of industrial output.

Since the process of constructing buildings to house educational or medical facilities may cause some pollution, construction facilities are treated as part of industrial capital. But little pollution and resource depletion are associated with the services provided by those buildings once they become part of the service capital stock. Similarly, the operation of a pesticide plant consumes resources, so the plant is categorized as part of industrial capital. Persistent materials introduced into the environment through the manufacture of pesticides are classed as industrial pollutants. Pesticides are agricultural capital. When this capital is used for agricultural output, the pesticides introduced into the ecosystem are classified as persistent pollution from agriculture.

While the stock of nonrenewable resources is calculated in a separate sector of World3, the capital allocated to obtaining resources (oil wells, mining equipment, smelters) is defined as part of the total industrial capital stock. Thus each of the nine major ISIC economic output divisions in Figure 3-2 is associated with a particular capital stock in World3. In our model the agriculture sector provides most of the output in the first ISIC division: agriculture, hunting, forestry, and fishing. The World3 industrial capital stock provides the output in ISIC divisions 2 through 5: mining and quarrying; manufacturing; electricity, gas, and water; and construction. Service capital in the model is associated with the activities listed under ISIC divisions 6 through 9: wholesale and retail trade, restaurants and hotels; transport, storage, and communication; financing, insurance, real estate, and business services; and community, social, and personal services. We have used these operational definitions of agriculture, industry, and services to convert the ISIC data presented by the United Nations (U.N. 1969) into a set of statistics on the economies of fifty-four countries. The data are presented in Figure 3-7 and will be used throughout this chapter to estimate the capital sector coefficients.

Columns 2, 3, 4, and 8 of Figure 3-7 are taken directly from the U.N. publication. Columns 5, 6, and 7 were obtained by summarizing the appropriate ISIC categories to obtain the total value of the agriculture, industry, and service components of GNP for each country. Each component of GNP (as defined in World3) was then divided by the country's total GNP to determine the relative share of each sector.

Basic Flows in the Productive System

Given the fourfold division of output we defined, it is possible to construct the summary flow chart of the goods and services involved in global production processes shown in Figure 3-8. (This figure would also apply to a single nation if exports and imports were added.)

The three capital stocks labeled agricultural capital, service capital, and industrial capital in Figure 3-8 represent the accumulated supplies of material equipment

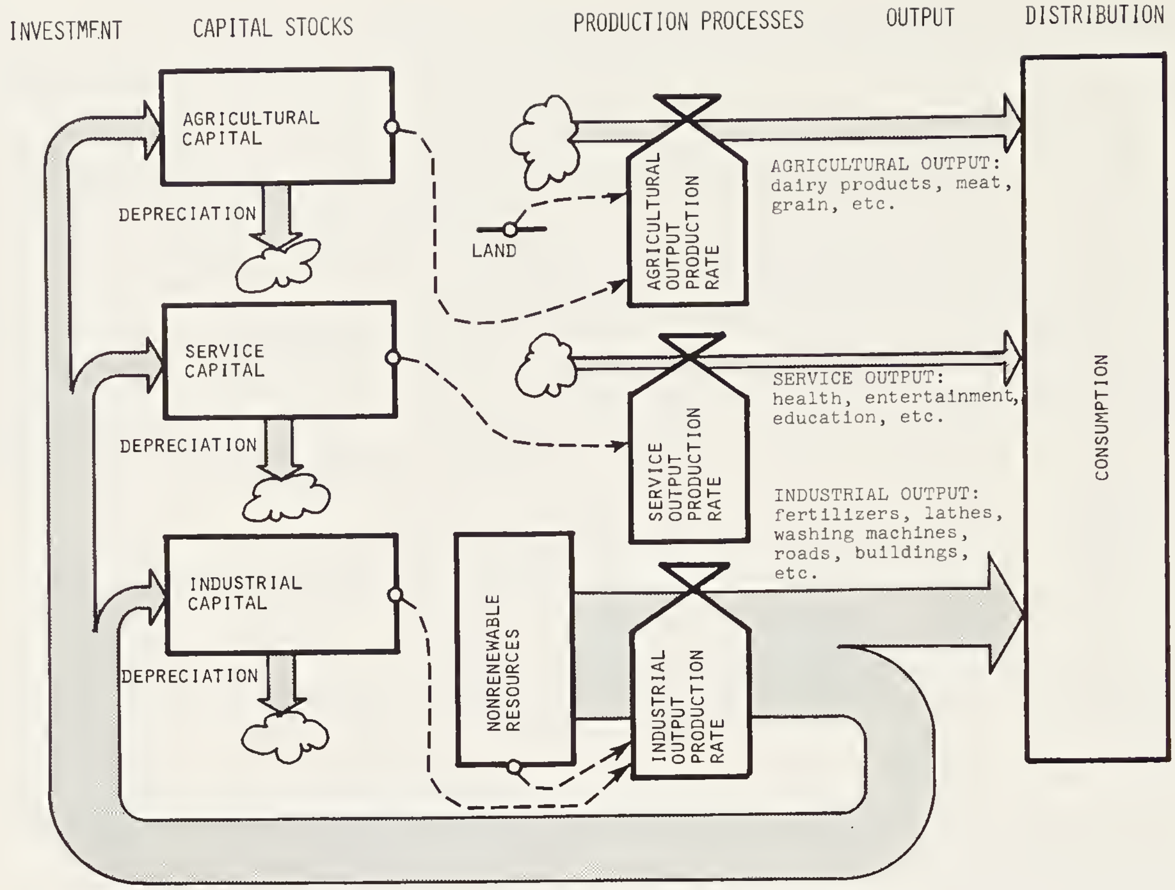

Figure 3-8 Capital stocks and output flows in the global economy

that can be used to produce goods and services. These stocks, with the addition of land and nonrenewable resources, can produce three types of output: agricultural output, which is a flow of edible foodstuffs; service output, a flow of social or personal services that are intangible; and industrial output, a flow that converts resources into material goods.

For the model we defined two uses for the output of the productive process: consumption and investment. All output that disappears within one year of its generation is treated as consumed. Thus all service outputs and all agricultural outputs are consumed (we ignored inventories of foodstuffs). The flow of material goods comprising industrial output may be either consumed or invested in the service, agriculture, or industrial sectors. The designation of the investment depends on the function it fulfills. An airplane could be classified as an investment in service, industrial, or agricultural capital if it were used for holiday tours, transporting transistors, or spraying crops, respectively. Lightbulbs are an example of industrial output that is defined as consumption. Industrial output in the form of household washing machines becomes investment in service capital, tractors an investment in agricultural capital, and coal excavators or lathes an investment in industrial capital.

Measurement of Capital and Output

So far we have discussed the production processes in physical terms, since World3 is primarily a model of physical flows. Because the model is highly aggregated, it was necessary to define some common measure for the diverse forms of capital and output. To be consistent with the four sectoral definitions described earlier, it was most convenient to use a measure that reflected a product's material content and its potential for generating pollution. It was also necessary, however, to employ a measure that would allow comparison with the financial statistics used by economists and recorded in the historical patterns of Figures 3-1, 3-3, 3-4, and 3-6. Market price itself is not an appropriate measure for our purposes, however, since the price of a product may fluctuate even though its material content and pollution potential remain the same. We thus chose to define a "dollar" measure for use in World3, making it subject to the following conditions:

1. A dollar is a material unit, not a monetary unit. A dollar of capital in the model is the average unit of capital that could have been purchased for one dollar in 1968. As a consequence of this definition, the model's capital sector is directly related to global capital and production statistics only in the year 1968.
2. Given appropriate capital-output ratios, a dollar of service or industrial output is a unit composed of the average bundle of services or material goods received for the equivalent of one U.S. dollar around the world in 1968. Food output is not measured in dollars but in vegetable-equivalent kilograms. The production of nonrenewable resources is measured in resource units. Thus there is no simple relationship in the model between dollars of output and the gross global income.
3. A dollar of capital represents the same amount of physical capital at any point during the simulation. Even if price and inflation were represented in World3, the dollar valuation of each unit of capital would not vary over time.

Use of Industrial Output Rather than GNP

Numerous studies have revealed that increases in GNP per capita are correlated in most countries with decreased demographic fertility, increased resource consumption, shifting food preferences, increased pollution generation, increased energy consumption, and shifts in the values of other important social and economic factors. Increased wealth does not cause all the social changes revealed in these studies. The correlation is observed because societies that have generated high average personal incomes have generally been characterized by the set of Western social norms, family structures, educational practices, technologies, and economic institutions that do cause decreased fertility, increased resource consumption, and so on. We concluded that industrial output per capita is superior to GNP per capita as an index of the changes in institutions, technology, and personal values that cause the secular trends often correlated with GNP per capita. Therefore, industrialization, measured by average industrial output per capita, is our general term for this total package of social changes.

The inadequacy of GNP per capita as a measure of social change is nicely illustrated by several oil-exporting countries where the typical historical relation between GNP per capita and industrial output per capita is not observed. Although their per capita GNP figures are comparable to those in the West, their industrial output per capita is low. Significantly, their social statistics (for example, crude birth rate, literacy, and mortality) and institutional forms are characteristic of much poorer nations.

Given the data in Figures 3-3 and 3-4, one can infer the approximate average industrial output per capita IOPC that has historically corresponded to any GNP per capita. Thus the empirical relationship of any factor, such as fertility, with GNP per capita can be converted to a function of IOPC. This conversion was employed throughout the model.

While one could weight and sum the four components of output in the model—services (1968 dollars per year), industrial output (1968 dollars per year), food (vegetable-equivalent kilograms), and resources (resource units per year)—to derive a crude measure of total world output, this process does not appear to be useful in understanding the causes and consequences of long-term growth in population and material output. Short-term governmental decision making is strongly influenced by forecasts of a policy's impact on GNP. However, both the market prices and the relative magnitudes of the components of the globe's GNPs will change so radically over the next century that little useful information is gained by attempting to derive aggregate product figures from the model's output. Thus no measure of gross world product is calculated in World3.

Exclusion of Labor

It appears that there has always been unemployment. The global stocks of industrial, service, and agricultural capital have never provided full-time jobs to the entire global work force. While there have been local shortages of workers skilled in specific trades, growth in the capital stock tends to occur in those sectors where labor is adequate. Thus we assumed that labor constraints will not limit the total output that can be produced by the various capital stocks over the next century. As a consequence, the production functions in World3 do not include labor as a causal factor. The ratio of total population to output will influence the composition of output. That relationship is included in World3.

It is likely that a severe decline in population would create labor shortages and thus decrease the efficiency of the global industrial capital plant. For this reason, there is a simple labor sector in World3 that affects the model's behavior only if the population declines faster than the industrial capital base. (This effect of labor will be described later in this chapter.) During the period of growth and equilibrium in World3, however, there is no substitution between capital and labor. The World3 industrial production function is a simplified version of the type developed by Harrod (1948) and Domar (1957) and discussed in detail by Allen (1967). It has fixed input coefficients:

$$Q = \min\left(\frac{\text{capital}}{\text{capital-output ratio}}, \frac{\text{labor}}{\text{labor-output ratio}}\right)$$

Because of the social implications of unemployment, we consider the exclusion of labor to be one of the least satisfactory simplifications of the global model. Although the inclusion of an explicit labor force and a representation of the causes and consequences of unemployment are unlikely to change the basic behavior modes of

World3, these additions would make the model much more relevant to studies of social welfare and political stability. Global unemployment, which is an immense problem today, is expected to worsen over the next several decades. It would therefore be useful to extend the model to include the causal mechanisms in which unemployment is involved.

Depreciation of Capital

As industrial capital is used to produce output, its productivity gradually decreases. Buildings deteriorate and equipment wears out. In calculating the value of an organization's assets, accountants recognize this loss in productive efficiency by subtracting an annual depreciation from the value of each organization's capital. One computational method for determining the magnitude of the depreciation employs the concept of a ''declining balance'' of capital. Each year a certain percentage, related to the lifetime of the capital, is deducted from the balance of capital remaining. The result is an exponential decline in the calculated value of each unit of capital. The relationships among the initial value, or purchase price, of a capital unit, its expected lifetime, and the value assigned to the capital unit over time are shown in Figure 3-9. For comparison, Figure 3-9 also illustrates the value over time of a capital unit that does not depreciate until it is discarded at the end of its productive lifetime.

In most cases the productivity of capital deteriorates through use. Moreover, some capital is discarded prematurely while other capital is used long beyond the period of use characteristic of items in its class. Thus the declining-balance approach appeared to be appropriate for use in World3. We approximated the depreciation of each capital stock by subtracting annually an amount equal to the quotient of capital and average lifetime of the capital (quantity of capital/average lifetime of capital).

If we combine in one causal structure the concept of declining-balance depreciation, our definitions of four capital and output categories, our emphasis on physical rather than financial flows, and a simple Harrod-Domar production function, it is possible to explain the two behavior modes—growth and shifting output composition—that characterize the global economy.

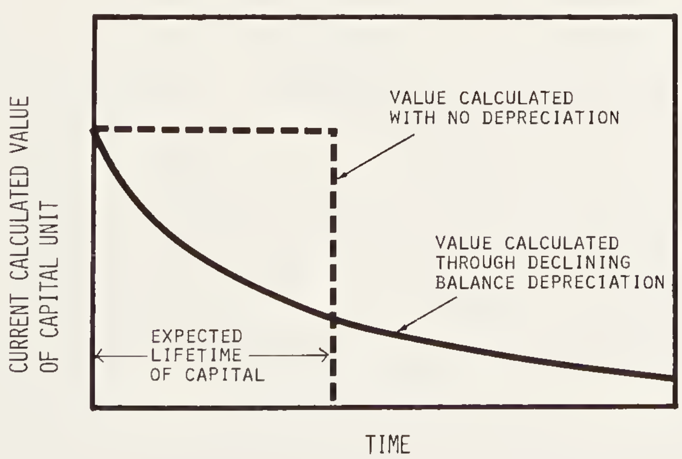

Figure 3-9 The current value of capital as a function of time, the capital's initial value, the expected lifetime of the capital, and the depreciation method

3.4 CAUSAL STRUCTURE

In the real world the relative fractions of output allocated to consumption or to investment in the agriculture, service, and industrial sectors are determined by market mechanisms and by political processes. Presumably the allocation is based in part on some assessment of the marginal utilities of additional units of output in each of the four categories. Because we are interested only in the gross sectoral composition of output and because the details of the investment process have led to the same development pattern in most countries, we chose not to model the detailed structure of investment decisions. Instead, we incorporated into the capital sector an allocation mechanism that allows the economy in the model to reproduce any specified development pattern.

The allocation mechanism involves one positive feedback loop that can lead to various rates of growth in industrial capital and output. Four negative loops influence the gain of the positive loop by diverting variable amounts of industrial output to the service and agriculture sectors. The principal elements constituting these loops are portrayed in Figure 3-10.

The relationships constituting the positive feedback loop in the capital sector are emphasized with heavy lines in Figure 3-10. As industrial capital increases, the industrial output rises. With increased industrial output, the industrial capital investment rate may increase, raising the industrial capital stock even more. The gain around this positive loop, hence the determinant of whether and how fast the industrial capital stock grows, is influenced in part by the fraction of industrial output allocated to capital investment. This fraction varies inversely with the fractions of industrial output allocated to services, agriculture, and consumption.

$$\text{FIOAI} = 1.0 - \text{FIOAS} - \text{FIOAA} - \text{FIOAC},$$

where

FIOAI = fraction of industrial output allocated to industry
FIOAS = fraction of industrial output allocated to services
FIOAA = fraction of industrial output allocated to agriculture
FIOAC = fraction of industrial output allocated to consumption

The fractions of industrial output allocated to services and to agriculture depend on the level and composition of societal demand—a composition that shifts as industrial output grows. We call the aggregate demand functions the indicated service and food outputs per capita and express them as functions of the industrial output per capita. Many conceivable relationships between industrial output per capita and the indicated service and food outputs per capita could be postulated and incorporated into World3. We based the relationships in the standard version of World3 (Figure 3-11) on the development patterns discovered by Chenery and Taylor (Figures 3-3 and 3-4). Figure 3-11 was obtained from the historical data of the earlier two figures by simply converting each GNP figure to the figure for industrial output per capita with which Chenery and Taylor show it has traditionally been associated.

The fractions of industrial output allocated to services and to agriculture depend on the ratio of the actual and the indicated output levels in the respective sectors.

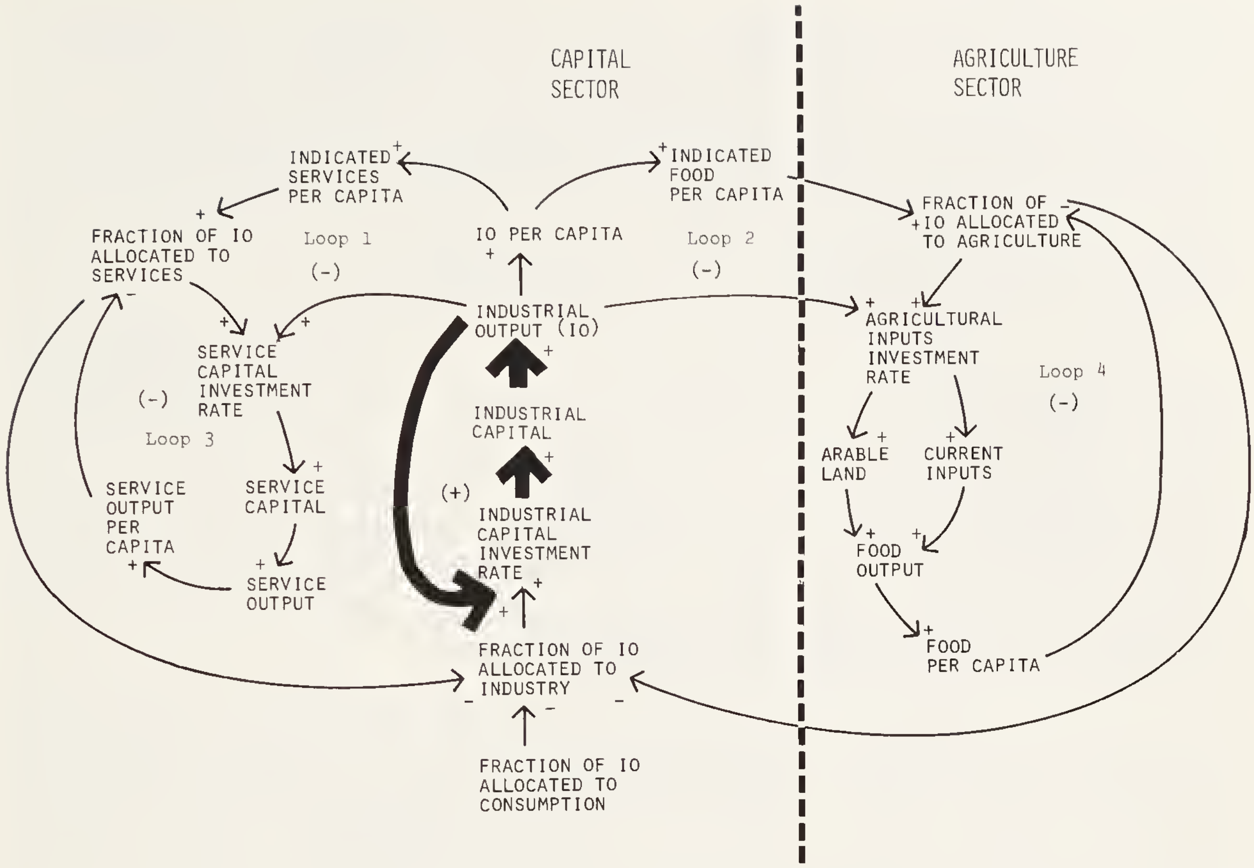

Figure 3-10 The causal relationships that can produce any specified development patterns

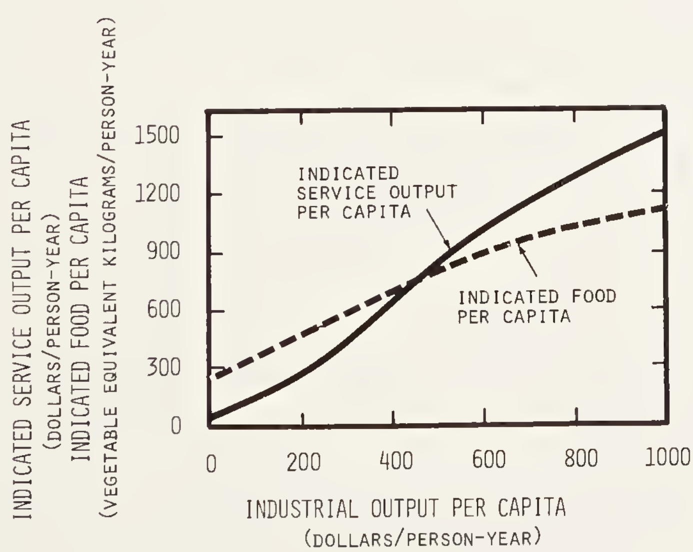

Figure 3-11 Standard form of the relationship between industrial output per capita and indicated service and food outputs per capita

When the ratio of actual to indicated output per capita is less than 1.0, for example, when fewer services are available than desired by the population at their current level of industrialization, the fraction of industrial output per capita allocated to services is increased. As a result, investment in services rises, increasing the level of the service capital stock and the amount of services produced. If the ratio of actual to indicated services is equal to or is greater than 1.0, the current fraction of industrial output allocated to services is maintained or is reduced, respectively.

Loop 1 of Figure 3-10 is composed of seven causal relationships that influence the amount of investment available to the service sector. As the industrial capital grows, industrial output increases. Increased output raises the industrial output per capita, which in turn raises the level of services indicated per capita and thus increases the fraction of industrial output allocated to services. As the fraction of industrial output invested in services increases, the fraction of output left for reinvestment in the industrial sector decreases, tending to counteract the initial rise in the industrial capital stock. An analogous set of relationships shown in loop 2 governs the fraction of industrial output allocated to agriculture.

Loop 3 is composed of five principal elements that moderate the change in the fraction of industrial output allocated to services. As that fraction increases, the investment in service capital increases, leading to growth in the service capital stock and thus to increased service output. For constant population the increase in service output leads to increased service output per capita. If the actual service output per capita increases, the fraction of industrial output allocated to services tends to decrease.

The elements in loop 4 are analogous to those in loop 3; they serve to moderate changes in the fraction of industrial output allocated to agriculture. There is one difference between the functions of loops 3 and 4. The industrial output allocated to services is employed only to increase the service capital stock. Industrial output allocated to the agriculture sector may be used either in the development of additional arable land or in raising the capital employed on the current land stock. However, either use serves to increase food output and, ultimately, to decrease the fraction of industrial output allocated to agriculture.

The capital sector contains only the endogenous determinants of service and industrial output. All the elements included in the sector are illustrated in Figure 3-12. The factors governing the use of industrial output to increase the stock of arable land and to increase land yields are discussed in the agriculture sector of the model, Chapter 4.

The more detailed representation of the causal relationships in the capital sector of the model, shown in Figure 3-12, supplements the relationships drawn in Figure 3-10 with two minor negative depreciation loops; the service and industrial capital-output ratios; and the variables outside the sector that influence or are influenced by the relationships within the sector. The depreciation loops have the implicit goal of decreasing the level of capital to zero. As the capital stock increases, the amount of capital depreciating each year also increases, counteracting the initial rise in capital. Of course, so long as investment is greater than depreciation the capital stock will

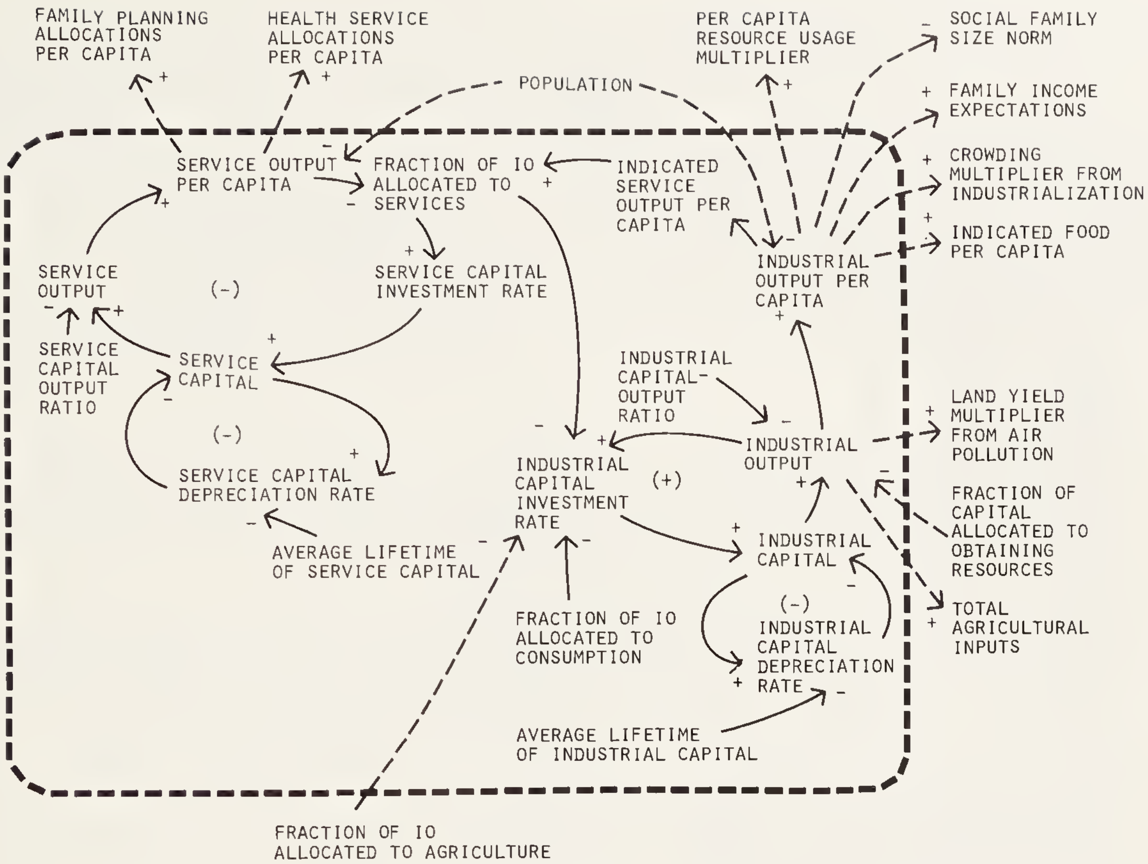

Figure 3-12 Causal-loop diagram of the capital sector

increase. The capital-output ratios simply indicate the quantities of capital required to produce one dollar of industrial and service output per year. Because the size of the labor force does not affect the level of industrial output during the growth phase of the World3 simulations, it is not represented in the causal-loop diagram.

It is in the formulation of capital investment that we departed furthest from our goal of representing the causal mechanisms underlying material and demographic growth. A causal representation of investment based explicitly on the diminishing returns to increased output in each sector and on political pressures would be useful for many purposes. Such a representation would probably also introduce additional short-term negative loops in the capital sector. We would not expect these short-term loops to change general long-term behavior modes, since the latter are governed by processes with very long time constants. However, the short-term causal loops would stabilize the model's behavior for a wider variety of coefficient values. Adding these influences on investment is an important goal for future extensions of the model.

Having described in general terms the investment allocation mechanisms employed in the model, we turn now to a description of the precise DYNAMO equations used to incorporate the causal relationships in the capital sector of World3.

3.5 DESCRIPTION OF EQUATIONS

Since the agriculture sector is described separately in Chapter 4, only the data and assumptions underlying the equations of the industrial and service sectors are discussed here. The DYNAMO flow diagram of these equations and their interfaces with other sectors of the global model are shown in Figure 3-13. The capital sector is composed of six dynamic substructures:

1. The current values of the stocks of industrial and service capital are computed by integrating the difference between their respective investment and depreciation rates.
2. The industrial output is found by dividing the stock of industrial capital not allocated to obtaining resources by the industrial capital-output ratio. The service output is calculated by dividing the total service capital stock by the service capital-output ratio.
3. A constant fraction of the industrial output is consumed each year and does not further influence any other model variable. The rest of the industrial output is considered to be capital goods, which are allocated among service capital investments, agricultural investments, and industrial capital investments.
4. The computational allocation of the industrial output among its different uses depends on the level of industrialization reached by the society as measured by the industrial output per capita.
5. The current total number of jobs in the industrial sector is computed by multiplying the total industrial capital by the number of jobs per industrial capital unit at the current level of industrial output. The current total number of jobs in the service sector is computed similarly. The number of jobs per hectare of arable land is a function of the capital inputs per hectare. The total number of agricultural jobs is the product of arable land and jobs per hectare.
6. The labor-capital ratio does not influence output under normal circumstances. Only when the size of the labor force is very small relative to the capital stock will industrial and service outputs be less than those suggested by the respective capital stocks and capital-output ratios.

The industrial output per capita IOPC is the central element of the capital sector with links to nearly every other sector of World3. We thus start the equation descriptions with this variable and work back through the other elements of the capital sector.

Industrial Output per Capita IOPC

```
IOPC.K=IO.K/POP.K                                          49, A
    IOPC    - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                PERSON-YEAR)
    IO      - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    POP     - POPULATION (PERSONS)
```

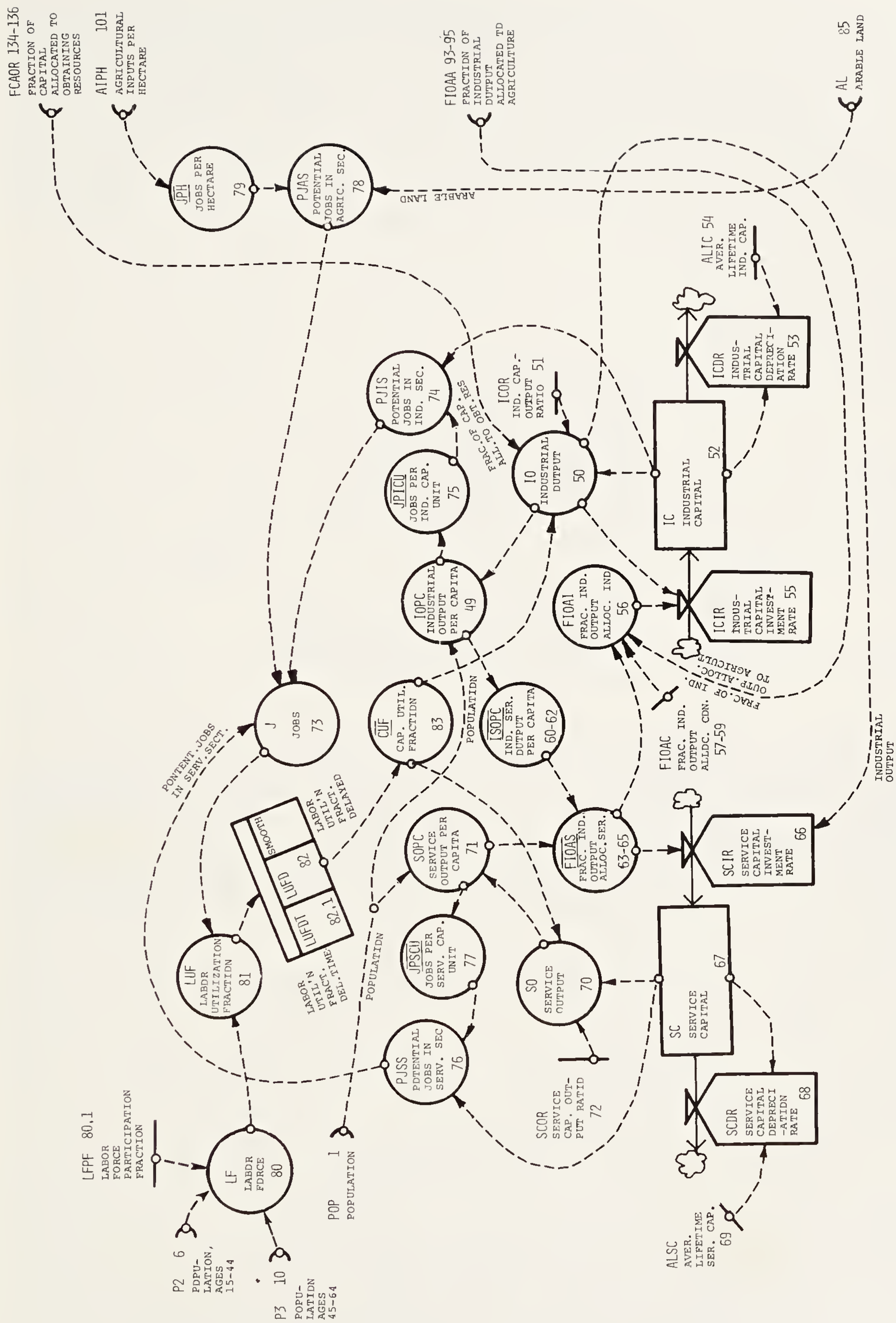

Figure 3-13 DYNAMO flow diagram of the capital sector

The industrial output per capita IOPC is obtained by dividing the current industrial output IO by the current population POP. This variable, measured in dollars per person-year, is an indication of the average amount of material goods available to each member of the population for consumption or investment. It has an impact on all other sectors of World3. The distribution of industrial output across the population is not reflected in the simple calculation of IOPC. As described in Chapter 2 in conjunction with the lifetime multiplier from food LMF, different global distributions of IO can be represented implicitly through changes in the numerous model relationships that depend on IOPC.

Industrial Output IO

```
IO.K=(IC.K)(1-FCAOR.K)(CUF.K)/ICOR.K                    50, A
    IO     - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    IC     - INDUSTRIAL CAPITAL (DOLLARS)
    FCAOR  - FRACTION OF CAPITAL ALLOCATED TO OBTAINING
               RESOURCES (DIMENSIONLESS)
    CUF    - CAPITAL UTILIZATION FRACTION
               (DIMENSIONLESS)
    ICOR   - INDUSTRIAL CAPITAL-OUTPUT RATIO (YEARS)

ICOR.K=CLIP(ICOR2,ICOR1,TIME.K,PYEAR)                   51, A
ICOR1=3                                                 51.1, C
ICOR2=3                                                 51.2, C
    ICOR   - INDUSTRIAL CAPITAL-OUTPUT RATIO (YEARS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    ICOR2  - ICOR, VALUE AFTER TIME=PYEAR (YEARS)
    ICOR1  - ICOR, VALUE BEFORE TIME=PYEAR (YEARS)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
```

The fraction of capital allocated to obtaining resources FCAOR (described in Chapter 5) is subtracted from the total industrial capital IC to leave in the calculation of output only the capital that is directly involved in the production of finished industrial goods. Industrial output is then calculated by dividing the remaining industrial capital, (IC)(1−FCAOR), by the industrial capital-output ratio ICOR. For reasons described later, we made the industrial capital-output ratio ICOR a constant with a normal value of 3.0. The industrial output thus calculated is that available through full utilization of the capital. If there were a sudden and serious shortage of labor, not all the capital could be utilized. The industrial output would then be less than that possible with full use of the industrial capital plant. The capital utilization fraction CUF varies between zero and 1.0 and is a crude measure of the impact of a labor shortage on industrial production. It is described in section 3.6. Under most circumstances it will have a value equal to 1.0 and thus no influence on IO.

Two assumptions about the industrial capital-output ratio ICOR are important: its specification as a constant rather than a variable, and the choice of its specific value, 3.0 years. Economic theory defines "capital deepening" as the process of accumulating capital goods faster than labor (Samuelson 1970, p. 719). An increase in the amount of capital per capita is rough evidence of capital deepening. When it occurs, as it has throughout the world over the last seventy years, one would normally expect the marginal productivity of capital to decrease (that is, the capital-output ratio to increase) so that each additional unit of capital would contribute proportionately less output. If capital did act in accordance with the law of diminishing returns, the relationship between industrial capital IC and industrial output IO would be that shown in Figure 3-14, curve A. As the marginal return to additional capital decreases, each unit added to the capital stock produces less additional output. Total output, as represented by curve A, thus moves toward some horizontal asymptote. When additions to the capital stock produce no increase in output, the marginal capital-output ratio is effectively infinite.

Curve B of Figure 3-14 represents the case in which the capital-output ratio remains constant, so that total output is directly proportional to total capital. In a period of capital deepening, the capital-output ratio can stay constant only if technical advances, improvements in the productive efficiency of new capital, are great enough to offset decreasing returns to scale. If constant returns to scale are observed, technical progress is filling the gap between curve B and curve A.

Economists disagree over whether technological advance in the means of production has in fact offset the tendency toward diminishing returns. Kuznets suggests that the reproducible (that is, physical machinery) capital-output ratio has risen (Kuznets 1966, p. 76) for Great Britain, Japan, and the United States. His data (Figure 3-15) suggest that between 1850 and 1950 the industrial capital-output ratio in the United States rose 11 percent, while the capital-output ratio for all forms of capital fell 23 percent.

Samuelson (1970), on the other hand, suggests an approximately constant capital-output ratio for the United States (Figure 3-16) by arguing that technology offset decreasing returns over the 1900–1968 period.

We chose to accept Samuelson's more optimistic analysis of the United States as representative of the global capital stock. The industrial capital-output ratio ICOR is assumed to be constant at a value of 3 years. Through the inclusion of a CLIP function, however, it is possible to alter the value of the capital-output ratio from ICOR1 to ICOR2 at any set time (PYEAR) during the course of a model run. In most analyses of World3, both values of ICOR were set equal to 3.0.

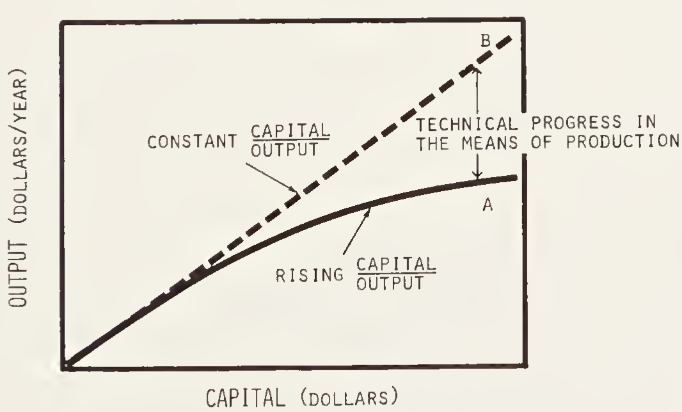

Figure 3-14 The relation between capital and output for rising and for constant capital-output ratios

			Capital-Product Ratio (years)		
		1 Period	2 Initial Date	3 Terminal Date	4 Percentage Change
Great Britain (current prices, national income)	Total capital	1885–1927	8.2	4.8	−41
	Reproducible	1865–1933	4.6	5.0	9
Belgium (current prices, national income)	Total capital	1846–1950	9.3	5.4	−42
Norway (1938 prices, NDP)	Net fixed assets	1865–1874 to 1947–1956	4.0	3.2	−20
West Germany (1950 prices, GNP)	Gross fixed assets	1913 to 1950–1955	5.4	4.0	−26
United States (1929 prices, GNP)	Total capital	1850–1950	3.5	2.7	−23
	Reproducible	1850–1950	1.9	2.1	11
Australia (current prices, GNP)	Total capital	1903–1956	6.4	4.0	−37
Japan (1928–1932 prices, national income)	Total capital	1905–1953	7.2	5.3	−26
	Reproducible	1905–1935	2.8	3.0	7

Figure 3-15 Capital-output ratios for seven selected countries
Source: Kuznets 1966.

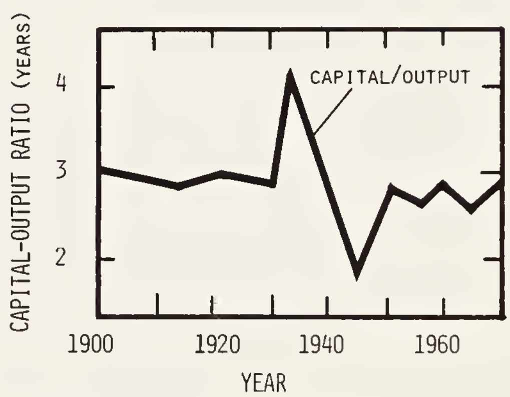

Figure 3-16 Evolution of the U.S. capital-output ratio, 1900–1968
Source: Samuelson 1970, p. 722.

Industrial Capital IC

```
IC.K=IC.J+(DT)(ICIR.JK-ICDR.JK)                          52, L
IC=ICI                                                   52.1, N
ICI=2.1E11                                               52.2, C
    IC      - INDUSTRIAL CAPITAL (DOLLARS)
    DT      - TIME INTERVAL BETWEEN CONSECUTIVE
                CALCULATIONS (YEARS)
    ICIR    - INDUSTRIAL CAPITAL INVESTMENT RATE
                (DOLLARS/YEAR)
    ICDR    - INDUSTRIAL CAPITAL DEPRECIATION RATE
                (DOLLARS/YEAR)
    ICI     - INDUSTRIAL CAPITAL INITIAL (DOLLARS)
```

The total industrial capital stock (measured in the dollar units defined in the introduction to this chapter) is the accumulation of all past investments in industry diminished by all past depreciations of that capital stock. Industrial capital IC consists of all manufactured goods used in the production of industrial output and in the extraction of nonrenewable resources. The capital stock includes factory buildings, production equipment, and material inventories but not raw material. It is thus reproducible capital only, excluding land and subsoil resources, which are handled in separate sectors of the global model. Improvements in the labor force are implicit in ICOR and are thus not incorporated in IC.

To summarize the net effect of all industrial capital investment and depreciation before the initial time period of the simulation, we had to specify the initial (1900) value of industrial capital ICI. It was set equal to 210 billion dollars worth of buildings and equipment by estimating the per capita industrial output IOPC in 1900, multiplying that figure by the population POP in 1900 and the capital-output ratio ICOR in 1900, and dividing by (1−the fraction of capital allocated to obtaining resources FCAOR) in 1900.

$$\mathrm{IC}(1900) = \frac{[\mathrm{IOPC}(1900)]\times[\mathrm{POP}(1900)]\times\mathrm{ICOR}}{[1-\mathrm{FCAOR}(1900)]} = [\mathrm{IOPC}(1900)]\times 5\times 10^9,$$

where

IOPC(1900)	=	industrial output per capita in 1900 (dollars)
POP(1900)	=	population in 1900 = 1.6×10^9 persons (from Chapter 2)
FCAOR(1900)	=	fraction of capital allocated to obtaining resources in 1900 = 0.05 (from Chapter 5)
ICOR	=	industrial capital-output ratio = 3.0 years (from preceding discussion of IO)

The absence of good data forced the use of a crude estimate of industrial output per capita IOPC in 1900. The average GNP per capita in 1968 was first estimated. Then, using an estimate of the average growth rate in GNP per capita during this century, we were able to infer the level of GNP per capita that must have existed globally in 1900. Finally, using the development patterns identified by Chenery and Taylor (1968), it was possible to estimate the fraction of the 1900 GNP per capita that was in the form of industrial output.

For our estimate of the 1968 world average GNP we used the GNP figures reported by the World Bank for 122 countries in 1968 (IBRD 1970). The weighted average of the reported GNP figures is about 660 dollars per person-year. Kuznets (1971) has provided data on some average growth rates of GNP per capita for seventeen countries for time periods between 1864 and 1967, which are summarized in Figure 3-17. The annual growth rates in these countries vary from a low of 0.6 percent per year in India to a high of 2.8 percent per year in Japan. Because such a large fraction of the population of those countries is in India, a reasonable average growth rate for the global GNP per capita is probably not greater than 2.0 percent per

Country	Time Period	Rate of Growth of GNP per Capita (% per decade)	Average Annual Rate of Growth (% per year)
Great Britain	1864–1967	13.4	1.25
France	1896–1966	18.6	1.7
Belgium	1904–1967	14.3	1.3
Switzerland	1910–1967	16.1	1.5
Denmark	1869–1967	20.2	1.85
Norway	1869–1967	21.3	1.9
Sweden	1869–1967	28.9	2.5
Italy	1899–1967	22.9	2.1
Japan	1879–1967	32.3	2.8
United States	1914–1967	18.4	1.7
Canada	1924–1967	20.9	1.9
Australia	1904–1967	13.1	1.2
Argentina	1904–1967	10.1	0.95
Mexico	1899–1967	18.2	1.65
Ghana	1891–1967	15.6	1.45
Philippines	1902–1967	10.3	1.0
India	1901–1958	6.3	0.6

Figure 3-17 National GNP per capita growth rates for seventeen countries for time periods during the interval 1864–1967 (noninflated)
Source: Kuznets 1971.

year. We chose 1.7 percent per year as the basis for our estimate. A GNP per capita of 200 dollars per person-year in 1900 would have grown to 660 dollars by 1968 if it increased 1.7 percent per year over the interval 1900–1968.

According to the development patterns portrayed in Figure 3-3B, when the GNP per capita is 200 dollars per person-year the industrial output per capita is typically about 21 percent of GNP, that is, about 42 dollars per person-year. Figure 3-18 summarizes our estimates of the magnitude and composition of the average global GNP per capita in 1900 and 1968. The initial value of industrial capital IC had to be chosen so that industrial output per capita IOPC in 1900 would equal 42 dollars per person-year. Using the equation for IC in 1900 given previously, we estimated

$IC(1900) = 2.1 \times 10^{11}$.

	1900	1968
GNP per capita (1968 dollars)	200	660
Industrial output per capita (1968 dollars per person-year)	42	220
Service output per capita (1968 dollars per person-year)	90	330

Figure 3-18 Estimates of the magnitude and composition of average global GNP per capita, 1900 and 1968

The uncertainties present even in the current data make our estimates of economic parameters in 1900 subject to error by a factor of two or more. It is important to realize, however, that the exact initial values set for the model levels have very little influence on the behavior modes subsequently generated—as can be verified by varying the initial values and comparing the resulting simulation runs.

Industrial Capital Depreciation Rate ICDR

```
ICDR.KL=IC.K/ALIC.K                                        53, R
    ICDR    - INDUSTRIAL CAPITAL DEPRECIATION RATE
                (DOLLARS/YEAR)
    IC      - INDUSTRIAL CAPITAL (DOLLARS)
    ALIC    - AVERAGE LIFETIME OF INDUSTRIAL CAPITAL
                (YEARS)
```

In World3 the magnitude of the industrial capital stock in any year depends upon the amount of capital existing in the preceding year, plus investments, less depreciation. The annual depreciation equals the current level of the capital stock divided by the average lifetime of the capital stock. The industrial capital depreciation rate ICDR has dimensions of capital units (dollars) per year. Although the contribution of each capital unit to the industrial capital stock declines after acquisition, as indicated in Figure 3-9, the total amount of effective capital generally tends to increase because investment normally exceeds depreciation.

Average Lifetime of Industrial Capital ALIC

```
ALIC.K=CLIP(ALIC2,ALIC1,TIME.K,PYEAR)                      54, A
ALIC1=14                                                   54.1, C
ALIC2=14                                                   54.2, C
    ALIC    - AVERAGE LIFETIME OF INDUSTRIAL CAPITAL
                (YEARS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    ALIC2   - ALIC, VALUE AFTER TIME=PYEAR (YEARS)
    ALIC1   - ALIC, VALUE BEFORE TIME=PYEAR (YEARS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
```

The numerical value required for the average lifetime of industrial capital ALIC is the average of the lifetime of every type of reproducible capital weighted by the contribution of each capital type to the total industrial output. An analogous figure is also required for the average life of service capital ALSC. Our estimates of the lifetimes of industrial and service capital were derived from data on total GNP, total depreciation, fraction of GNP in industry, and fraction of GNP in services (columns 3, 4, 6, and 7 in Figure 3-7). To minimize the effect of agricultural capital depreciation, we used data only from those countries in which agricultural output was less than 5 percent of total output. To relate those figures to capital lifetimes we used the following approximation:

$$TD = \frac{IC}{ALIC} + \frac{SC}{ALSC}$$

$$TD = \frac{IO \times ICOR}{ALIC} + \frac{SO \times SCOR}{ALSC} ,$$

where

TD = total depreciation (dollars per year)
IC = industrial capital (dollars)
IO = industrial output (dollars per year)
ICOR = industrial capital-output ratio (years)
ALIC = average lifetime of industrial capital (years)
SC = service capital (dollars)
SO = service output (dollars per year)
SCOR = service capital-output ratio (years)
ALSC = average lifetime of service capital (years)

Using the estimates of service and industrial capital-output ratios derived elsewhere, one can determine a least-squares estimate for the relation between ALIC and ALSC for the countries included in the sample. However, other information must be used to select the most appropriate pair of values for ALIC and ALSC that satisfy the relationship. Because of the greater contribution of buildings to service capital, it is reasonable to expect that the average life of service capital ALSC will be greater than the average life of industrial capital ALIC. Kuznets has estimated lifetimes of 50 years for building and construction materials and 10 years for producers' equipment (Kuznets 1966, p. 258). We would expect the average lifetime for all industrial capital to fall between these two figures. We therefore estimated the following approximate values for the two parameters: ALSC= 20 years, ALIC = 14 years. The CLIP function in the equation for ALIC permits one to change the value of ALIC from ALIC1 to ALIC2 during the simulation when TIME = PYEAR.

Industrial Capital Investment Rate ICIR

```
ICIR.KL=(IO.K)(FIOAI.K)                                    55, R
    ICIR    - INDUSTRIAL CAPITAL INVESTMENT RATE
                (DOLLARS/YEAR)
    IO      - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    FIOAI   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                INDUSTRY (DIMENSIONLESS)
```

The amount reinvested each year in industrial capital (the industrial capital investment rate ICIR) is by definition the product of industrial output IO and the fraction of industrial output allocated to industry FIOAI. The latter is the fraction that is not allocated to services (FIOAS), agriculture (FIOAA), or consumption (FIOAC). Since depreciation is represented separately, ICIR measures gross investment. FIOAC and FIOAS are described later in this chapter; FIOAA is described in Chapter 4.

```
FIOAI.K=(1-FIOAA.K-FIOAS.K-FIOAC.K)                    56, A
    FIOAI  - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                 INDUSTRY (DIMENSIONLESS)
    FIOAA  - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                 AGRICULTURE (DIMENSIONLESS)
    FIOAS  - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                 SERVICES (DIMENSIONLESS)
    FIOAC  - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                 CONSUMPTION (DIMENSIONLESS)
```

Fraction of Industrial Output Allocated to Consumption FIOAC

```
FIOAC.K=CLIP(FIOACV.K,FIOACC.K,TIME.K,IET)             57, A
IET=4000                                               57.1, C
    FIOAC  - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                 CONSUMPTION (DIMENSIONLESS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    FIOACV - FIOAC VARIABLE (DIMENSIONLESS)
    FIOACC - FIOAC CONSTANT (DIMENSIONLESS)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    IET    - INDUSTRIAL EQUILIBRIUM TIME (YEAR)

FIOACC.K=CLIP(FIOAC2,FIOAC1,TIME.K,PYEAR)              58, A
FIOAC1=.43                                             58.1, C
FIOAC2=.43                                             58.2, C
    FIOACC - FIOAC CONSTANT (DIMENSIONLESS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    FIOAC2 - FIOAC, VALUE AFTER TIME=PYEAR
                 (DIMENSIONLESS)
    FIOAC1 - FIOAC, VALUE BEFORE TIME=PYEAR
                 (DIMENSIONLESS)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
```

In all but the equilibrium runs, the fraction of industrial output allocated to consumption was assumed to be a constant, FIOACC. However, after TIME=IET (industrial equilibrium time), FIOAC is set equal to a variable FIOACV. Since IET normally was assigned the value 4,000, FIOAC was typically constant. A CLIP function was included in the equation defining FIOACC so that its value could be changed during the course of the simulation run. After TIME=PYEAR the value of the constant consumption fraction shifts from FIOAC1 to FIOAC2. During most of our analyses both constants were assigned the value of 0.43.

As defined in World3, FIOAC includes all goods generated by the industrial sector that have a lifetime of one year or less and are not invested in agriculture. Thus it includes most textiles, toys, paper, chemicals, packaging, and, as we mentioned earlier, fuel oil and other petroleum products not directly utilized in the production process.

The value of 0.43 for FIOACC was derived from the individual country data of Figure 3-7, which gives consumption as a fraction of total GNP (column 8). If we assume that all agricultural and service outputs are included in total consumption, the component of industrial output IO that is consumed will equal the total consumption minus the sum of service and agricultural output. The fraction of industrial output allocated to consumption FIOAC will be this quantity divided by industrial output IO:

$$\text{FIOAC} = \frac{\text{TC}-\text{SO}-\text{AO}}{\text{IO}},$$

where

FIOAC	=	fraction of industrial output allocated to consumption
TC	=	total consumption (dollars per year)
SO	=	service output (dollars per year)
AO	=	agricultural output (dollars per year)
IO	=	industrial output (dollars per year)

The data required for this calculation are provided for most of the countries listed in Figure 3-7. The mean value of FIOAC for those countries on which data are available is 0.43, with a very wide variance about this mean.

National differences in the fraction of industrial output allocated to consumption FIOAC are probably more directly explained by social and political differences and by the income distribution within each country than by the country's average GNP per capita. For Figure 3-19 we plotted GNP per capita versus FIOAC for 33 countries. There is no clear relationship between the two variables. Because the rate of industrial growth is strongly influenced by FIOAC, future extensions of the model should represent the sociopolitical determinants of consumption in more detail.

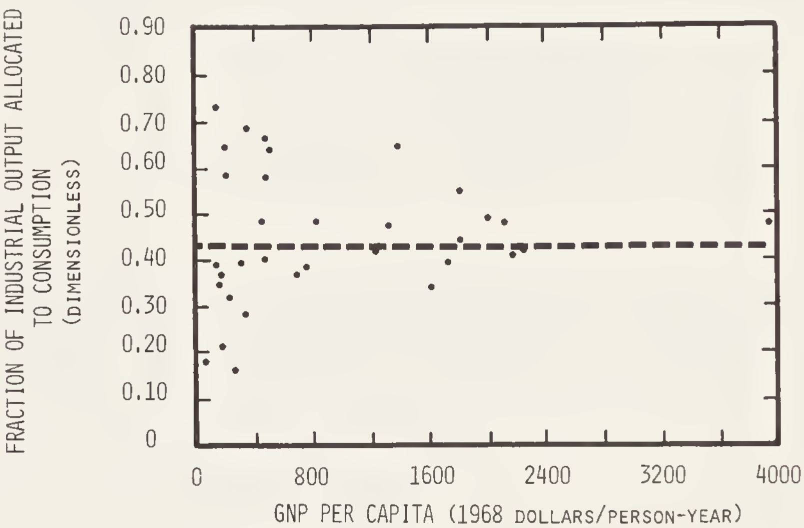

Figure 3-19 The fraction of industrial output allocated to consumption versus GNP per capita

The total consumed fraction of output was taken to include both private and government consumption expenditures. Thus the production of military hardware is defined in World3 as part of the industrial output that is consumed without feeding back to influence other model variables. Using data from the *World Bank Atlas* (IBRD 1970) and the United Nations (U.N. 1970), one can calculate the fraction of GNP devoted to defense expenditures. With very few exceptions they are less than 5 percent of the total GNP. Percentages for the United States, the Soviet Union, Japan, and West Germany are 10 percent, 8 percent, 1 percent, and 4 percent of GNP, respectively. Our treatment of military expenditures does not imply that they are unimportant in absolute terms. The approximately 250 billion dollars spent annually on military hardware and on maintaining armies would have an important influence on the growth of population and capital if it were invested in the service or agriculture sectors of the global economy. However, since the causes and consequences of military expenditures are found primarily among the sociopolitical factors that are omitted from our model, we did not find it useful to distinguish military from other types of consumption.

In some of the equilibrium runs it was useful to define the consumption fraction as a variable FIOACV dependent upon the level of industrial output per capita and on some level of desired industrial output per capita IOPCD. The assumption implicit in the definition of FIOACV is that consumption will increase and thus investment will decrease once IOPC has reached the level desired by the global population. The nature of the assumed relationships is specified in a table FIOACVT, Figure 3-20.

```
FIOACV.K=TABHL(FIOACVT,IOPC.K/IOPCD,0,2,.2)          59, A
FIOACVT=.3/.32/.34/.36/.38/.43/.73/.77/.81/.82/.83  59.1, T
IOPCD=400                                            59.2, C
    FIOACV - FIOAC VARIABLE (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FIOACVT- FIOACV TABLE
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
               PERSON-YEAR)
    IOPCD  - INDUSTRIAL OUTPUT PER CAPITA DESIRED
               (DOLLARS/PERSON-YEAR)
```

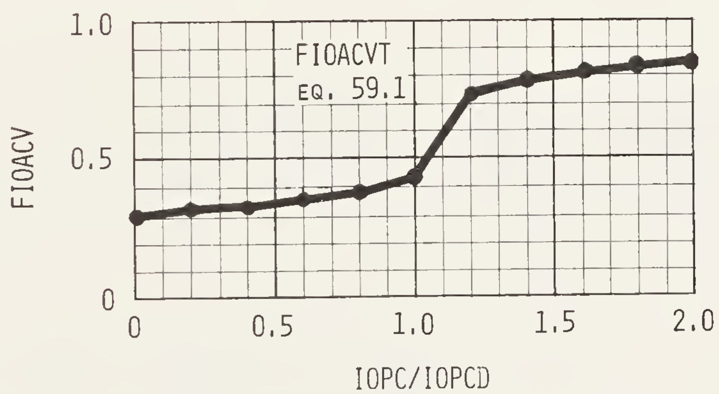

Figure 3-20 Fraction of industrial output allocated to consumption table

Indicated Service Output per Capita ISOPC In section 3.4 we described the general features of the process employed in World3 to allocate industrial output among the service, agriculture, and industrial sectors. The detailed DYNAMO flow diagram for the investment in services is shown in Figure 3-21.

The growth in the service sector results from an increased service capital investment rate SCIR, defined to be a function of industrial output IO and the fraction of industrial output allocated to services FIOAS. The latter is determined by the actual service output per capita SOPC and the indicated service output per capita ISOPC. The value of ISOPC at any level of industrialization depends on the relative values society places on saving, material goods, food, and services. Implicit in the

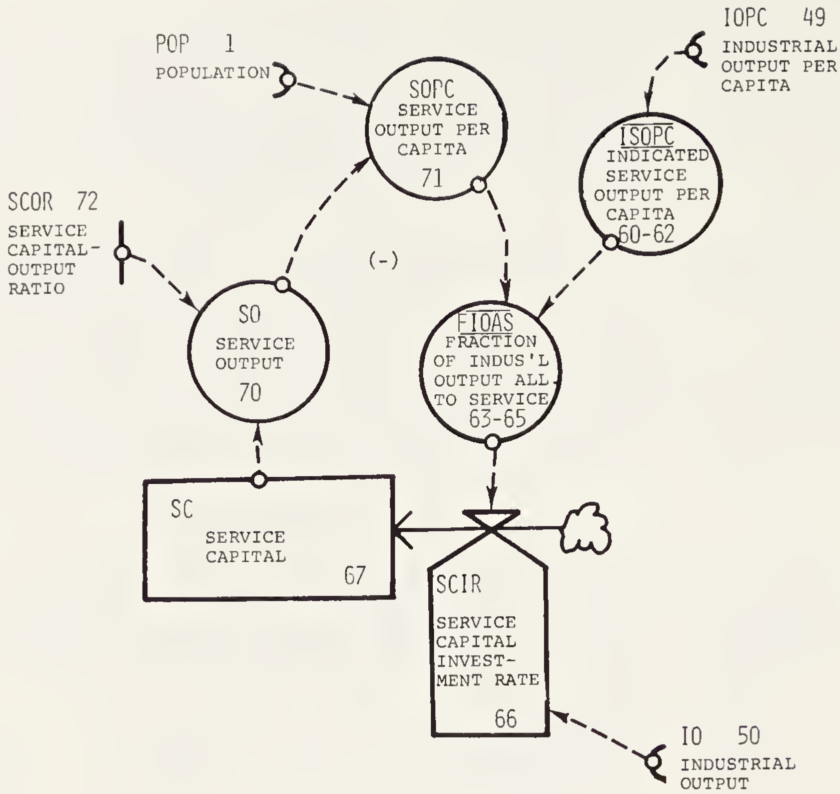

Figure 3-21 DYNAMO flow diagram of feedback loop governing investment in services

formulation of ISOPC are assumptions about the shift in values that accompanies industrialization. We tried to base the model relationship on the value shift that has been historically observed to occur with economic development. Because some new pattern may emerge in the future, however, we made it possible to change the definition of ISOPC during the course of any simulation run.

We employed a relationship between ISOPC and IOPC related to that observed between the magnitudes of service output per capita and industrial output per capita during the economic development of most nations (Chenery and Taylor 1968). Because our definitions of service, agriculture, and industry differ slightly from those employed by Chenery and Taylor we rederived the industry-service output relationship using the cross-sectional statistics on GNP provided in Figure 3-7. Figure 3-22 illustrates the relation of service output per capita (Figure 3-7, column 2 × column 7) to industrial output per capita (Figure 3-7, column 2 × column 6) for the 38 countries for which appropriate data are available.

The cross-sectional and longitudinal studies of Chenery and Taylor suggest that current relationships among the various constituents of GNP in different countries are similar to those observed in most countries over the course of their industrialization. We therefore employed our cross-sectional curve of service output per capita versus industrial output per capita (Figure 3-22) as indicative of the relationship that will prevail in the future, barring major value changes within the global population.

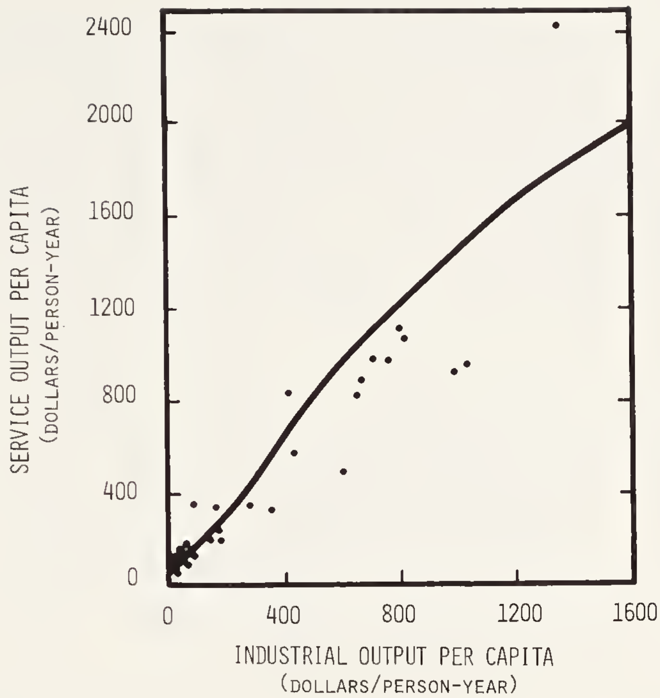

Figure 3-22 The relation of service output per capita to industrial output per capita

To permit a change in the assumed relationship between IOPC and ISOPC during a simulation run, ISOPC is specified with a CLIP function that shifts the value of ISOPC from ISOPC1 to ISOPC2 at TIME=PYEAR. Both ISOPC1 and ISOPC2 are defined as tabular relationships. The tables that indicate the two relationships, ISOPC1T and ISOPC2T, are normally identical to the line in Figure 3-22. Their form in most simulations is shown in Figure 3-23.

```
ISOPC.K=CLIP(ISOPC2.K,ISOPC1.K,TIME.K,PYEAR)          60, A
    ISOPC  - INDICATED SERVICE OUTPUT PER CAPITA
               (DOLLARS/PERSON-YEAR)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    ISOPC2 - ISOPC, VALUE AFTER TIME=PYEAR (DOLLARS/
               PERSON-YEAR)
    ISOPC1 - ISOPC, VALUE BEFORE TIME=PYEAR (DOLLARS/
               PERSON-YEAR)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

ISOPC1.K=TABHL(ISOPC1T,IOPC.K,0,1600,200)             61, A
ISOPC1T=40/300/640/1000/1220/1450/1650/1800/2000      61.1, T
    ISOPC1 - ISOPC, VALUE BEFORE TIME=PYEAR (DOLLARS/
               PERSON-YEAR)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    ISOPC1T- ISOPC1 TABLE
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
               PERSON-YEAR)

ISOPC2.K=TABHL(ISOPC2T,IOPC.K,0,1600,200)             62, A
ISOPC2T=40/300/640/1000/1220/1450/1650/1800/2000      62.1, T
    ISOPC2 - ISOPC, VALUE AFTER TIME=PYEAR (DOLLARS/
               PERSON-YEAR)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    ISOPC2T- ISOPC2 TABLE
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
               PERSON-YEAR)
```

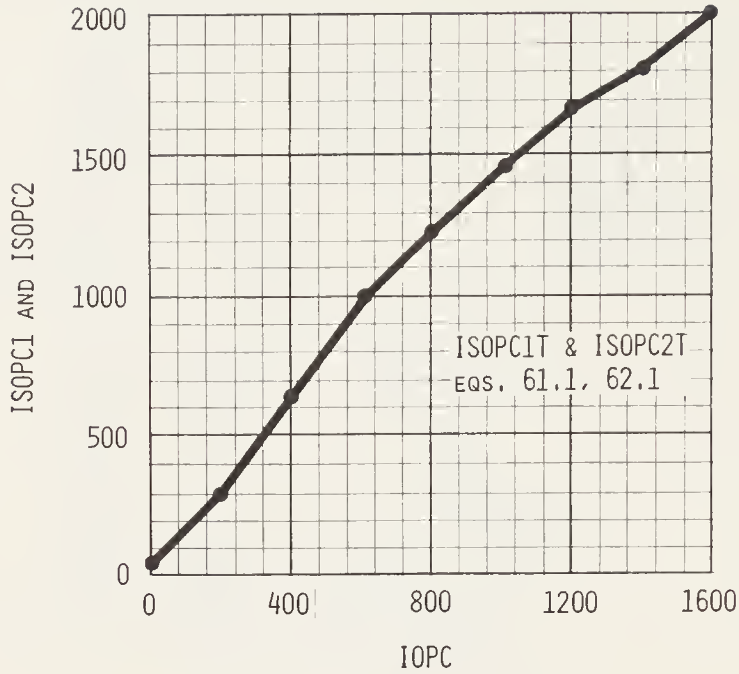

Figure 3-23 Indicated service output per capita table

Fraction of Industrial Output Allocated to Services FIOAS The fraction of industrial output allocated to services FIOAS influences the quantity of capital invested each year in the service sector to increase the material stock of service capital. If current service output per capita SOPC is lower than that indicated by the current level of industrial output per capita IOPC, then greater emphasis is placed on investing in the service sector, and FIOAS increases. When SOPC is found to be higher than would be indicated by the level of IOPC, FIOAS is decreased.

As shown in Figure 3-24, the fraction of industrial output allocated to services FIOAS was defined as a function of the ratio of SOPC to ISOPC. If the ratio is greater than 1.0, meaning that the actual output is greater than the indicated output, then less industrial output is invested in services. If the ratio is less than 1.0, meaning that the actual output is less than the indicated output, then more industrial output is invested in services. When the actual and indicated outputs are equal (SOPC/ISOPC = 1.0), 10 percent of industrial output is invested in services. This is the percentage that we found, by experimenting with the model, to be necessary to offset depreciation of service capital.

The slope of the table function determines the magnitude of the response to any discrepancy between actual and indicated service output levels. Thus it is an expression of the response time of the system to a relative surplus or scarcity of output in the service sector. If the line is made steeper, a given change in the ratio of SOPC and ISOPC will produce a larger change in FIOAS. As a consequence, the discrepancy will be more quickly eliminated.

There is no general criterion by which to choose a "best" slope for this table function; any slope that gives a relatively short adjustment time and an equilibrium value for the ratio near unity is acceptable. The slope chosen gives an adjustment time of about three years and an equilibrium ratio of SOPC to ISOPC during the growth phase of slightly less than unity. To permit a change in the slope of the FIOAS curve during the simulation (at TIME=PYEAR), two FIOAS curves, FIOAS1 and FIOAS2, were defined in the DYNAMO listing.

```
FIOAS.K=CLIP(FIOAS2.K,FIOAS1.K,TIME.K,PYEAR)          63, A
    FIOAS   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                SERVICES (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    FIOAS2  - FIOAS, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    FIOAS1  - FIOAS, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

FIOAS1.K=TABHL(FIOAS1T,SOPC.K/ISOPC.K,0,2,.5)         64, A
FIOAS1T=.3/.2/.1/.05/0                                64.1, T
    FIOAS1  - FIOAS, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FIOAS1T- FIOAS1 TABLE
    SOPC    - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
                YEAR)
    ISOPC   - INDICATED SERVICE OUTPUT PER CAPITA
                (DOLLARS/PERSON-YEAR)

FIOAS2.K=TABHL(FIOAS2T,SOPC.K/ISOPC.K,0,2,.5)         65, A
FIOAS2T=.3/.2/.1/.05/0                                65.1, T
    FIOAS2  - FIOAS, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FIOAS2T- FIOAS2 TABLE
    SOPC    - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
                YEAR)
    ISOPC   - INDICATED SERVICE OUTPUT PER CAPITA
                (DOLLARS/PERSON-YEAR)
```

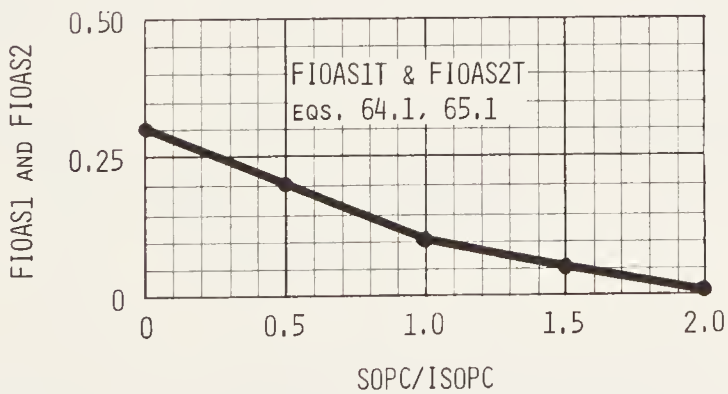

Figure 3-24 Fraction of industrial output allocated to services table

Service Capital Investment Rate SCIR

```
SCIR.KL=(IO.K)(FIOAS.K)                                  66, R
    SCIR   - SERVICE CAPITAL INVESTMENT RATE (DOLLARS/
               YEAR)
    IO     - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    FIOAS  - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
               SERVICES (DIMENSIONLESS)
```

The service capital investment rate SCIR augments the stock of service capital, thereby increasing the ability of the economy to produce services. The amount of goods and equipment invested in the service sector each year is simply the industrial output IO multiplied by the fraction of industrial output allocated to services FIOAS. As in the industrial sector, the rate represents gross investment.

Service Capital SC

```
SC.K=SC.J+(DT)(SCIR.JK-SCDR.JK)                          67, L
SC=SCI                                                   67.1, N
SCI=1.44E11                                              67.2, C
    SC     - SERVICE CAPITAL (DOLLARS)
    DT     - TIME INTERVAL BETWEEN CONSECUTIVE
               CALCULATIONS (YEARS)
    SCIR   - SERVICE CAPITAL INVESTMENT RATE (DOLLARS/
               YEAR)
    SCDR   - SERVICE CAPITAL DEPRECIATION RATE (DOLLARS/
               YEAR)
    SCI    - SERVICE CAPITAL INITIAL (DOLLARS)
```

Service capital SC is the physical stock of buildings and equipment that produces a stream of services through time. The stock is the accumulation of previous service capital investment rates SCIR minus previous service capital depreciation rates SCDR.

The initial (1900) value of service capital SCI was obtained through an analysis similar to that presented in connection with the initial value of industrial capital ICI earlier in this section. As shown there, we assumed a service output per capita SOPC in 1900 of 90 dollars per person-year. We then set the service capital-output ratio SCOR equal to one year, so that the initial value of service capital SC is

$$\begin{aligned} SC(1900) &= [SOPC(1900)]\times[POP(1900)]\times SCOR \\ &= \$90\times 1.6\times 10^{9}\times 1 \\ &= \$1.4\times 10^{11}, \end{aligned}$$

where

SC(1900) = service capital in 1900 (dollars)
POP(1900) = population in 1900 (people)
SCOR = service capital-output ratio (years)
SOPC(1900) = service output per capita in 1900 (dollars per person-year)

Service Capital Depreciation Rate SCDR

```
SCDR.KL=SC.K/ALSC.K                                        68, R
    SCDR    - SERVICE CAPITAL DEPRECIATION RATE (DOLLARS/
                YEAR)
    SC      - SERVICE CAPITAL (DOLLARS)
    ALSC    - AVERAGE LIFETIME OF SERVICE CAPITAL (YEARS)
```

The depreciation rate of service capital SCDR was formulated in the same manner as the depreciation of industrial capital ICDR, the depreciation in any year being the current stock of service capital SC divided by the average lifetime of service capital ALSC.

Average Lifetime of Service Capital ALSC

```
ALSC.K=CLIP(ALSC2,ALSC1,TIME.K,PYEAR)                      69, A
ALSC1=20                                                   69.1, C
ALSC2=20                                                   69.2, C
    ALSC    - AVERAGE LIFETIME OF SERVICE CAPITAL (YEARS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    ALSC2   - ALSC, VALUE AFTER TIME=PYEAR (YEARS)
    ALSC1   - ALSC, VALUE BEFORE TIME=PYEAR (YEARS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
```

The average lifetime of service capital ALSC can be expected to be longer than the average lifetime of industrial capital ALIC because of the larger proportion of buildings in the stock of service capital. We chose a lifetime of 20 years—a value compatible with the national accounts data presented in Figure 3-7—by the procedure discussed in connection with the derivation of the average lifetime of industrial capital ALIC. Uncertainty about the numerical value of this parameter caused us to include a CLIP function in its definition so that its value can be changed from ALSC1 to ALSC2 during the run at TIME=PYEAR.

Service Output SO

```
SO.K=(SC.K*CUF.K)/(SCOR.K)                                 70, A
    SO      - SERVICE OUTPUT (DOLLARS/YEAR)
    SC      - SERVICE CAPITAL (DOLLARS)
    CUF     - CAPITAL UTILIZATION FRACTION
                (DIMENSIONLESS)
    SCOR    - SERVICE CAPITAL-OUTPUT RATIO (YEARS)
```

Under most conditions, all service capital SC will be fully utilized, and the service output SO will equal the ratio of SC to the service capital-output ratio SCOR. Under rare circumstances, however, a severe shortage of labor might force some service capital to remain idle, and the effective service capital would be less than the value of SC. To incorporate this possible effect we defined a capital utilization factor CUF whose value may range from zero to 1.0 depending upon the availability of labor. Typically, CUF equals 1.0 and thus does not affect the model's behavior.

Service Output per Capita SOPC

```
SOPC.K=SO.K/POP.K                                          71, A
    SOPC    - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
                YEAR)
    SO      - SERVICE OUTPUT (DOLLARS/YEAR)
    POP     - POPULATION (PERSONS)
```

Service output per capita SOPC is a measure of the average amount of service output SO available to each person in the population POP. By definition, SO is intangible and entirely consumed. As is the case with industrial output per capita IOPC, uneven distribution of service output SO is not explicitly represented in the equation for SOPC but is reflected in the formulation of the variables that depend on it.

Service Capital-Output Ratio SCOR

```
SCOR.K=CLIP(SCOR2,SCOR1,TIME.K,PYEAR)                      72, A
SCOR1=1                                                    72.1, C
SCOR2=1                                                    72.2, C
    SCOR   - SERVICE CAPITAL-OUTPUT RATIO (YEARS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    SCOR2  - SCOR, VALUE AFTER TIME=PYEAR (YEAR)
    SCOR1  - SCOR, VALUE BEFORE TIME=PYEAR (YEAR)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
```

Although we could find no direct empirical evidence to suggest an appropriate value for the service capital-output ratio SCOR, the provision of services is typically much more labor-intensive than the manufacture of industrial output. Because labor was excluded from our production function for services, SCOR was reduced to compensate for the omission. We assumed SCOR to be equal to 1.0 years in most runs, but we incorporated in the model a CLIP function that permits the value of SCOR to be changed from SCOR1 to SCOR2 when TIME=PYEAR.

3.6 THE JOB SECTOR

We suggested in the basic concepts section (3.3) of this chapter that more labor has been available historically than was required for full utilization of the world's capital stock. Given the form of our industrial production function, labor normally has no influence on the industrial output produced by a given amount of industrial capital. Only if the labor force were very small compared with the industrial capital stock would one expect the effective capital to decrease. The job sector was incorporated in World3 to represent this possible effect of an extreme labor scarcity. Because of a lack of available data on a global basis and the high level of aggregation of the entire model, it is improper to interpret the interactions within the job sector as anything more than a demonstration of the possible effect of a drastically reduced work force on the amount of goods and services produced by the world's capital. The main effect of the sector is to avoid unrealistically high values of SOPC and IOPC during those runs in which population declines more rapidly than capital.

The addition of this sector to World3 was our only effort to include model relationships that may be in effect during the period of population decline. The model's utility remains in its ability to clarify the dynamics of growth, not in portraying realistic collapse modes. Thus the job sector described here is a preliminary representation of the gross physical implications of an extreme labor shortage; it is not an adequate representation of the factors involved in the problem of global unemployment. The causes of unemployment are sufficiently important and complex to warrant separate modeling efforts. Some of the data and concepts presented here may provide useful points of departure for those efforts.

Jobs J

```
J.K=PJIS.K+PJAS.K+PJSS.K                              73, A
    J       - JOBS (PERSONS)
    PJIS    - POTENTIAL JOBS IN INDUSTRIAL SECTOR
                (PERSONS)
    PJAS    - POTENTIAL JOBS IN AGRICULTURAL SECTOR
                (PERSONS)
    PJSS    - POTENTIAL JOBS IN SERVICE SECTOR (PERSONS)
```

The total number of jobs J in World3 is calculated as the sum of the potential jobs in the industrial, agriculture, and service sectors (PJIS, PJAS, and PJSS, respectively).

Potential Jobs in Industrial Sector PJIS

```
PJIS.K=(IC.K)(JPICU.K)                                74, A
    PJIS    - POTENTIAL JOBS IN INDUSTRIAL SECTOR
                (PERSONS)
    IC      - INDUSTRIAL CAPITAL (DOLLARS)
    JPICU   - JOBS PER INDUSTRIAL CAPITAL UNIT (PERSONS/
                DOLLAR)
```

The number of potential jobs in the industrial sector PJIS equals the industrial capital IC multiplied by the number of jobs per unit of industrial capital JPICU (a function of the industrial output per capita IOPC). Employing data from the International Labor Organization (ILO 1970) and the United Nations (U.N. 1969), we estimated the relationship between IOPC and JPICU by

1. Multiplying the entries in column 4 by the entries in column 5 of Figure 3-25 to determine the number of jobs in the industrial sector of each country.
2. Multiplying the entries in column 6 of Figure 3-7 by the entries in column 3 of Figure 3-25 to approximate each country's industrial output.
3. Multiplying each country's industrial output by 3.0 (ICOR) to produce an estimate of the level of industrial capital in each country.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Country	ILO Year	GNP (billions of 1968 dollars)	Labor Force (thousands)	Percentage of Labor Force in Industry	Service	Agriculture
Gabon	1966	0.257	46	36.5	41.0	22.5
Kenya	1965	0.982	593	15.1	49.6	35.4
Mauritius	1967	0.199	105	9.8	37.8	52.5
United Arab Republic	1967	5.736	7634	15.1	34.3	50.7
Zambia	1967	1.175	308	49.5	39.1	11.7
British Honduras	1963	0.034	16	33.3	39.0	27.7
Canada	1963	40.134	6375	31.8	56.3	11.8
Panama	1968	0.844	381	18.4	39.9	41.5
Puerto Rico	1967	3.740	680	29.2	56.8	14.0
Trinidad and Tobago	1968	0.748	306	23.8	53.5	22.8
United States	1963	599.705	52164	39.2	51.3	8.9
China (Taiwan)	1968	4.199	4145	24.0	36.3	39.9
Israel	1968	4.005	908	32.0	57.6	10.4
Japan	1963	67.956	46130	30.8	40.9	28.1
Korea (Republic of)	1968	5.900	9261	17.4	30.1	52.5
Philippines	1968	10.814	12423	14.6	27.4	58.0
Ryukyu	1963	0.278	400	14.2	45.5	40.2
Syria	1968	1.425	1643	12.8	20.7	66.6
Austria	1968	11.350	2297	47.9	49.3	2.9
Belgium	1968	20.716	3614	44.0	50.5	5.6
Spain	1968	25.200	12123	34.8	32.8	32.2
Finland	1968	8.009	2099	33.9	40.3	25.8
France	1963	83.449	19126	39.4	41.0	19.5
West Germany	1963	94.400	26455	48.2	39.6	12.2
Ireland	1968	2.981	1059	27.6	42.8	29.6
Italy	1968	74.786	19069	40.6	37.1	22.2
Malta	1968	0.183	93	33.1	59.8	6.9
Norway	1968	9.021	1463	35.6	49.0	15.4
Sweden	1963	16.960	3747	39.9	46.8	13.2
United Kingdom	1963	86.227	23060	47.9	49.1	2.5
Australia	1968	29.830	4452	38.4	51.5	9.9
New Zealand	1967	5.471	1028	36.5	50.2	13.4

Figure 3-25 Labor force statistics for thirty-two countries
Source: ILO 1970.

4. Dividing the industrial sector jobs by the industrial capital to provide estimates of JPICU for each country.
5. Dividing the estimate of each country's industrial output (step 2) by the size of its population (from Appendix B to Chapter 2) to estimate its industrial output per capita.

6. Plotting the estimates of JPICU versus the industrial output per capita to derive the desired relationship for the 16 countries on which all the necessary data are available (see Figure 3-26).

This empirical relationship revealed in Figure 3-26 is incorporated in the model as a table JPICUT (Figure 3-27).

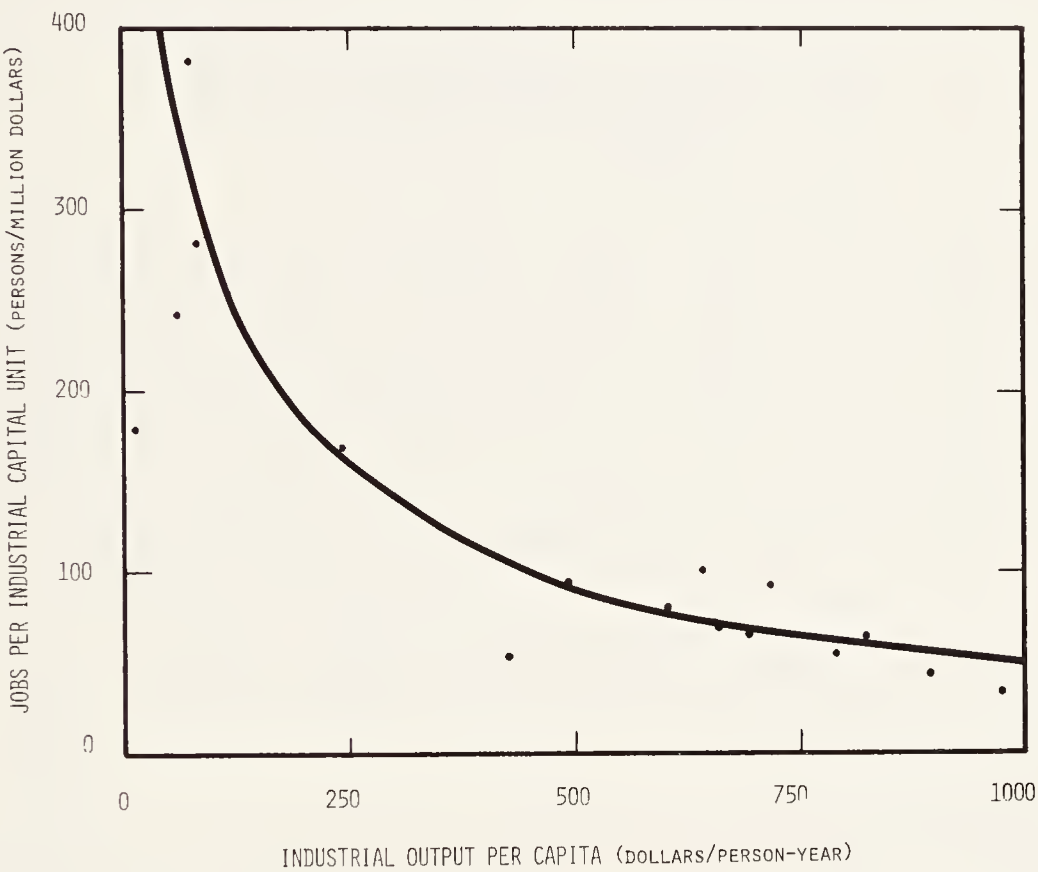

Figure 3-26 Empirical relationship between the jobs per industrial capital unit and the industrial output per capita for sixteen countries

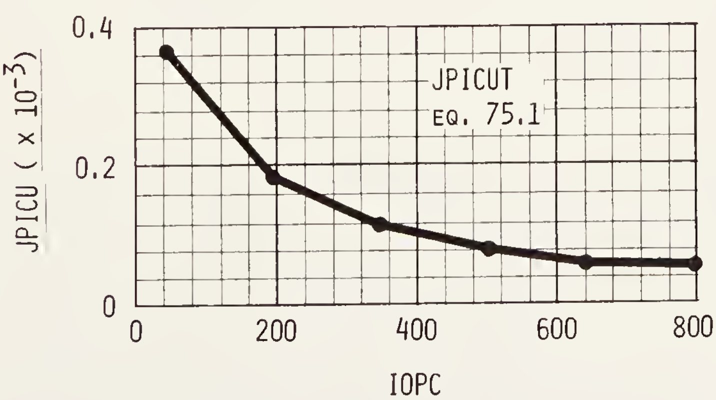

Figure 3-27 Jobs per industrial capital unit table

```
JPICU.K=(TABHL(JPICUT,IOPC.K,50,800,150))*1E-3        75, A
JPICUT=.37/.18/.12/.09/.07/.06                        75.1, T
    JPICU  - JOBS PER INDUSTRIAL CAPITAL UNIT (PERSONS/
                 DOLLAR)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    JPICUT - JPICU TABLE
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                 PERSON-YEAR)
```

Potential Jobs in Service Sector PJSS

```
PJSS.K=(SC.K)(JPSCU.K)                                 76, A
    PJSS   - POTENTIAL JOBS IN SERVICE SECTOR (PERSONS)
    SC     - SERVICE CAPITAL (DOLLARS)
    JPSCU  - JOBS PER SERVICE CAPITAL UNIT (PERSONS/
                 DOLLAR)
```

The potential jobs in the service sector PJSS are taken as the product of service capital SC and the number of jobs per service capital unit JPSCU. The relationship of JPSCU to the service output per capita SOPC was computed from Figures 3-7 and 3-25 through six steps analogous to those employed to determine the relation of JPICU to IOPC. SCOR was assumed to equal 1.0 in estimating the magnitude of the service capital stock in each country. The necessary data were available for 16 countries, and the relationship they suggest is shown in Figure 3-28. The empirical results of Figure 3-28 were incorporated in a table JPSCU (Figure 3-29).

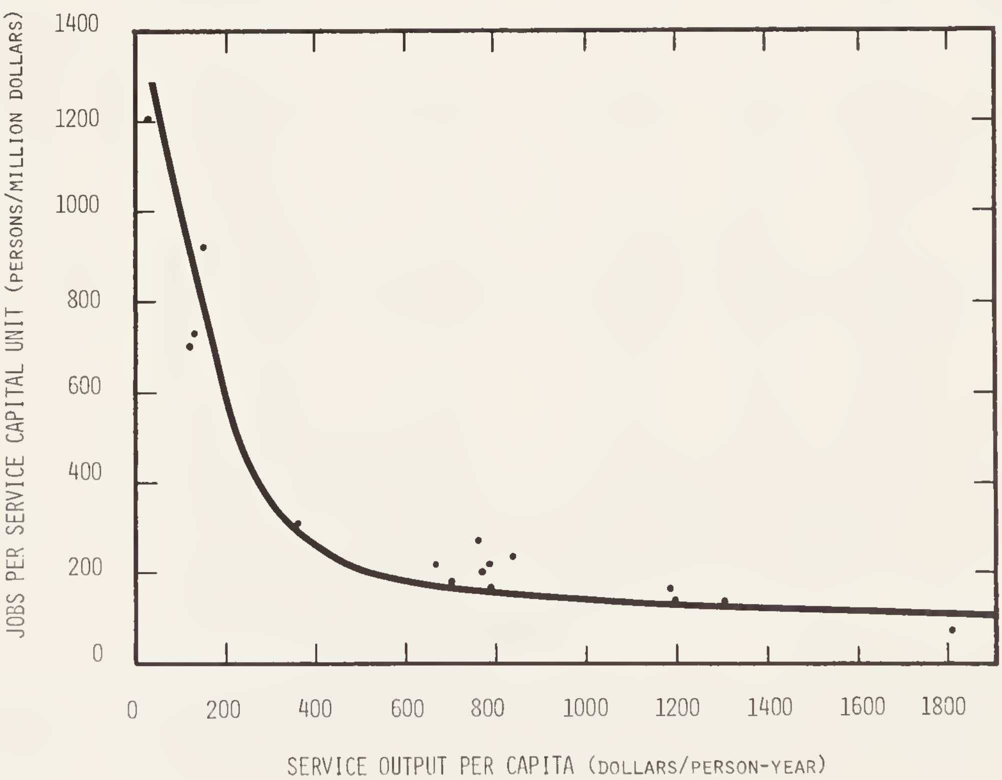

Figure 3-28 Empirical relationship between the jobs per service capital unit and the service output per capita for sixteen countries

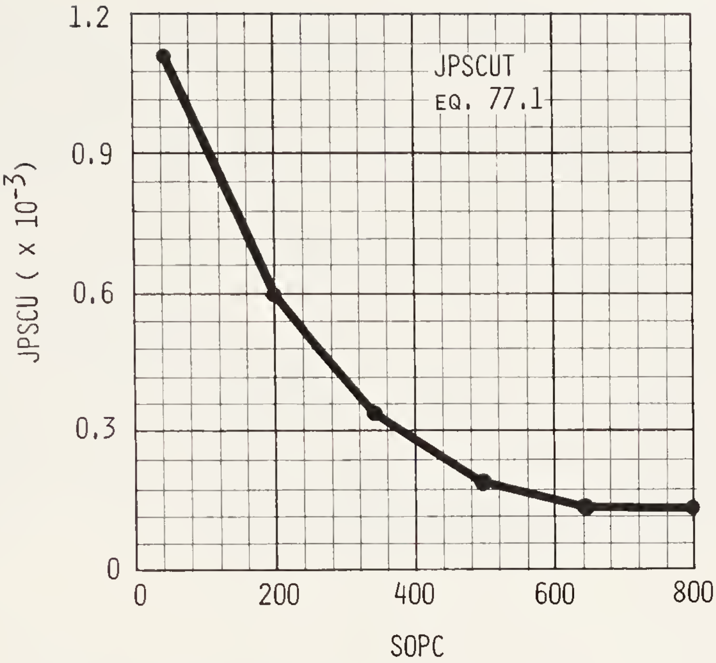

Figure 3-29 Jobs per service capital unit table

```
JPSCU.K=(TABHL(JPSCUT,SOPC.K,50,800,150))*1E-3        77, A
JPSCUT=1.1/.6/.35/.2/.15/.15                          77.1, T
    JPSCU   - JOBS PER SERVICE CAPITAL UNIT (PERSONS/
                DOLLAR)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    JPSCUT  - JPSCU TABLE
    SOPC    - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
                YEAR)
```

Potential Jobs in Agriculture Sector PJAS

```
PJAS.K=(JPH.K)(AL.K)                                    78, A
    PJAS    - POTENTIAL JOBS IN AGRICULTURAL SECTOR
                (PERSONS)
    JPH     - JOBS PER HECTARE (PERSONS/HECTARE)
    AL      - ARABLE LAND (HECTARES)
```

The potential number of jobs in the agriculture sector PJAS is defined to be the product of the jobs per hectare JPH and the total number of hectares of arable land AL. JPH is a function of the agricultural inputs per hectare AIPH, defined in Chapter 4. We did find empirical data relating the jobs per hectare to the GNP per capita for nineteen countries. However, our information on agricultural inputs per hectare in those countries was obtained indirectly through the use of several approximations. Employing data from the United States Department of Agriculture

(U.S.D.A. 1965) and the United Nations (U.N. 1969), we estimated the relationship between AIPH and JPH by

1. Simulating the world model without the job sector to obtain synthetic time-series data on AIPH and IOPC between 1900 and 2010. The resulting data and an extrapolation to IOPC=0 are plotted in Figure 3-30.
2. Converting the relationship between GDP per capita and jobs per hectare (Figure 3-31) to a relationship between jobs per hectare and industrial output per capita using the data provided in column 6 of Figure 3-7. This involves the assumption that the fraction of GDP composed of industrial output in 1960 was about the same as the equivalent fraction in 1968.
3. Employing the relationships obtained in steps 1 and 2 to relate AIPH to JPH. The results for ten countries, summarized in Figure 3-32, were incorporated in the World3 table function JPHT (Figure 3-33).

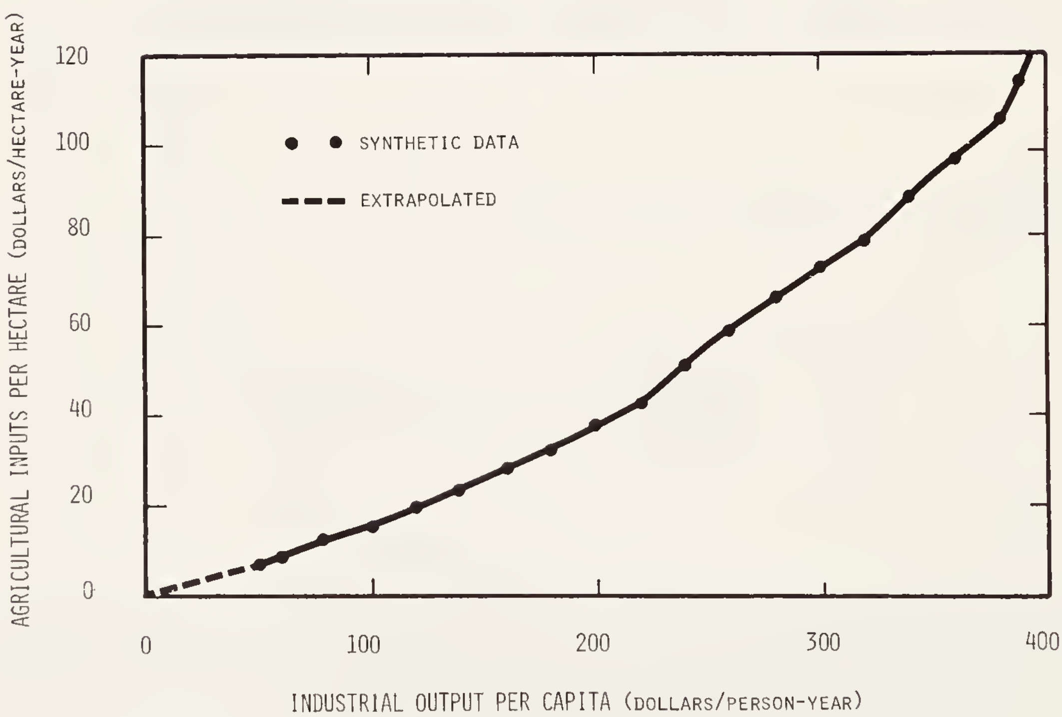

Figure 3-30 Agricultural inputs per hectare versus industrial output per capita (synthetic data from World3)

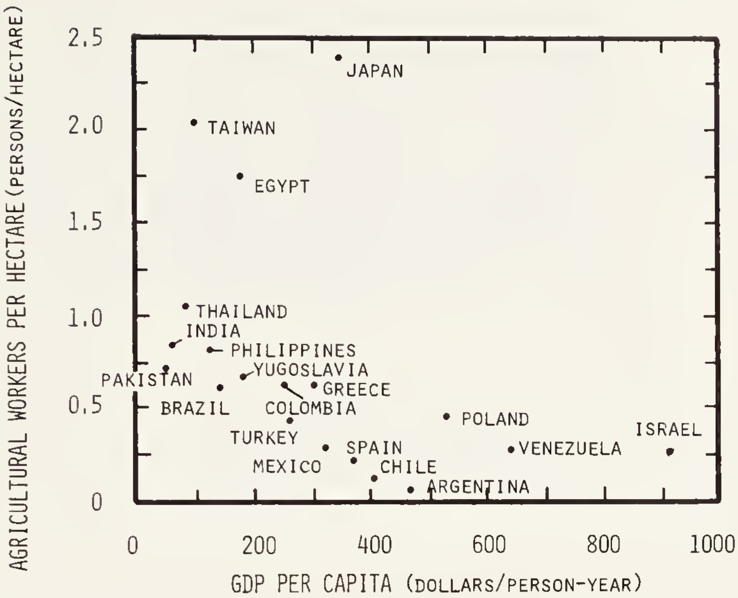

Figure 3-31 Number of agricultural workers per hectare versus gross domestic product for nineteen countries, 1960

Source: U.S.D.A. 1965.

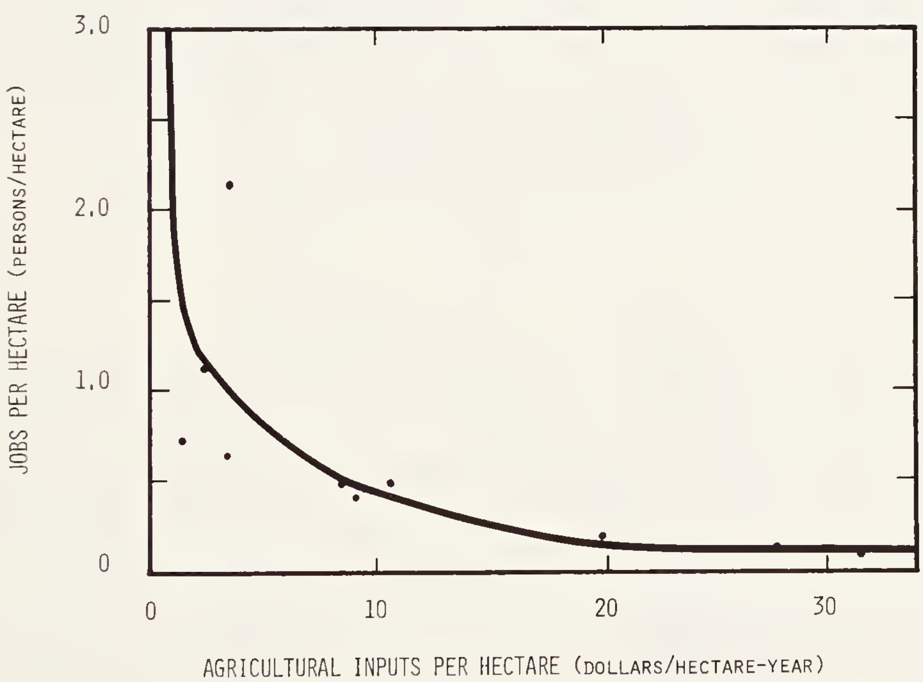

Figure 3-32 Jobs per hectare versus agricultural investment per hectare for ten countries

```
JPH.K=TABHL(JPHT,AIPH.K,2,30,4)                          79, A
JPHT=2/.5/.4/.3/.27/.24/.2/.2                            79.1, T
    JPH    - JOBS PER HECTARE (PERSONS/HECTARE)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    JPHT   - JPH TABLE
    AIPH   - AGRICULTURAL INPUTS PER HECTARE (DOLLARS/
               HECTARE-YEAR)
```

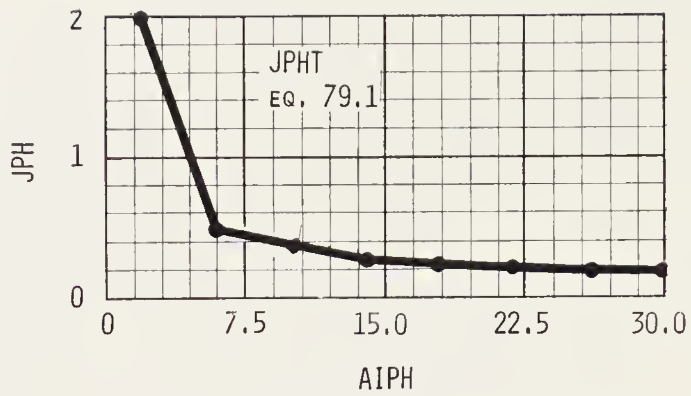

Figure 3-33 Jobs per hectare table

Implicit in our specification of JPH is the assumption that further economic development will bring displacement of labor by capital in the agriculture sector. This shift in inputs has been the historical trend, but a few countries, like Japan, have retained labor-intensive agricultural practices even with great increases in the use of agricultural capital inputs. Future patterns of development other than those in Figure 3-32 are conceivable. Figure 3-34 portrays three alternative relationships between capital and labor inputs to agriculture. With a model whose production functions explicitly included labor, it would be important to analyze the implications of alternative agricultural development strategies.

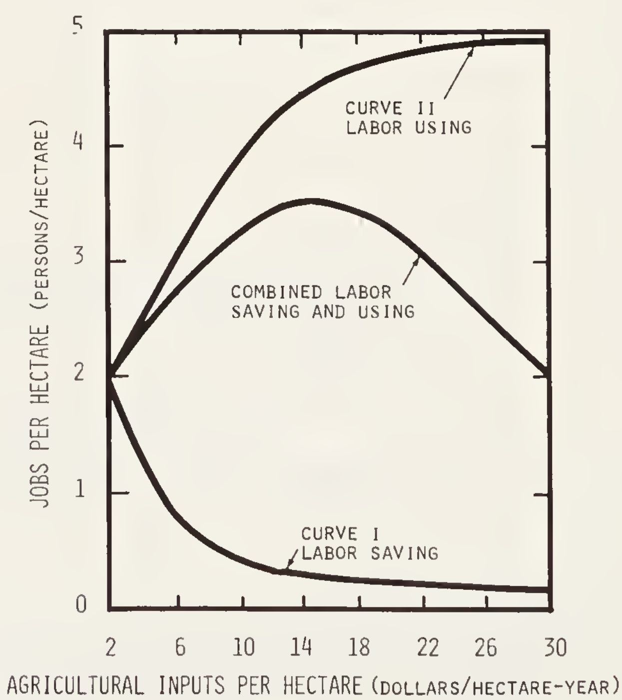

Figure 3-34 Alternative possible assumptions concerning jobs per hectare

Labor Force LF

```
LF.K=(P2.K+P3.K)*LFPF                                        80, A
LFPF=.75                                                     80.1, C
    LF      - LABOR FORCE (PERSONS)
    P2      - POPULATION, AGES 15-44 (PERSONS)
    P3      - POPULATION, AGES 45-64 (PERSONS)
    LFPF    - LABOR FORCE PARTICIPATION FRACTION
                (DIMENSIONLESS)
```

In World3 the labor force LF is defined to be the total number of people in the working-age group (15 years to 60 years) multiplied by the labor force participation fraction LFPF of 0.75. We assumed that only 75 percent of the population in the working-age group (which includes women) is actually willing or able to pursue employment.

Impact of Labor Scarcity on Capital Utilization CUF

```
LUF.K=J.K/LF.K                                               81, A
    LUF     - LABOR UTILIZATION FRACTION (DIMENSIONLESS)
    J       - JOBS (PERSONS)
    LF      - LABOR FORCE (PERSONS)

LUFD.K=SMOOTH(LUF.K,LUFDT)                                   82, A
LUFDT=2                                                      82.1, C
    LUFD    - LABOR UTILIZATION FRACTION DELAYED
                (DIMENSIONLESS)
    SMOOTH  - FIRST-ORDER EXPONENTIAL INFORMATION DELAY
    LUF     - LABOR UTILIZATION FRACTION (DIMENSIONLESS)
    LUFDT   - LABOR UTILIZATION FRACTION DELAY TIME
                (YEARS)
```

The labor utilization fraction LUF is a measure of the degree to which the labor force LF is occupied by the available jobs. For example, if LF is twice the number of jobs J, then LUF is 0.5; if LF is half the number of jobs, LUF is 2.0. Values of the labor utilization fraction LUF greater than 1.0 indicate a labor shortage in which the number of jobs exceeds the labor force.

The capital utilization fraction CUF depends on the labor utilization fraction delayed LUFD, a two-year exponential average value of LUF. CUFT, the table function incorporating the relation between LUFD and CUF into the model, is illustrated in Figure 3-35.

```
CUF.K=TABHL(CUFT,LUFD.K,1,11,2)                              83, A
CUF=1                                                        83.1, N
CUFT=1/.9/.7/.3/.1/.1                                        83.2, T
    CUF     - CAPITAL UTILIZATION FRACTION
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    CUFT    - CUF TABLE
    LUFD    - LABOR UTILIZATION FRACTION DELAYED
                (DIMENSIONLESS)
```

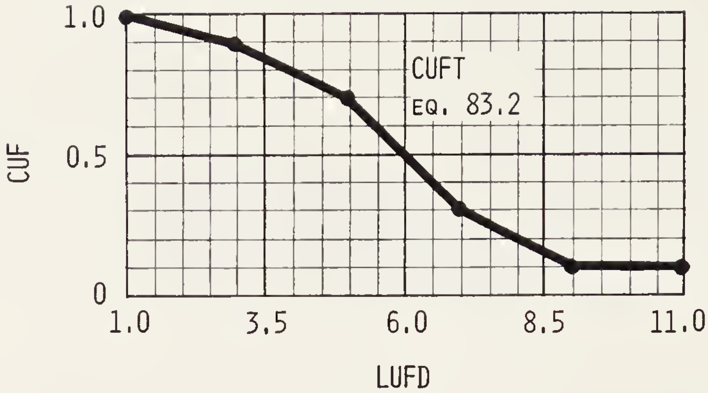

Figure 3-35 Postulated relationship between the labor utilization fraction delayed and the capital utilization factor

As LF falls, LUFD rises and CUF falls, decreasing the effective amount of capital available to produce industrial and service output. We assumed that if LUFD rises to 10, corresponding to ten jobs for every worker, CUF will fall to 0.1. The slope and the asymptotes of the curve must be roughly correct. However, since the curve comes into effect only during the collapse of population, the precise form of the relationship is subject to speculation.

The actual relation between LUFD and CUF depends on the distribution of the labor shortage across the industrial, agriculture, and service sectors. Here we assume that the industrial and service sectors bear proportionately the same burden of coping with any lack of labor. An alternative approach would be to multiply each sector by its own capital utilization factor. However, this refinement is certainly not justified in World3, where the labor sector is active only during the collapse mode of the model. Because so many relationships that are likely to be important during a collapse are completely missing from World3, the model's utility in studying a population decline would not be increased by slightly refining the labor sector.

3.7 SIMULATION RUNS

The combined capital and job sector can be simulated in isolation from the rest of World3 if exogenous values are provided for population POP, the fraction of capital allocated to obtaining resources FCAOR, the fraction of industrial output allocated to agriculture FIOAA, the population of working age P2 and P3, arable land AL, and agricultural inputs per hectare AIPH. For the simulations reported here, these variables were specified directly or indirectly as functions of time; in the complete model runs, these variables were endogenously determined by the other model sectors. The equations used to generate the following runs are listed in the appendix to this chapter.

Standard Run

In this simulation we established values for the exogenous variables so that population POP follows its historical values, growing from 1.6 billion in 1900 to 3.6 billion in 1970, the fraction of capital allocated to obtaining resources FCAOR remains constant at 0.05, and the fraction of industrial output allocated to agriculture FIOAA stays constant at 0.10. Arable land AL and agricultural inputs per hectare AIPH are assigned the same values over time that they exhibit in the World3 standard run. Arable land increases from 0.9 to 2.4 billion hectares between 1900 and 2100. The inputs per hectare rise from 5 to 123 dollars per hectare-year between 1900 and 2020 and then decline. The populations from ages 15 to 44 and 45 to 64, P2 and P3, are each taken to be one-fourth of the total population. The values for the five driving functions between 1900 and 1970 are shown in Figure 3-36.

The behavior of the capital sector in response to these inputs is shown in Run 3-1 (Figure 3-37). Industrial output per capita IOPC and service output per capita SOPC roughly pass through their assumed historical values for 1900 and 1970: IOPC(1900) = 40 dollars per person-year, IOPC(1970) = 250 dollars per person-year, SOPC(1900) = 90 dollars per person-year, and SOPC(1970) = 350 dollars per person-year. The fraction of industrial output allocated to services FIOAS is constant at about 0.12, implying that indicated service output per capita ISOPC is slightly higher than SOPC. The labor force is great enough to make the capital utilization fraction CUF equal 1.0 throughout. The growth resulting from positive feedback in the capital sector is clearly evident.

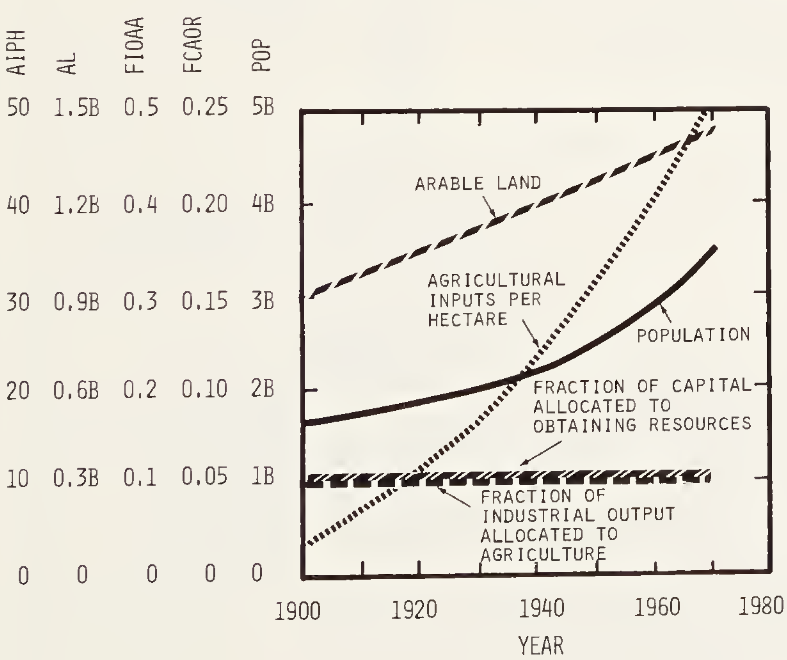

Figure 3-36 Driving functions for the standard run of the capital sector

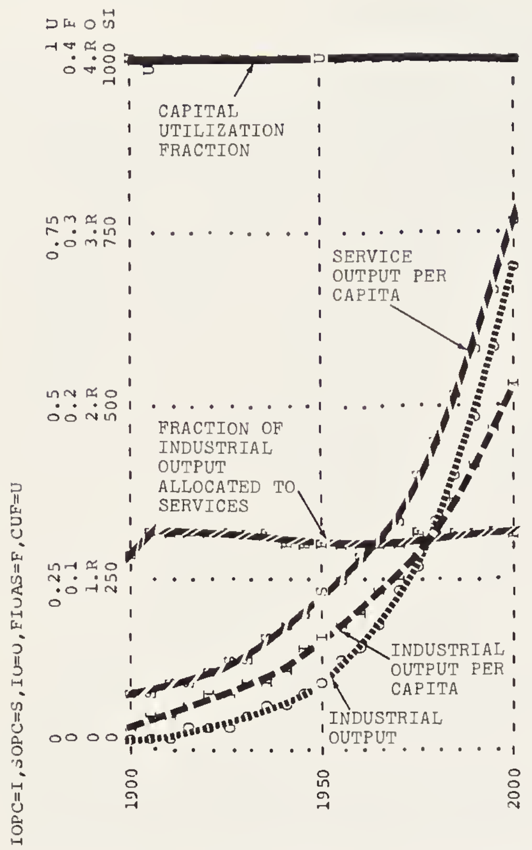

Figure 3-37 Run 3-1: standard run of the capital sector with exogenous inputs

Sensitivity Tests of the Capital Sector

The cardinal determinant of behavior in the capital sector is the rate of growth engendered in the feedback loop linking industrial capital IC, industrial output IO, and the industrial capital investment rate. The change in industrial capital over time may be expressed with the following differential equation:

$$\frac{d(IC)}{dt} = \frac{(IC)(1-FCAOR)(CUF)}{ICOR}(FIOAI) - \frac{IC}{ALIC}.$$

The annual growth rate in industrial capital is

$$G = \frac{d(IC)/dt}{IC}$$

$$= \frac{(1-FCAOR)(CUF)}{ICOR}(1-FIOAS-FIOAS-FIOAA-FIOAC) - \frac{1}{ALIC},$$

where

ALIC	=	average life of industrial capital (years)
FCAOR	=	fraction of capital allocated to obtaining resources
FIOAA	=	fraction of industrial output allocated to agriculture
FIOAC	=	fraction of industrial output allocated to consumption
FIOAI	=	fraction of industrial output allocated to industry
FIOAS	=	fraction of industrial output allocated to services
G	=	annual growth rate of industrial capital
IC	=	industrial capital (dollars)
ICOR	=	industrial capital–output ratio (years)

In the standard run of the capital sector we defined FIOAA = 0.1, ALIC = 14.0, FIOAC = 0.43, ICOR = 3.0, and FCAOR = 0.05 and found FIOAS = 0.12 and CUF = 1.0. Thus the gain around the capital loop is about 0.04, and the doubling time of industrial output is about 18 years. Since population is also growing, but at a slower rate, the doubling time for industrial output per capita is about 30 years. Any change in the model that influences the value of FCAOR, ICOR, FIOAS, FIOAA, FIOAC, ALIC, or CUF will alter the growth rate G of industrial capital IC. If the value of G as defined here is greater than 0, IC will grow exponentially; if G = 0, IC will be constant over time, with the industrial output allocated to industrial investment (FIOAI × IO) only replacing depreciation. If G < 0, the amount of capital stock will decline exponentially toward zero over time. Runs 3-2 (Figure 3-38) and 3-3 (Figure 3-39) illustrate the behavior of the capital sector for different values of G greater than 1.0. To obtain Run 3-2 we changed the average lifetime of industrial capital ALIC from 14 to 21 years. The result is a substantial increase in the growth rate of the sector. Instead of reaching 250 dollars per person-year by 1970, IOPC now reaches 900 dollars per person-year by 1970. Run 3-3 illustrates the capital sector's behavior when we assumed an industrial capital-output ratio ICOR of 2 years. When less capital is required to produce the same output, capital growth can proceed much more quickly than in the standard capital sector run (Run 3-1). When ICOR is reduced by one-third, all else being equal, IOPC rises to 250 dollars per person-year by 1922 and is substantially beyond the scale limit of 1000 dollars per person-year by 1970. Run 3-4 (Figure 3-40) portrays the results when ICOR was set equal to 4 years, an increase of 33 percent from the standard

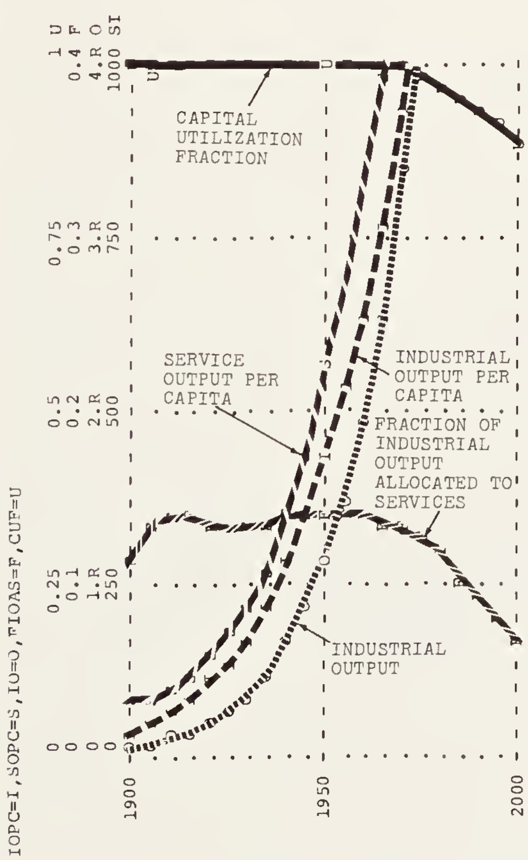

Figure 3-38 Run 3-2: behavior of the capital sector when the average lifetime of industrial capital is increased from 14 to 21 years with standard inputs

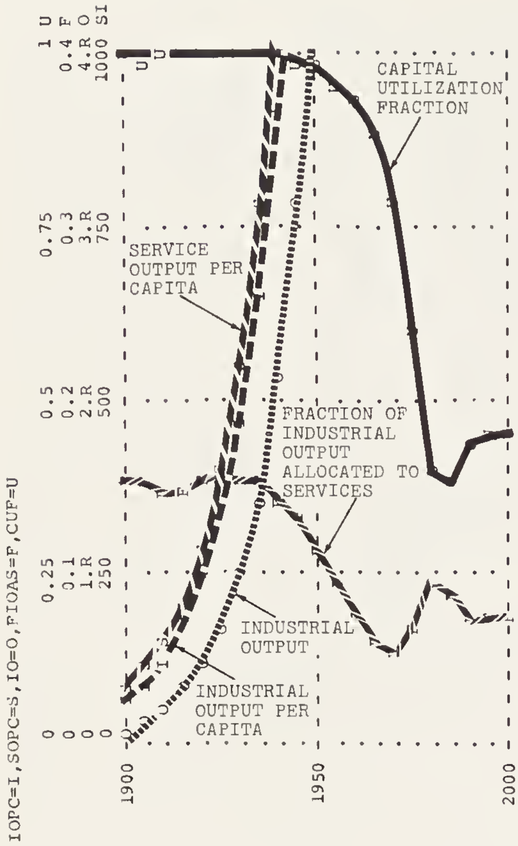

Figure 3-39 Run 3-3: behavior of the capital sector when the capital-output ratio is decreased from 3 to 2 years with standard inputs

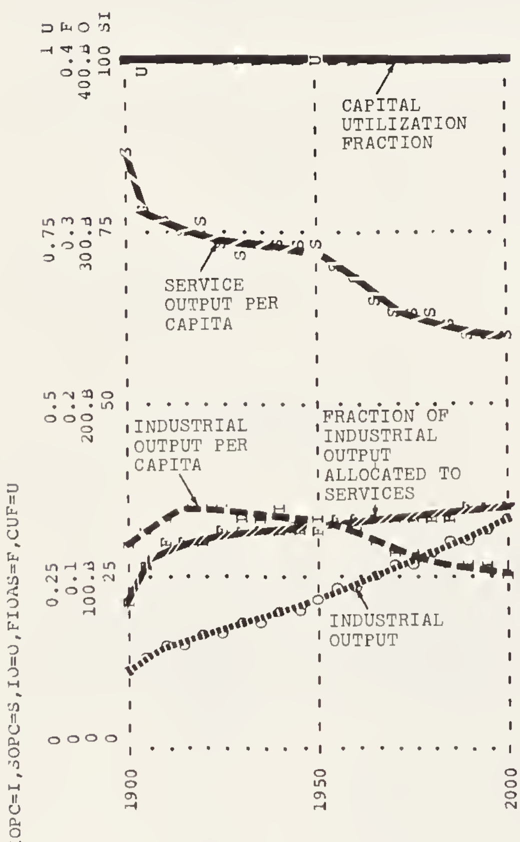

Figure 3-40 Run 3-4: behavior of the capital sector when the industrial capital-output ratio is increased from 3 to 4 years with standard inputs.

Note: Scales for IOPC, SOPC, and IO have been changed from their normal values.

run. With this higher capital-output ratio, IOPC increases very little beyond its initial value in 1900. If ICOR were raised to 4.6, the growth of the capital investment loop would be zero, IO would remain constant, and IOPC would decline. Run 3-5 (Figure 3-41) portrays the effects of decreasing the growth in industrial capital below zero by increasing FCAOR to 0.35, an increase of 700 percent. Notice that the IOPC scale has been altered in Runs 3-4 and 3-5 to provide more detail. In Run 3-5 the industrial output per capita IOPC declines from 25 to 12 dollars per person-year between 1900 and 1970.

It should be clear that all the variables in the service capital sector have indirect effects on the growth rate of capital. Suppose, for example, that productivity in the service sector were only 50 percent of the original estimate and the service capital-output ratio SCOR equaled 2 years rather than 1 year. Run 3-6 (Figure 3-42) illustrates the resulting behavior when this change is made; a higher level of investment is needed in the service sector to generate the indicated service output per capita ISOPC. The fraction of industrial output allocated to services FIOAS increases from 0.12 in the standard run to 0.18, thus effectively decreasing the investment in the industrial sector. The result is that industrial output IO barely grows from 1900 to 1970. The annual industrial output per capita IOPC is only about 70 dollars per person-year in 1970.

While it appears that the parameter values chosen for the standard run produce a behavior that is consistent with the few historical data cited, it is also clear that small changes in parameter values can cause the sector to generate entirely different behavior modes. Since the precision of our data is so low, there is need for additional study of the minor subloops that could be incorporated in future versions of the world model to make its behavior less sensitive to reasonable changes in coefficients.

Alternative Behavior Modes of the Capital Sector

Growth, equilibrium, and decay are the three long-term endogenous behavior modes of the capital sector. In the runs just discussed, the constants and exogenous inputs were chosen to exhibit each of these modes from the beginning of the simulation. When the capital sector is enmeshed in World3, population POP, fraction of industrial output allocated to agriculture FIOAA, fraction of capital allocated to obtaining resources FCAOR, arable land AL, agricultural inputs per hectare AIPH, and service capital investment rate SCIR will all change over time. Although changes in these parameters cannot force the capital sector into any behavior mode not already seen, changes in the inputs could lead the capital sector to shift from one behavior mode to another during the run. Several additional simulations will be presented here to illustrate typical ways in which this shift might occur.

By altering the driving functions for POP, FCAOR, and FIOAA, we determined the reaction of the capital sector to alternative conditions outside the sector. For example, if resources were suddenly to become severely depleted midway through the simulation run, FCAOR would increase markedly. The inputs necessary to represent this change are shown in Figure 3-43. AL and AIPH retain their standard values.

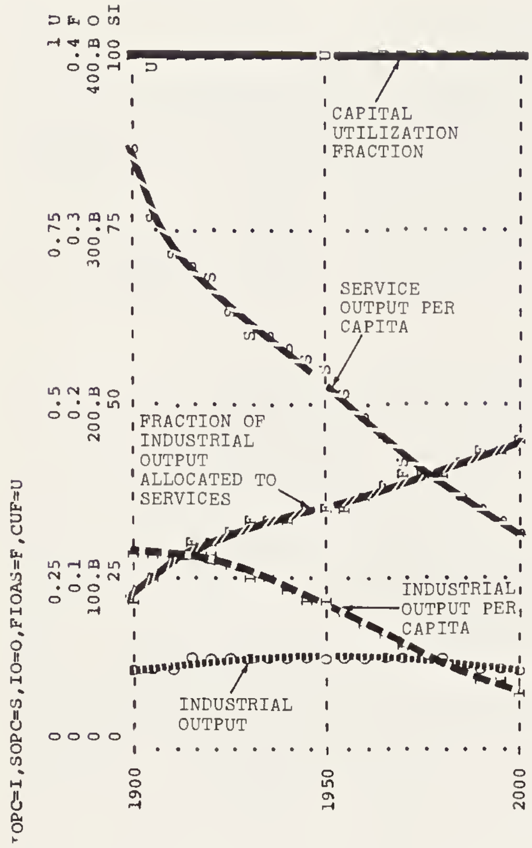

Figure 3-41 Run 3-5: behavior of the capital sector when the fraction of capital allocated to obtaining resources is increased from 0.05 to 0.35 with other inputs at their standard values.

Note: Scales for IOPC, SOPC, and IO have been changed from their normal values.

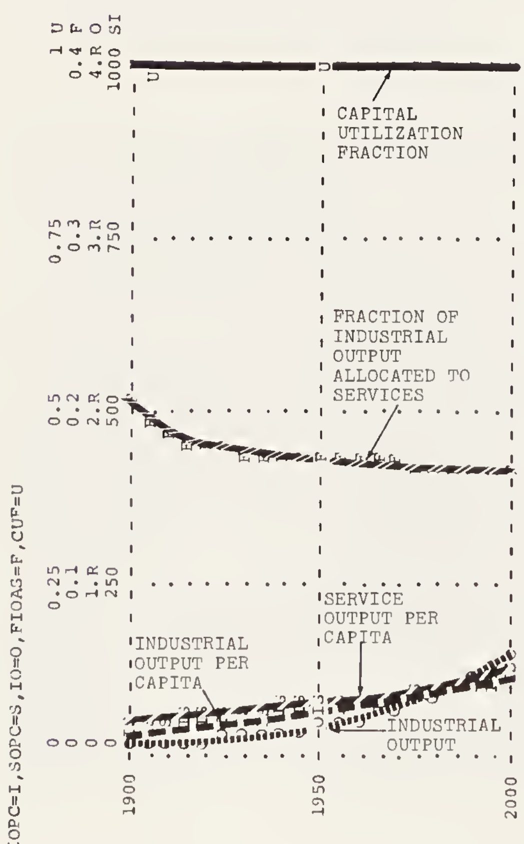

Figure 3-42 Run 3-6: behavior of the capital sector when the service capital-output ratio is increased from 1 to 2 years with standard inputs

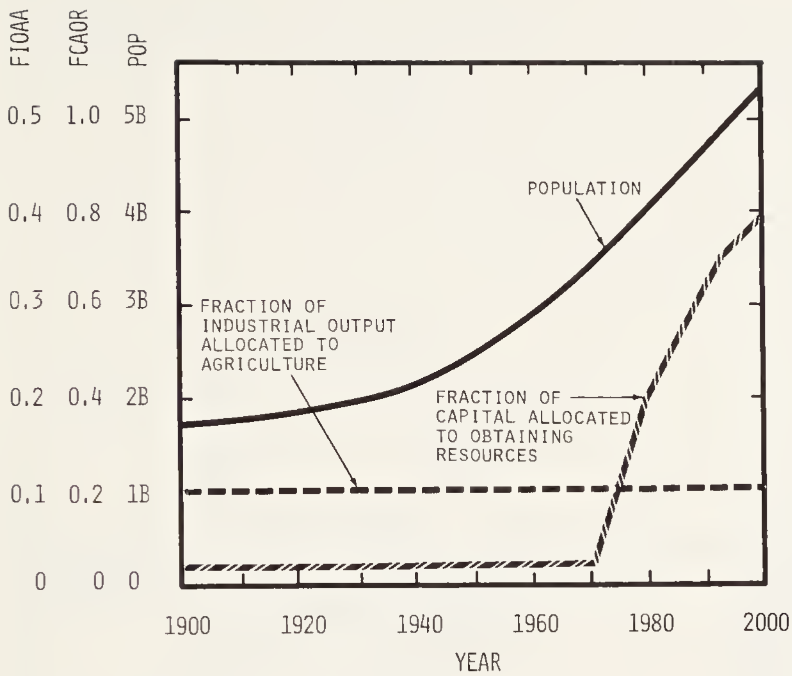

Figure 3-43 Driving functions for capital sector experiencing increasing resource costs

The consequences of increased resource costs are shown in Run 3-7 (Figure 3-44). When FCAOR rises above 0.2, the industrial capital investment rate ICIR is depressed below the depreciation rate ICDR, forcing industrial capital IC to decline. This behavior illustrates the effect of the resource crisis on the capital sector. Declining resource reserves cause increased costs and force a reallocation of capital out of production and into obtaining resources. This reduces the industrial output and thus decreases the amount that may be invested in future time periods, leading to lower industrial capital and output in the future. A resource crisis is not abrupt and does not cause capital to lie idle. At each point in time, the industrial system is producing the maximum amount of material output possible. However, through time the amount of possible output declines.

In Figure 3-45 we specify driving functions that represent the effects of a rising need for investment in agriculture. All inputs are the same as those employed in the standard capital run except for the fraction of industrial output allocated to agriculture FIOAA, which rises from 0.1 to 0.3 between 1970 and 1980. An increase in FIOAA might result from a loss of arable land, from declining agricultural productivity, or from decreasing the marginal return to capital invested in agriculture.

The output from the simulation of the model with this change is shown in Run 3-8 (Figure 3-46). As FIOAA begins to rise, industrial output IO is redirected from investment in services and reinvestment in industrial capital; thus industrial output IO

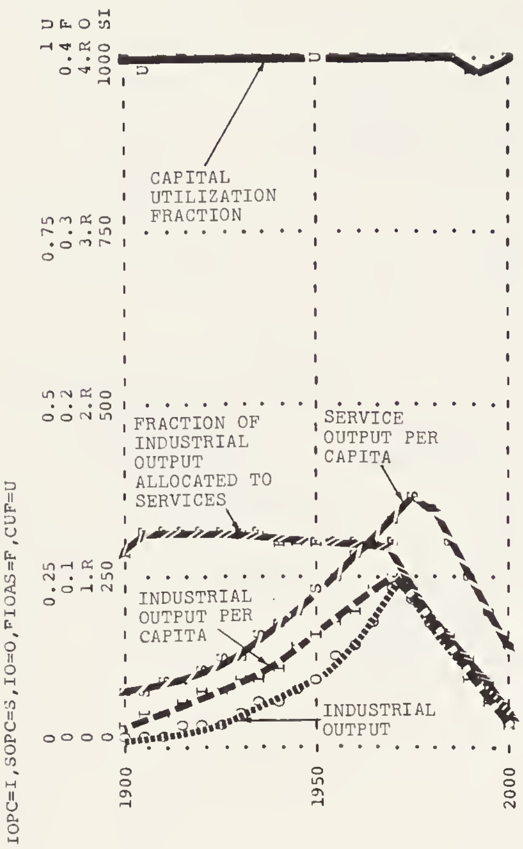

Figure 3-44 Run 3-7: behavior of the capital sector when the fraction of capital allocated to obtaining resources increases after 1970

and the industrial output per capita IOPC begin to fall. This is the effect of a food crisis on the industrial sector. Investing a large fraction of output in agriculture causes industrial investment to drop below depreciation, and output per capita declines.

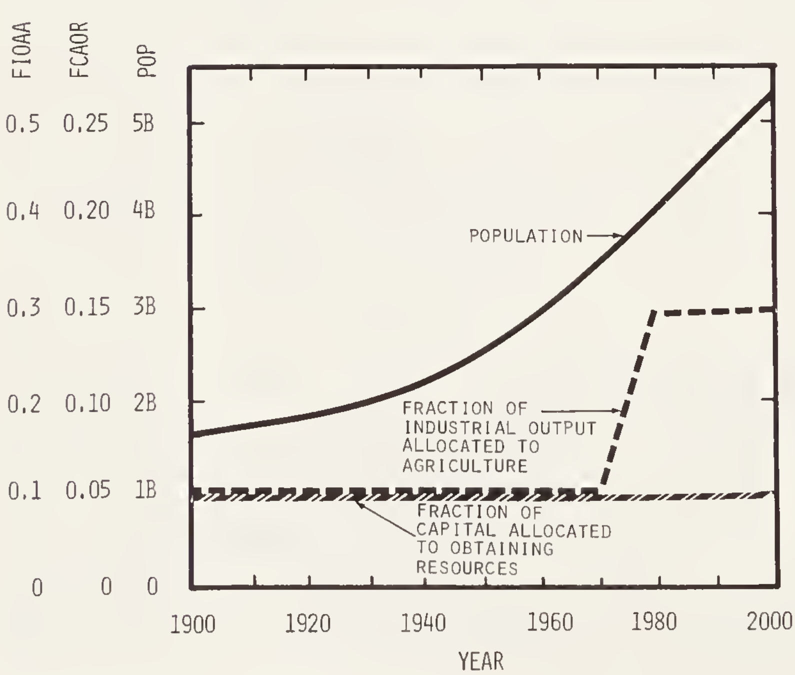

Figure 3-45 Driving functions for capital sector undergoing increasing food costs

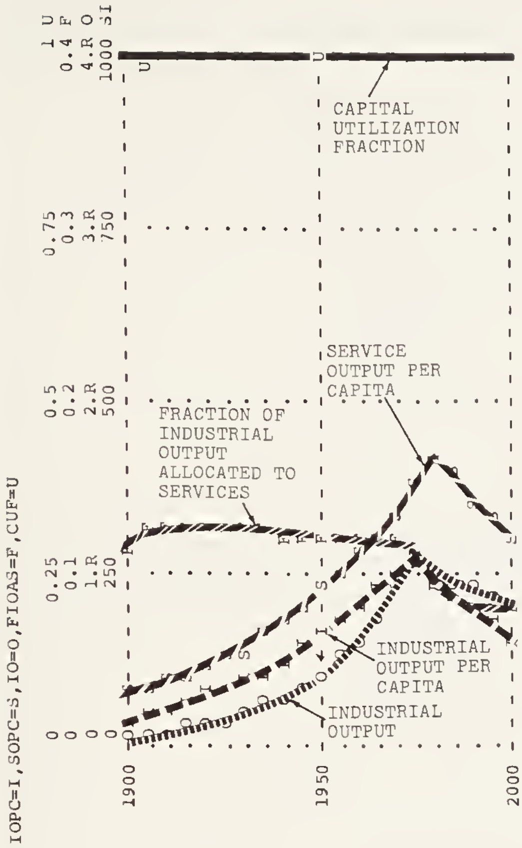

Figure 3-46 Run 3-8: behavior of the capital sector when the fraction of industrial output allocated to agriculture increases after 1970.

Finally, we can simulate a hypothetical reduction in population POP, and thus a shortage of labor. A decline in the population would lead to a higher labor utilization fraction LUF and thus a lower capital utilization factor CUF. The external parameters for this simulation are given in Figure 3-47. The effects of this change are

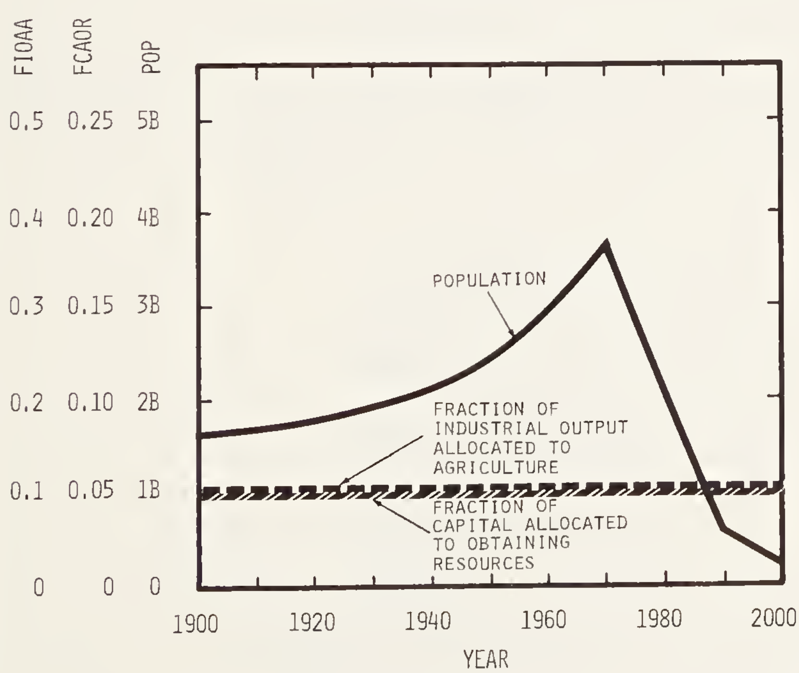

Figure 3-47 Driving functions for a population decline in the capital sector

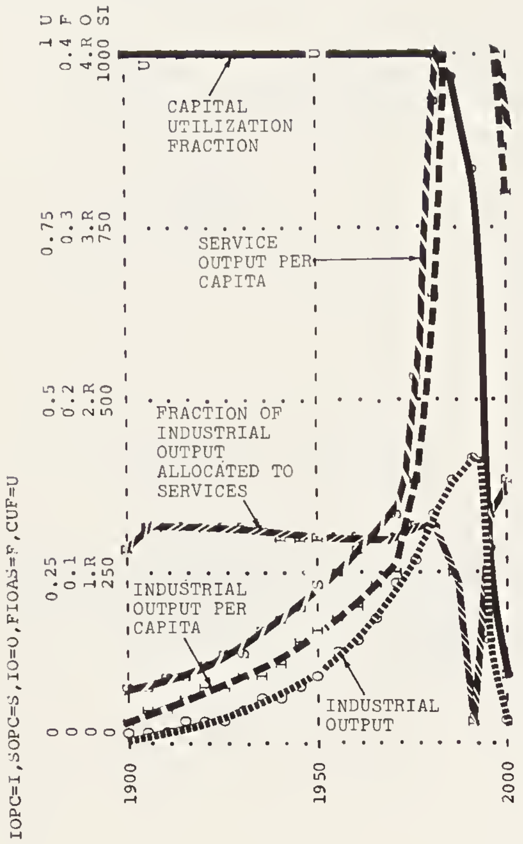

Figure 3-48 Run 3-9: behavior of the capital sector when the population declines after 1970

simulated in Run 3-9 (Figure 3-48). The decline in population after 1970 has the immediate effect of increasing both service and industrial outputs per capita SOPC and IOPC. However, SOPC begins to fall by 1970 because of the declining labor force LF and the consequent unutilized capital, which eventually force SOPC and, later, IOPC to decline as well.

The structure of the capital sector is sufficiently simple that the nine runs presented in Chapter 3 portray all modes of capital's behavior witnessed in our analyses of World3. However, through interaction with the population, pollution, resource, and agriculture sectors, the behavior mode of the capital sector may change several times during the course of a simulation run. To understand that interaction more fully we describe the structure of the agriculture sector in Chapter 4.

APPENDIX : PROGRAM LISTING

```
        CAPTR

        *       CAPITAL SECTOR WITH EXOGENOUS INPUTS
        NOTE
        NOTE    INDUSTRIAL SUBSECTOR
        NOTE
49      A       IOPC.K=IO.K/POP.K
50      A       IO.K=(IC.K)(1-FCAOR.K)(CUF.K)/ICOR.K
51      A       ICOR.K=CLIP(ICOR2,ICOR1,TIME.K,PYEAR)
        C       ICOR1=3
        C       ICOR2=3
52      L       IC.K=IC.J+(DT)(ICIR.JK-ICDR.JK)
        N       IC=ICI
        C       ICI=2.1E11
53      R       ICDR.KL=IC.K/ALIC.K
54      A       ALIC.K=CLIP(ALIC2,ALIC1,TIME.K,PYEAR)
        C       ALIC1=14
        C       ALIC2=14
55      R       ICIR.KL=(IO.K)(FIOAI.K)
56      A       FIOAI.K=(1-FIOAA.K-FIOAS.K-FIOAC.K)
57      A       FIOAC.K=CLIP(FIOACV.K,FIOACC.K,TIME.K,IET)
        C       IET=4000
58      A       FIOACC.K=CLIP(FIOAC2,FIOAC1,TIME.K,PYEAR)
        C       FIOAC1=.43
        C       FIOAC2=.43
59      A       FIOACV.K=TABHL(FIOACVT,IOPC.K/IOPCD,0,2,.2)
        T       FIOACVT=.3/.32/.34/.36/.38/.43/.73/.77/.81/.82/.83
        C       IOPCD=400
        NOTE
        NOTE    SERVICE SUBSECTOR
        NOTE
60      A       ISOPC.K=CLIP(ISOPC2.K,ISOPC1.K,TIME.K,PYEAR)
61      A       ISOPC1.K=TABHL(ISOPC1T,IOPC.K,0,1600,200)
        T       ISOPC1T=40/300/640/1000/1220/1450/1650/1800/2000
62      A       ISOPC2.K=TABHL(ISOPC2T,IOPC.K,0,1600,200)
        T       ISOPC2T=40/300/640/1000/1220/1450/1650/1800/2000
63      A       FIOAS.K=CLIP(FIOAS2.K,FIOAS1.K,TIME.K,PYEAR)
64      A       FIOAS1.K=TABHL(FIOAS1T,SOPC.K/ISOPC.K,0,2,.5)
        T       FIOAS1T=.3/.2/.1/.05/0
65      A       FIOAS2.K=TABHL(FIOAS2T,SOPC.K/ISOPC.K,0,2,.5)
        T       FIOAS2T=.3/.2/.1/.05/0
66      R       SCIR.KL=(IO.K)(FIOAS.K)
67      L       SC.K=SC.J+(DT)(SCIR.JK-SCDR.JK)
        N       SC=SCI
        C       SCI=1.44E11
68      R       SCDR.KL=SC.K/ALSC.K
69      A       ALSC.K=CLIP(ALSC2,ALSC1,TIME.K,PYEAR)
        C       ALSC1=20
        C       ALSC2=20
70      A       SO.K=(SC.K)(CUF.K)/SCOR.K
71      A       SOPC.K=SO.K/POP.K
72      A       SCOR.K=CLIP(SCOR2,SCOR1,TIME.K,PYEAR)
        C       SCOR1=1
        C       SCOR2=1
        NOTE
        NOTE    JOB SUBSECTOR
        NOTE
73      A       J.K=PJIS.K+PJAS.K+PJSS.K
74      A       PJIS.K=(IC.K)(JPICU.K)
75      A       JPICU.K=(TABHL(JPICUT,IOPC.K,50,800,150))(1E-3)
        T       JPICUT=.37/.18/.12/.09/.07/.06
76      A       PJSS.K=(SC.K)(JPSCU.K)
77      A       JPSCU.K=(TABHL(JPSCUT,SOPC.K,50,800,150))(1E-3)
        T       JPSCUT=1.1/.6/.35/.2/.15/.15
78      A       PJAS.K=(JPH.K)(AL.K)
79      A       JPH.K=TABHL(JPHT,AIPH.K,2,30,4)
        T       JPHT=2/.5/.4/.3/.27/.24/.2/.2
80      A       LF.K=(P2.K+P3.K)*LFPF
        C       LFPF=.75
81      A       LUF.K=J.K/LF.K
82      A       LUFD.K=SMOOTH(LUF.K,LUFDT)
        C       LUFDT=2
83      A       CUF.K=TABHL(CUFT,LUFD.K,1,11,2)
        N       CUF=1
        T       CUFT=1/.9/.7/.3/.1/.1
        NOTE
        NOTE    EXOGENOUS INPUTS TO THE CAPITAL SECTOR
```

```
NOTE
NOTE   AGRICULTURAL INPUTS PER HECTARE
NOTE
A      AIPH.K=TABHL(AIPHT,TIME.K,1900,2100,20)
T      AIPHT=5/11/21/34/58/86/123/61/23/8/3
NOTE
NOTE   ARABLE LAND
NOTE
A      AL.K=(TABHL(ALT,TIME.K,1900,2100,20))(1E8)
T      ALT=9/10/11/13/16/20/23/24/24/24/24
NOTE
NOTE   POPULATION
NOTE
A      POP.K=(TABHL(POPT,TIME.K,1900,2000,10))(1E9)
T      POPT=1.65/1.73/1.8/2.1/2.3/2.55/3/3.65/4/4.6/5.15
A      P2.K=.25*POP.K
A      P3.K=.25*POP.K
NOTE
NOTE   FRACTION OF CAPITAL ALLOCATED TO OBTAINING RESOURCES
NOTE
A      FCAOR.K=TABHL(FCAORT,TIME.K,1900,2000,10)
T      FCAORT=.05/.05/.05/.05/.05/.05/.05/.05/.05/.05/.05
NOTE
NOTE   FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO AGRICULTURE
NOTE
A      FIOAA.K=TABHL(FIOAAT,TIME.K,1900,2000,10)
T      FIOAAT=.1/.1/.1/.1/.1/.1/.1/.1/.1/.1/.1
NOTE
NOTE   CONTROL CARDS
NOTE
C      PYEAR=4000
N      TIME=1900
SPEC   DT=1/LENGTH=2000/PRTPER=0/PLTPER=5
PLOT   IOPC=I,SOPC=S(0,1000)/IO=O(0,4E12)/
X      FIOAS=F(0,.4)/CUF=U(0,1)
NOTE
NOTE   PARAMETER CHANGES FOR THE CAPITAL SECTOR RUNS
NOTE
NOTE   CAPITAL SECTOR STANDARD RUN
NOTE
RUN    FIGURE 3-37: CAPITAL SECTOR STANDARD RUN
NOTE
NOTE   SENSITIVITY TESTS
NOTE
C      ALIC1=21
RUN    FIGURE 3-38: INCREASED ALIC BY 50%
C      ICOR1=2
RUN    FIGURE 3-39: DECREASED ICOR BY 33%
C      ICOR1=4
PLOT   IOPC=I,SOPC=S(0,100)/IO=O(0,4E11)/
X      FIOAS=F(0,.4)/CUF=U(0,1)
RUN    FIGURE 3-40: INCREASED ICOR BY 33%
T      FCAORT=.35/.35/.35/.35/.35/.35/.35/.35/.35/.35/.35
PLOT   IOPC=I,SOPC=S(0,100)/IO=O(0,4E11)/
X      FIOAS=F(0,.4)/CUF=U(0,1)
RUN    FIGURE 3-41: INCREASED FCAOR FROM .05 TO .35
C      SCOR1=2
PLOT   IOPC=I,SOPC=S(0,1000)/IO=O(0,4E12)/
X      FIOAS=F(0,.4)/CUF=U(0,1)
RUN    FIGURE 3-42: INCREASED SCOR 100% FROM 1 TO 2
T      FCAORT=.05/.05/.05/.05/.05/.05/.05/.05/.4/.6/.8
NOTE
NOTE   RUNS ILLUSTRATING ALTERNATIVE BEHAVIOR MODES
NOTE
RUN    FIGURE 3-44: INCREASED RESOURCE COSTS AFTER 1970
T      FIOAAT=.1/.1/.1/.1/.1/.1/.1/.1/.3/.3/.3
RUN    FIGURE 3-46: INCREASED AGRICULTURAL COSTS AFTER 1970
T      POPT=1.65/1.73/1.8/2.1/2.3/2.55/3/3.65/2/.5/.2
RUN    FIGURE 3-48: SHARP POPULATION DECREASE AFTER 1970
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REFERENCES

Allen 1967	Allen, R. G. D. *Macroeconomic Theory*. New York: Macmillan Co., 1967.
Benoit 1972	Benoit, Emile. "Closing the International Income Gap: Is It Urgent?" *Columbian Journal of World Business*, no. 2 (March–April 1972).
CEQ 1972	Council on Environmental Quality. "Summary of Long-Range Forecasting Activities Performed by the Federal Agencies." Interagency memorandum. Washington, D. C., August 11, 1972.
Chenery and Taylor 1968	Chenery, Hollis B., and Lance Taylor."Development Patterns: Among Countries and Over Time." *Review of Economics and Statistics* 50, no. 4 (November 1968).
Domar 1957	Domar, E. D. *Essays in the Theory of Economic Growth*. Fair Lawn, N.J.: Oxford University Press, 1957.
Harrod 1948	Harrod, R. F. *Towards a Dynamic Economics*. London: Macmillan & Co., 1948.
IBRD 1970	International Bank for Reconstruction and Development. *World Bank Atlas*. Washington, D.C., 1970.
ILO 1970	International Labor Organization. *Yearbook of Labor Statistics*. Geneva, 1970.
ISIC 1968	United Nations. "International Standard Industrial Classification of All Economic Activities." Statistical Papers, series M, no. 4, rev. 2. New York, 1968.
Kuznets 1966	Kuznets, Simon. *Modern Economic Growth*. New Haven: Yale University Press, 1966.
Kuznets 1971	Kuznets, Simon. *Economic Growth of Nations*. Cambridge, Mass.: Harvard University Press, 1971.
Maslow 1954	Maslow, A. H. *Motivation and Personality*. New York: Harper, 1954.
Samuelson 1970	Samuelson, Paul A. *Economics*. New York: McGraw-Hill, 1970.
Temin 1967	Temin, Peter. "A Time-Series Test of Patterns of Industrial Growth." *Economic Development and Cultural Change* 15:174–182.
U.N. 1969	United Nations. Statistical Office. *Yearbook of National Accounts Statistics*. New York, 1969.
U.N. 1970	United Nations. Department of Economic and Social Affairs. *Statistical Yearbook, 1969*. New York, 1970.
U.S.D.A. 1965	United States. Department of Agriculture. *Changes in Agriculture in 26 Developing Nations, 1948–1963*. Foreign Agricultural Economic Report, no. 27. Washington, D.C., 1965.

4
Agriculture Sector

Jørgen Randers and Erich K. O. Zahn

4.1 INTRODUCTION

The fundamental assumption of the agriculture sector of the world model is that the total amount of food that can be produced on the earth each year has some limit. It is well known that the allocation of more physical resources (land, water, fertilizer, and labor) to food production will increase the annual food output. However, we postulate that the physical resources that can be allocated to food production are limited: in World3 the available agricultural land is limited, the amount of fertilizer is limited by the total global industrial production capacity, and the land fertility is limited by pollution absorption mechanisms. Although technological innovations may lead to higher yields on a given land area, we postulate that there are decreasing returns to technology's ability to increase land yields by diverting other limited resource inputs to the agriculture sector.

The purpose of this chapter is threefold: to propose a structure that relates the land and capital used in agriculture to the food output obtained, to describe the mechanisms by which food output can be increased, and to identify within the chosen structure the forces that can potentially limit total annual food production. We present, in sequence, a set of real-world data illustrating the historical behavior of the elements in this sector, a set of basic concepts underlying the model formulation, the precise causal assumptions of the sector and their exposition in equation form, and simulation runs of the sector as a driven system.

4.2 HISTORICAL BEHAVIOR MODES

The most conspicuous characteristic of the world's food production system is its rather spectacular increase in total output over the last few decades (Figure 4-1). The increase is more impressive in terms of total food production than in per capita food production, since the world population has also increased greatly. The gain in total food output can probably be attributed to two factors: an increase in the cultivated land area, and an increase in the average land yield (Figure 4-2). The observed average land yield has risen sharply within the last hundred years (Figure 4-3), largely because of the advent of modern agricultural inputs such as fertilizer, pesticides, new seed, and farm machinery (Figures 4-4 and 4-5).

There are indications that the recent increases in total global food output cannot continue indefinitely. Opportunities for expanding the amount of arable land are limited (FAO 1970*a*): some arable land is taken out of cultivation for building cities, roads, and airports; some becomes unsuitable for agricultural use through erosion, laterization, or salinization. Future increases in food production may also be restricted by decreasing returns to the use of modern agricultural inputs (Figure 4-6).

Another trend may be occurring globally: land fertility may be gradually decreasing, although little direct evidence is available to support or refute this hypothesis. Here it is useful to make a distinction between land yield (the actual food output per hectare-year obtained through the use of fertilizer, pesticides, and machinery) and land fertility (the intrinsic ability of the soil to produce food without modern

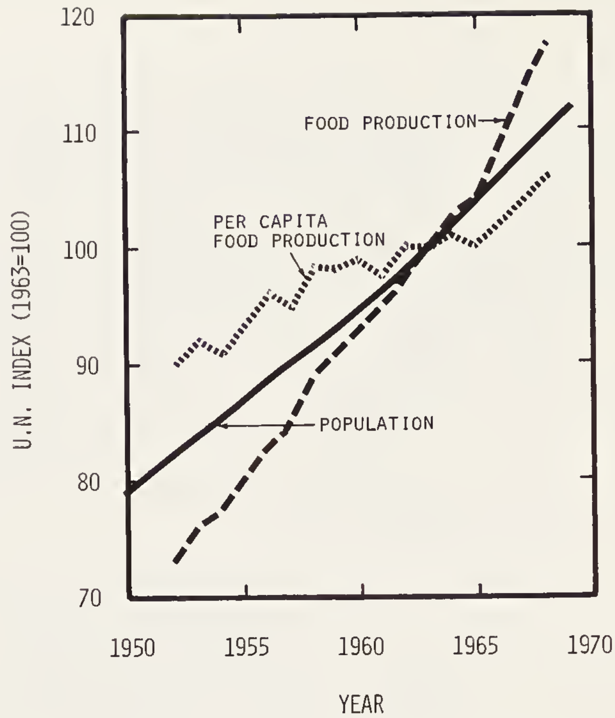


Figure 4-1 Food, food per capita, and population for the world, 1952–1970
Source: Data from U.N. 1970*a*, pp. xxiii, xxv.

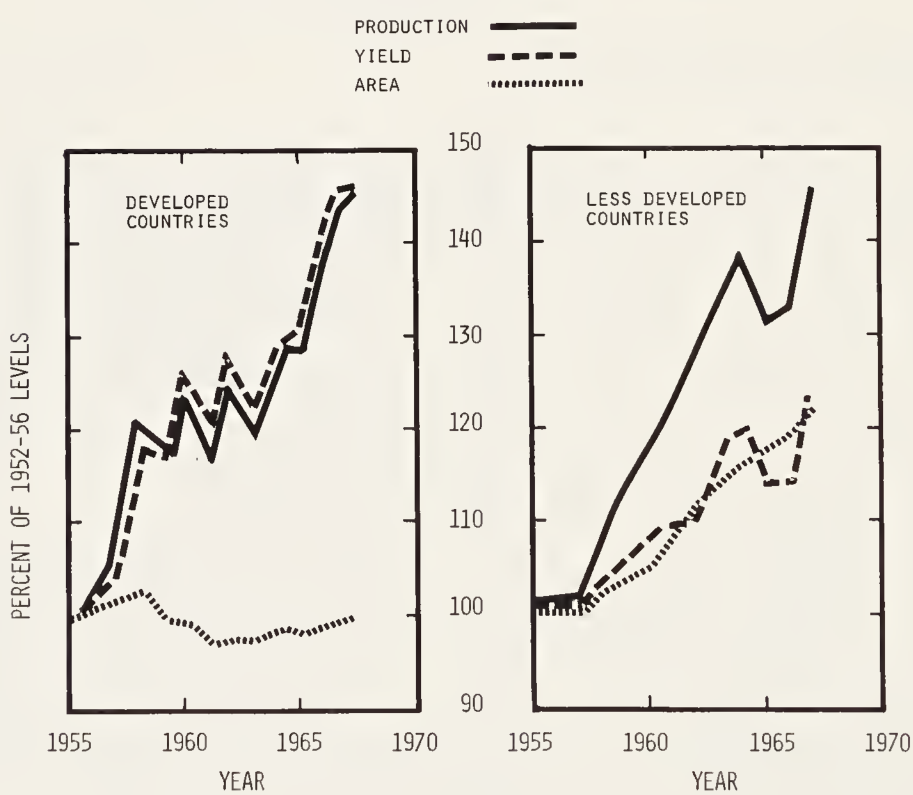


Figure 4-2 Grain production, yield (food output per hectare-year), and cultivated land area for industrialized and nonindustrialized nations, 1952–1970
Source: U.S.D.A. 1970.

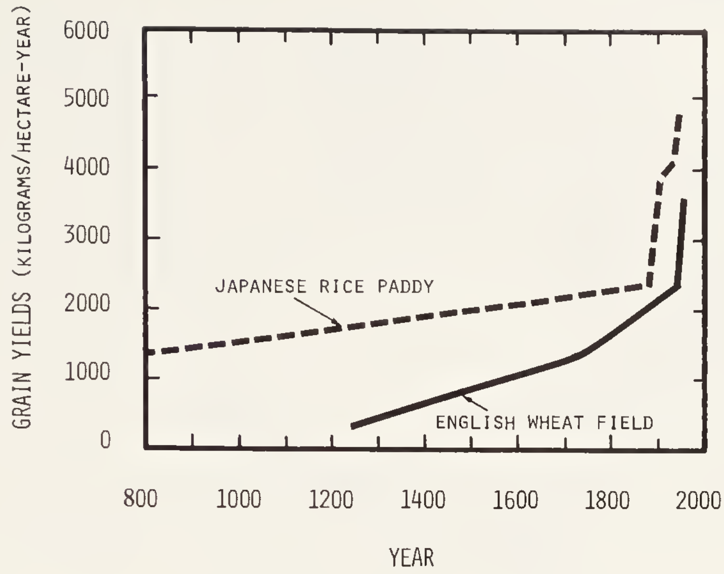


Figure 4-3 Grain yields, 800–1970
Source: U.S.D.A. 1965.

agricultural inputs). The use of large amounts of modern agricultural inputs makes it possible for land yields to remain constant or increase, even if land fertility (the stock of natural nutrients) is decreasing. Figure 4-7 illustrates the trends of observed land yield and probable fertility in one region of the United States.

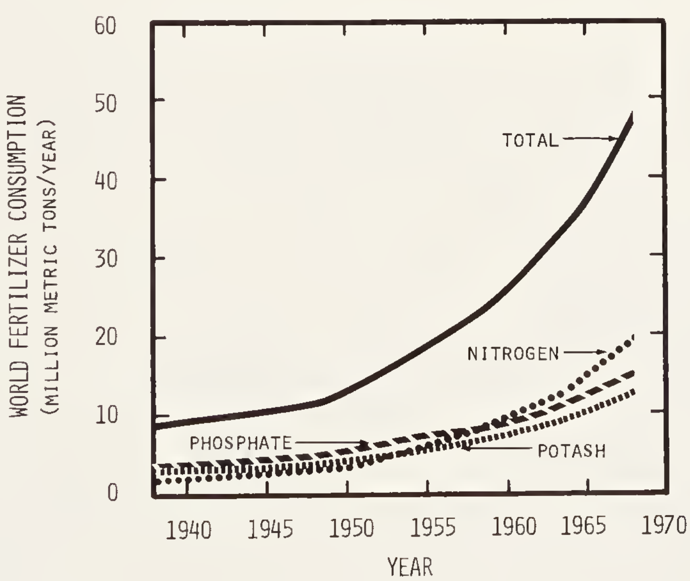


Figure 4-4 The global consumption of fertilizer, 1938–1968
Source: Data from U.N. 1970*a*.
Note: Figures do not include the USSR or the People's Republic of China.

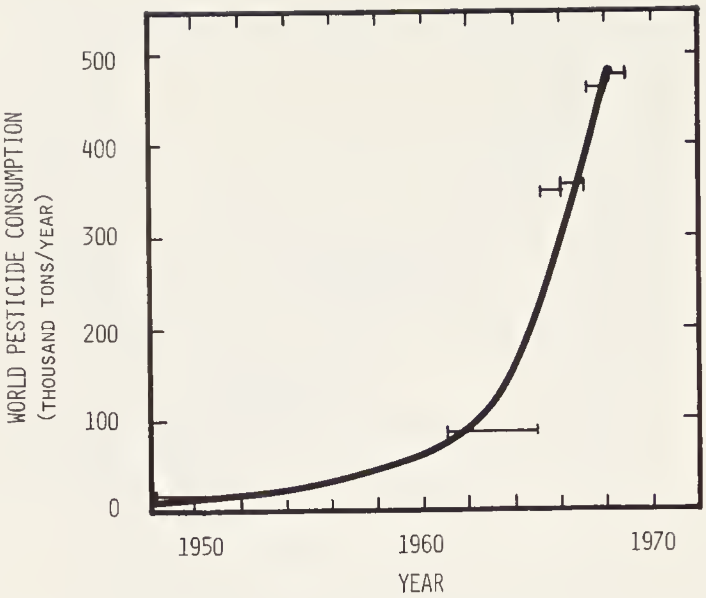


Figure 4-5 The global consumption of pesticides, 1948–1968
Source: Data from FAO 1970*b*.

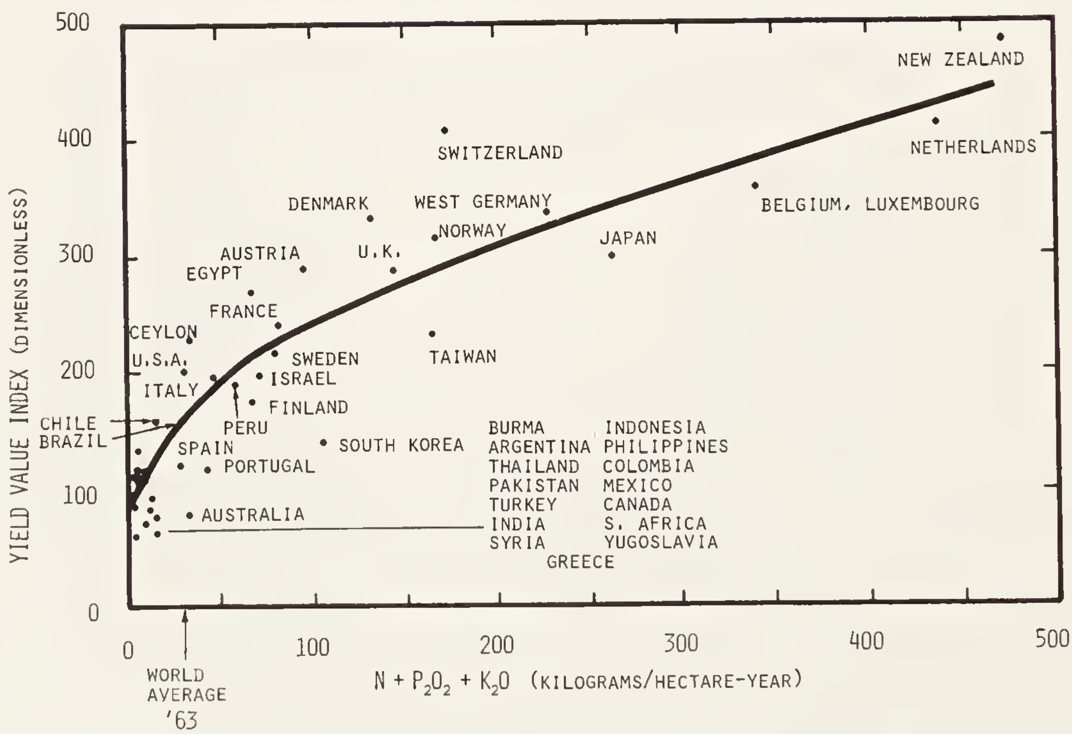


Figure 4-6 Decreasing returns to fertilizer use
Source: Williams and Couston 1962.

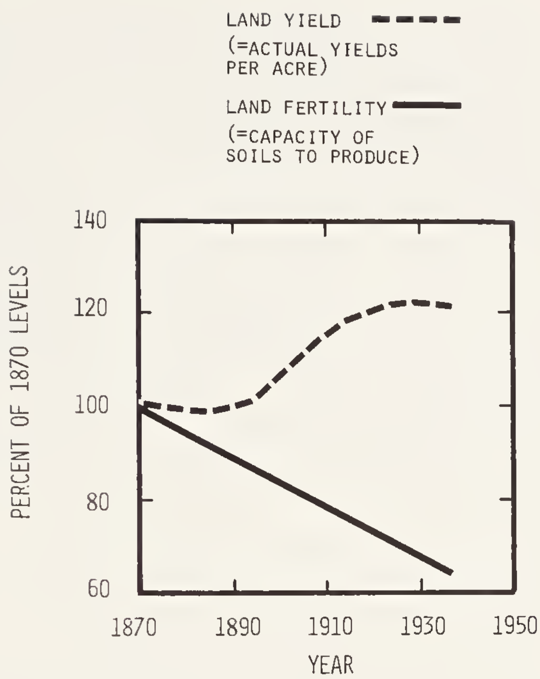


Figure 4-7 Land fertility decrease in Ohio, U.S.A., 1870–1938

The high yields are maintained through modern agricultural inputs (fertilizer, pesticides, and machinery), even though the natural capacity of the soil to produce seems to be decreasing.

Source: Salter, Lewis, and Slipher 1941.

4.3 BASIC CONCEPTS

Definitions of Food and Arable Land

Food is produced not only by the cultivation of arable land, although land cultivation is at present by far the most important source of food for human consumption. Other sources of food are the ocean and the world's grazing lands (lands that cannot be cultivated but still produce vegetation in amounts that can sustain grazing animals). However, the current and potential food output from fisheries and from livestock feeding on grazing land is small compared with the food output from the cultivation of arable land, as we shall show in the following paragraphs. Because we believe that these other sources of food are relatively insignificant and will remain so, we chose to neglect food obtained from the ocean and from grazing land in World3.

The world's grazing lands currently cover 3.6 billion hectares, an area somewhat larger than the potentially arable land area of 3.2 billion hectares (see Figure 4-17). The average carrying capacity of the world's grazing lands is roughly 1 animal unit per 20 hectares (PSAC 1967, vol. 2, p. 429), where 1 animal unit is equivalent to the production of 100 kilograms of meat per year. If it is assumed that 7 kilograms of vegetable crops are needed to produce 1 kilogram of meat (see section 4.5, loop 1), this yield amounts to 35 vegetable-equivalent kilograms per hectare-year. Thus the vegetable-equivalent food yield from grazing land is low even compared with the traditional yield of 600 vegetable-equivalent kilograms per hectare-year that can typically be obtained from arable land without the use of modern agricultural inputs. The grazing land yield is only about 2 percent of the present world average cultivated land yield of around 2,000 vegetable-equivalent kilograms per hectare-year (section 4.5). Full utilization of all grazing land would result in a mere 140 billion ($35 \times 4 \times 10^9$) vegetable-equivalent kilograms per year, or less than 10 percent of the current world grain production of 1,815 billion vegetable-equivalent kilograms per year (Figure 4-8). Finally, the potential global meat output from grazing land—20 billion kilograms of meat per year—is only about one-fourth of the present global meat production of 78 billion kilograms per year (U.N. 1970*a*, p. xxxi). Most livestock is being raised today on grain cultivated on arable land rather than on grasses from grazing land. In summary, the food output from grazing land is relatively unimportant.

On the basis of estimates of the rate at which plankton fix carbon in the ocean, that is, the rate at which biomass is created at the lowest level in the marine food chain, it is usually accepted that there is a maximum possible sustainable catch of fish from the ocean. Measured in kilocalories, the potential fish output from the ocean amounts to about 100×10^{12} kilocalories per year (CRAM 1969, p. 107). Since we assumed 3,500 kilocalories per kilogram of crops (see Figure 4-20), the maximum world fish catch is equivalent to roughly 30 billion vegetable-equivalent kilograms per year. This upper limit is even smaller than the potential food production from grazing land. In the late 1960s the total catch was around 60×10^{12} kilocalories of fish per year, or about 60 percent of the maximum catch (Ryther 1969). Although fish are an important source of protein, the caloric output from the oceans is relatively unimportant.

Yields from both ocean and grazing land might conceivably be increased by improved technologies. However, for these new technologies to have a significant impact, yields of both oceans and grazing land would have to be increased by several hundred percent. We have assumed that such developments are unlikely to occur over the next few decades (see CRAM 1969, chaps. 4, 5), although they were included as test policies in the model runs. Figure 4-8 summarizes the preceding discussion.

	Arable Land	**Oceans**	**Grazing Land**
Current output (billion vegetable-equivalent kilograms per year)	1,815	18	< 140
Potential output (billion vegetable-equivalent kilograms per year)	20,000[a]	300[b]	1,400[b]

[a]Estimate assuming all potentially arable land (3.2 billion hectares) is cultivated at 10 times the traditional land yield, that is, at 6,000 vegetable-equivalent kilograms per hectare-year. It is not certain that food output of this size can be sustained for long periods of time. See later discussion of the numerical values chosen.

[b]Estimate assuming all oceans and grazing land could produce 10 times their currently estimated maximum yields, that is, respectively, 1,000 trillion kilocalories of fish per year and 50 kilograms of meat per hectare-year. Even using this unwarranted assumption, potential food from oceans and grazing land is only of the order of magnitude of the current output from arable land.

Figure 4-8 Current and potential food output from the world's arable land, oceans, and grazing land

Thus for the purposes of World3 the current and potential food output from the oceans and the world's grazing lands is insignificant compared with the output from agricultural land. We therefore chose to neglect these two sources of food in the world model. Hence "food" in World3 is defined as the total production of the world's arable land, measured in vegetable-equivalent kilograms.

Throughout this report the terms "arable land" and "harvested area" are used according to the strict FAO definitions:

> The expressions "arable land" and "harvested land" are used as follows: (a) arable land includes all areas which are used from time to time or full-time to grow crops and includes area under annual crops, area under permanent crops (tree crops, bananas, sugar cane), area under temporary grass and fodder crops, and fallow; (b) harvested area includes the harvested area of annual crops, and permanent crops. [FAO 1970*a*, p. 42]

Note that "arable land" includes fallow land as well as land actually cultivated in any given year.

The Fundamental Postulate of the Agriculture Sector

The world model is based on the fundamental assumption that there is an upper limit to the total amount of food that can be produced annually by the world's agricultural system. In more detail, it is assumed that there is some upper bound on the amount of land that can be brought under cultivation and that the land yield—the annual output from each hectare—is also bounded. Thus the equations of the agriculture sector reflect upper bounds on both arable land and land yield. The parameters of the postulate, namely, the exact values we chose to put on the two upper bounds, are specified in section 4.5.

The implication of the basic assumption is that investments in raising arable land area and annual output per hectare must exhibit decreasing marginal returns, until at some point additional investments yield no return. This assumption of decreasing marginal returns is consistent with real-world trends, although there is probably no current real-world example of zero marginal returns to agricultural investment.

Two Concepts of Land Wastage

In World3 we assumed that capital investments in agriculture can increase total food output in two ways: by increasing the stock of arable land through land development, and by increasing land yield through the application of modern agricultural inputs. The agriculture sector also distinguishes between two phenomena that can reduce overall food production. We defined "land erosion" as an irreversible process, taking place over centuries, that physically removes land from production. In other words, land erosion reduces the amount of arable land by physically eliminating the land (usually into freshwater systems and ultimately the ocean). The rate at which land erodes can be large or small, depending on the human action taken to control the erosion rate, but we assumed that the direction of land movement cannot be changed. The erosion rate can become zero, but it will never become negative.

In World3 we also assumed that the total food output can be reduced through a reduction in land yield caused by lower land fertility—a reduction in the humus and nutrient content of the soil. Such degradation of the land's fertility occurs only when insufficient resources are allocated to the enhancement of the natural soil regeneration mechanisms; thus the regeneration forces do not manage to keep up with the continually occurring degradation forces. The decay of land fertility is assumed to be reversible, so that higher current investments in land maintenance will restore the soil and undo damage resulting from earlier negligence. The reversible process of land fertility degradation and regeneration occurs within decades and is thus much faster than the irreversible erosion process.

The distinction between a long-term, irreversible process and a short-term, reversible process is made clear in Held and Clawson's classification of the three influences man can have on soil: "The numerous effects which modern man exerts upon soil may be divided into three general categories: (1) permanent impairment, (2) temporary damage, and (3) improved productivity" (Held and Clawson 1965, p. 23). Category (1) is represented in the model by land erosion, (2) by land fertility degradation, and (3) by raising the land yield through agricultural inputs. Because of the dynamic differences among these categories, such as differing time lags and economic determinants, each of the three categories was modeled as a distinct element in the agriculture sector.

The Aggregation of the Sector

We chose to include all arable land in a single level, so the model reflects in a single quantity the aggregate of all different cultivable lands with their varying characteristics. This aggregation of land would not be permissible if the model were to be applied to designing detailed land development plans. However, the purpose of the agriculture sector in World3 was to represent the aggregated dynamic response of total food output to the influence of aggregated agricultural investment, persistent pollution, and population pressures. We were primarily interested in the characteristics of food production that are common to all types of land, and a high level of aggregation is all that is needed, given the purpose of this particular model. Because of the wide variance in real-world agricultural parameters, conclusions drawn from this sector should not automatically be considered valid in a practical, specific situation unless the conclusion is robust with respect to major parameter changes. The structure of the model is generally applicable to agricultural subsystems, but for each specific application, parameter values characteristic of each subsystem must be substituted for the general global averages used here.

Technology in the Agriculture Sector

Technological change affects relationships in the agriculture sector in a variety of ways. Some of the effects of advances in technological capability are included endogenously in the sector. For instance, we assumed that the allocation of more investment to increasing land yield will have roughly the same success in the total global agricultural system as in the localized areas where these investment-intensive methods were developed. Such an assumption implies that the obstacles posed by different soils, climates, and traditional cultivation procedures will be overcome by technological advance. In the same manner we assumed that the allocation of investment to land maintenance—that is, to regenerate land fertility—will always succeed as well on a global scale as in localized regions. Again, this implies that technological advances will be able to combat fertility degradation problems regardless of where they occur and regardless of the size of the inflicted area.

The agriculture sector also includes several fixed relationships that could be changed in the real world through technological advances if the decision should be made to develop the needed technology. Examples of such relations are:

1. The increase in the costs of developing new land as the land area not yet cultivated diminishes. The cost could be reduced through developing cheaper forest removing equipment, improved water transportation schemes, and population relocation plans.
2. The reduction in land yield caused by a higher level of air pollution in the ambient air. The drop in yields could be reduced by developing pollution-resistant strains or by directly controlling air pollution.
3. The marginal improvement in global land yield caused by a certain increase in investment in modern agricultural inputs per hectare. The possible gains in yield might be increased over those observed in localized regions by unprecedented, regionally specialized innovations in, for example, grain and fertilizer types.
4. The amount of regeneration of land fertility resulting from higher investment in land maintenance. The effectiveness of maintenance might be increased through better soil conservation programs.
5. The increase in irreversible soil erosion caused by pursuing a higher land yield. This relation falls into a somewhat special category because the rate of erosion accompanying a specific land yield depends not only on technological capability but also on the farmers' decision to employ a cultivation procedure that minimizes erosion. In many cases, the available erosion-reducing procedures are not used, simply because erosion is such a slow process that the farmer can rarely observe the erosion damage caused by his cultivation methods. Thus the relation between yield and erosion can change in the real world through both educational and technological innovation.

None of the technologies that affect these relations were included endogenously in World3. We assumed throughout the model that new technological advances that are not a part of current trends do not occur automatically but, rather, as the result of man's deliberate action to ameliorate a problem. We chose to simulate decisions to act and the ensuing technological breakthrough by exogenous changes in the appropriate model relationships. These changes can be made at any time in the computer run when the modeler speculates that a technological breakthrough might occur. Examples are shown in the simulation runs in section 4.6.

Finally, technological advances in the real world might increase both the amount of potentially arable land and the maximum land yield. It is of course impossible to know what extraordinary technological breakthroughs will occur to increase land area or agricultural yields in the future. One could assume that essentially infinite yields might someday be attainable or at least that yields might regularly increase at a rate faster than the rate of increase of the global demand for food. With no way of assessing the total benefits and costs of future technologies, we preferred to study the implications of known technologies; it seemed more useful to develop long-term plans for the global society that take into account the foreseeable problems rather than to assume that problems will never arise.

4.4 CAUSAL STRUCTURE

The major historical trends in world agriculture can be summarized as overall growth in total and per capita food production and in the use of manufactured inputs such as fertilizers and pesticides. To model this behavior, the following set of assumptions were employed:

1. Food is produced from arable land and agricultural inputs (fertilizer, seed, pesticides).
2. Food output increases when the arable land area, the land fertility, or the amount of agricultural inputs are increased.
3. There are decreasing marginal returns to the use of agricultural inputs.
4. The amount of potentially arable land is finite, and development costs per hectare (for clearing, roads, irrigation dams) increase as the stock of potentially arable land decreases; in other words, the best and most accessible land is used first.
5. Newly developed land enters at the current *average* land fertility.
6. Arable land erodes irreversibly on a time scale of centuries when subject to intense cultivation, unless countermeasures are taken.
7. The stock of arable land is decreased by urban-industrial building activity, the rate of decrease depending on both population and industrial growth.
8. Total investment in agriculture increases in the long run with increasing industrial output per capita and in the short run when forced to do so by food shortages.
9. Agricultural investment can be used to develop new land or to increase the amount of agricultural inputs on present land. Investment is allocated on the basis of the relative marginal productivities of the options measured in vegetable-equivalent kilograms per dollar-year.
10. The capital-intensive use of land can lead to persistent pollution of the land (high pesticide concentrations, salinity, heavy-metal poisoning).
11. Land fertility decreases on a time scale of decades when the level of persistent pollutants becomes high.

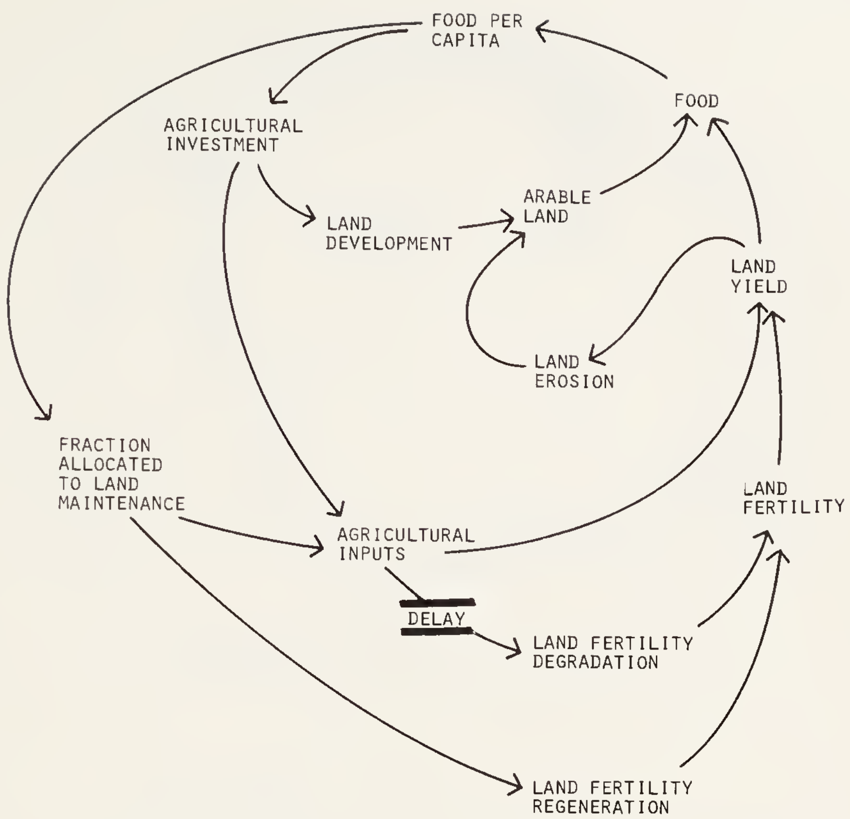


Figure 4-9 The feedback-loop structure of the agriculture sector

12. Land fertility regenerates itself over decades, and the process can be speeded up by proper land maintenance.
13. Farmers tend to maintain soil fertility by the proper use of capital except when pressured by extreme food shortages.
14. Land yield is reduced by air pollution.

The remainder of this section describes how these fourteen assumptions were combined into a feedback-loop structure. Figure 4-9 shows the feedback-loop structure assumed to govern the global aggregate food production in World3.

Loop 1: Food from Investment in Land Development

The output of food can be increased in World3 either by increasing the cultivated land area (the arable land) or by increasing the intensity at which existing arable land is used. Loop 1 (Figure 4-10) represents the process whereby the arable land area is increased.

When the available food per capita decreases, pressures arise to allocate more industrial output to agricultural activities. The resulting agricultural investment is allocated to developing new land or to increasing the intensity of use of existing land, depending on where the marginal productivity is larger.

The allocation of agricultural investments to land development ultimately results in a larger amount of arable land. However, land development is assumed to become increasingly expensive because the cheapest (most accessible, easiest to cultivate with

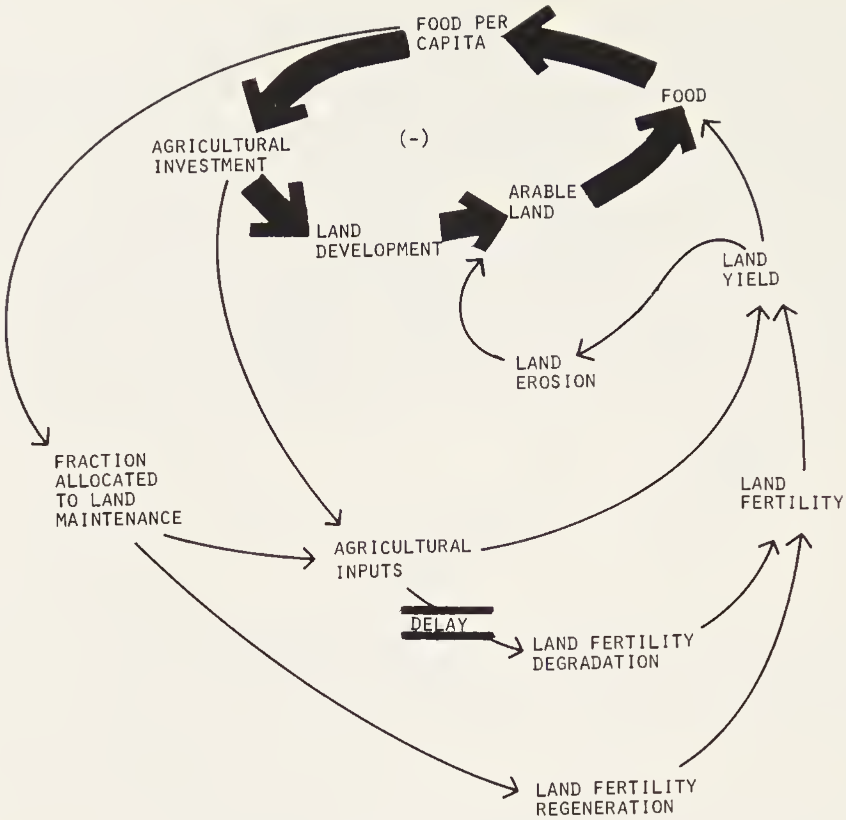


Figure 4-10 Loop 1: food from investment in land development

current techniques) land is developed first. Therefore, the amount of arable land arising from a given investment in land development, or the marginal return on land investment, will steadily decline. However, throughout the operation of the model, investment will continue to increase the stock of land, resulting finally in more food and thus more food per capita—assuming that everything else remains constant.

This land development loop is a negative loop that attempts to adjust the food available from the current arable land area to equal the food output judged desirable by the population.

Loop 2: Food from Investment in Agricultural Inputs

The output of food can also be raised in World3 by increasing the intensity at which arable land is used, or the land yield (measured in vegetable-equivalent kilograms per hectare-year). Loop 2 (Figure 4-11) indicates the process of increasing land yield through the use of modern agricultural inputs such as improved seed, fertilizer, pesticides, and farm machinery.

As pressures for more food rise and more resources are invested in agriculture, investment in agricultural inputs will also increase. Again—ceteris paribus—this investment is assumed to lead to increased land yield and hence more food and food per capita.

Loop 2 is also a negative feedback loop. It attempts to adjust the actual food per capita to the level desired by the population. Together, loops 1 and 2 (Figures 4-10 and 4-11) represent the basic behavioral assumption that man tries to keep food

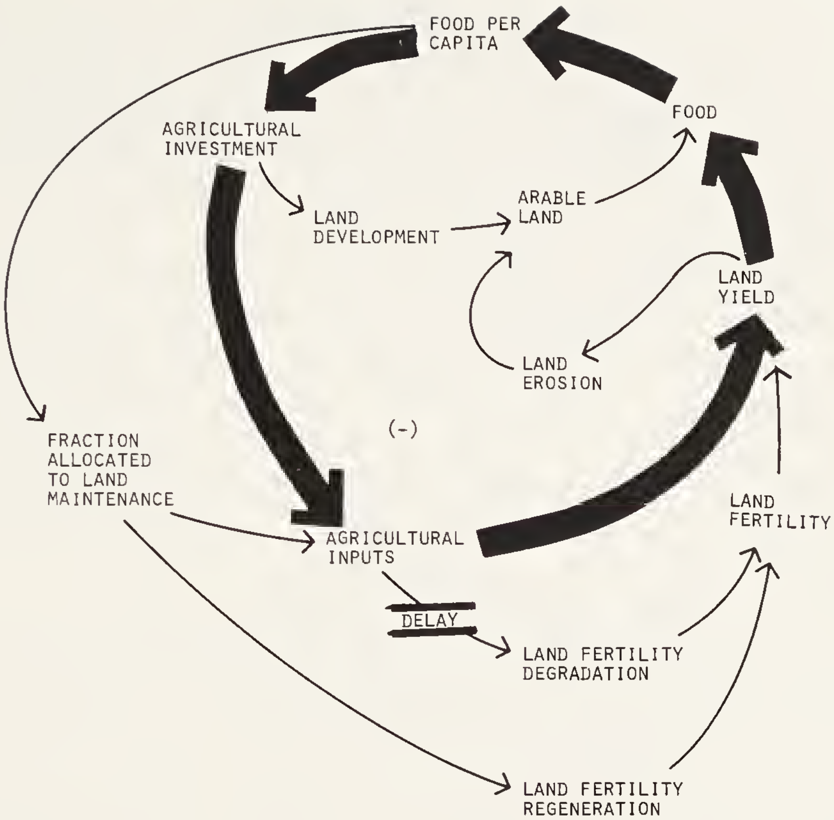


Figure 4-11 Loop 2: food from investment in agricultural inputs

availability at a level he judges desirable, a level that is a function of both total population and the desired or indicated food per capita determined by his level of income. He does so by increasing agricultural investment when food is scarce and by decreasing investment when the food supply is ample.

Loop 3: Land Erosion

If loops 1 and 2 were the only ones affecting the adjustment of food output to the demand for food in World3, it would be relatively simple to achieve a balance between food supply and demand in the long run, although the inevitable short-run reallocation problems would still exist. However, other factors make it more difficult to achieve an allocation of agricultural investment that is optimal in the long run. As mentioned in the basic concepts section (4.3), we assumed two processes by which the productive capacity of arable land can be reduced. Both arise from the assumption that the intensive use of land, and in fact any human use of land, disturbs the ecological balance that naturally sustains the soil and its fertility. The first process, which we termed fertility degradation, occurs when the soil is not restored—through fertilization, drainage, periods of fallow, and other means—to its original quality between growing seasons. It is assumed that under normal circumstances such restoration is usually performed, because fertility would otherwise decline catastrophically even within the lifespan of a farmer. It is also assumed that the damage incurred through occasional negligence is reversible, if action is taken to undo it.

The second process, which we termed erosion, is of a more serious nature. Erosion in our use of the term includes any process that irreversibly removes the topsoil from arable land, thereby making further cultivation impossible. The actual movement of the soil particles is most commonly caused by wind or water. Laterization, the seemingly irreversible solidification of some tropical soils, is also included in our erosion category.

There will always be some erosion of land. Natural erosion of uncultivated land is caused by the incessant action of rain and water over thousands of years. However, such slow rates of erosion are roughly balanced by equally slow land-creating processes. Man's cultivation activities often lead to an increased rate of erosion, which occurs when land is stripped of its protective cover of forest and grass. But even this higher erosion rate normally requires generations to inflict perceptible damage, and much can be done (for example, terracing, planting of hedges, contour plowing) to keep the erosion rate low while the land is cultivated.

In World3 we hypothesized that in the global agricultural system sufficient resources are not normally allocated to hold the erosion rate as low as its "natural" minimum. This assumption seemed reasonable, since such conservation procedures are time-consuming and costly. The incentive to perform them is low, especially because the costs of neglecting the erosion threat are usually paid only several generations later. In addition, it is difficult for a farmer to judge differential rates of erosion on his land, for the time constants involved may vary from 100 to 1,000 years. As a result, even if erosion prevention is a specific social goal, its practice is not easily carried out.

The harder the land is pressured for higher yields, the more conservation activity is probably needed to maintain a constant erosion rate, even though the increased need is probably not perceived because of the extreme slowness of the erosion process. Thus if one assumes that the same effort is allocated to controlling erosion regardless of cultivation procedures, one is forced to the conclusion that the erosion rate will increase when the intensity of cultivation and the departure from the normal ecological state of the land increase. To the extent that higher land yield accompanies unecological cultivation procedures, higher erosion rates will accompany higher land yields.

Following such reasoning, we assumed in World3 that while increased investment in agricultural inputs does lead to increased land yield, on a longer time scale that increased yield can also result in larger losses of arable land due to erosion (loop 3, Figure 4-12). But it should be stressed that the erosion losses can be reduced if society decides to reduce them and if sufficient resources are allocated to the task.

When most of the potentially arable land in a given area has already been developed, as in Asia today, land erosion can become a serious problem. Food output can be increased only by more intensive use of the existing arable land, as little or no land remains for new development. More intensive land use, if not accompanied by increased efforts to combat erosion, may cause higher erosion rates and ultimately less arable land, less food, and less food per capita. Instead of relieving food shortages as intended, more intensive use of land can lead to a deterioration of the

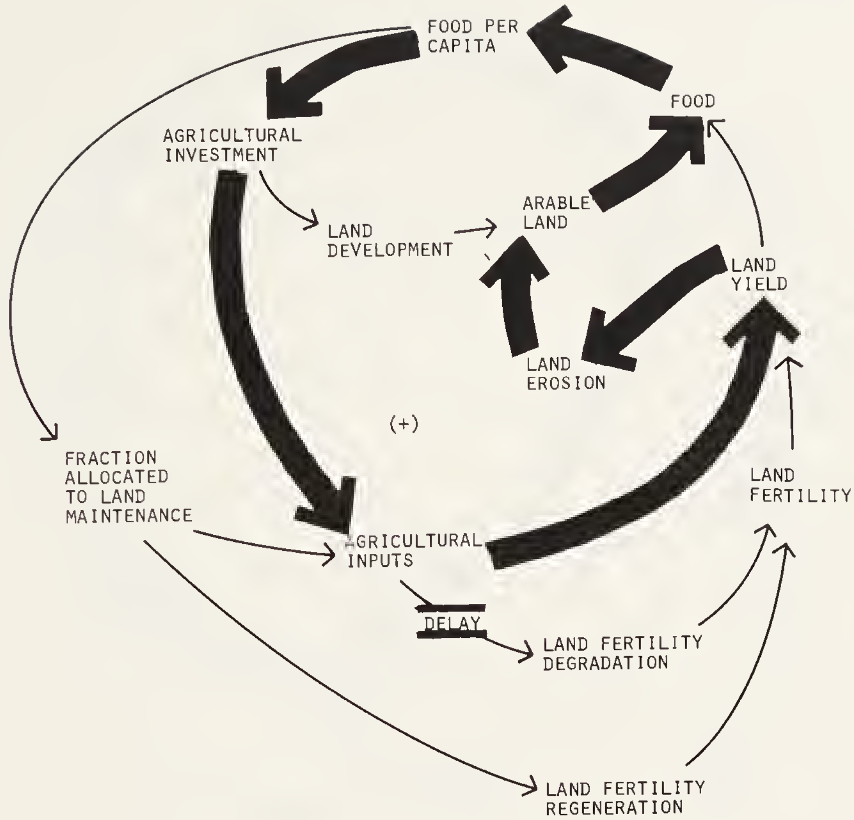


Figure 4-12 Loop 3: land erosion accompanying high yields

situation through the chain of causes and effects represented by loop 3, a positive feedback loop. When loop 3 becomes dominant, it will drive arable land and hence food output toward zero, at a rate that increases with increasing land yields. A reduction in arable land in World3 will cause a need for higher yields on the remaining land, with an even faster erosion of land as a result. The time constant assumed for loop 3 is rather long—of the order of several decades to thousands of years, depending on the land yield—so that the erosion caused by increased high cultivation intensity will not significantly reduce the food output in World3 unless it is allowed to persist for a substantial length of time.

Loop 4: Land Fertility Impairment

We defined "land fertility" as the inherent capability of the arable land to produce crops with the use of traditional inputs only (cow manure, natural irrigation, animal power). It should be distinguished from the land yield, which we defined as the output one can achieve through the use of all modern agricultural inputs. In a society using modern agricultural inputs, land yield is equal to land fertility multiplied by a number larger than one.

The land fertility is a function of the biological and physical characteristics of the soil. It is very sensitive to changes in any of these characteristics and is easily impaired—even by widely used procedures such as fertilizing, irrigation, and the use of farm machinery. In the long run, these three processes can lead to a reduction of

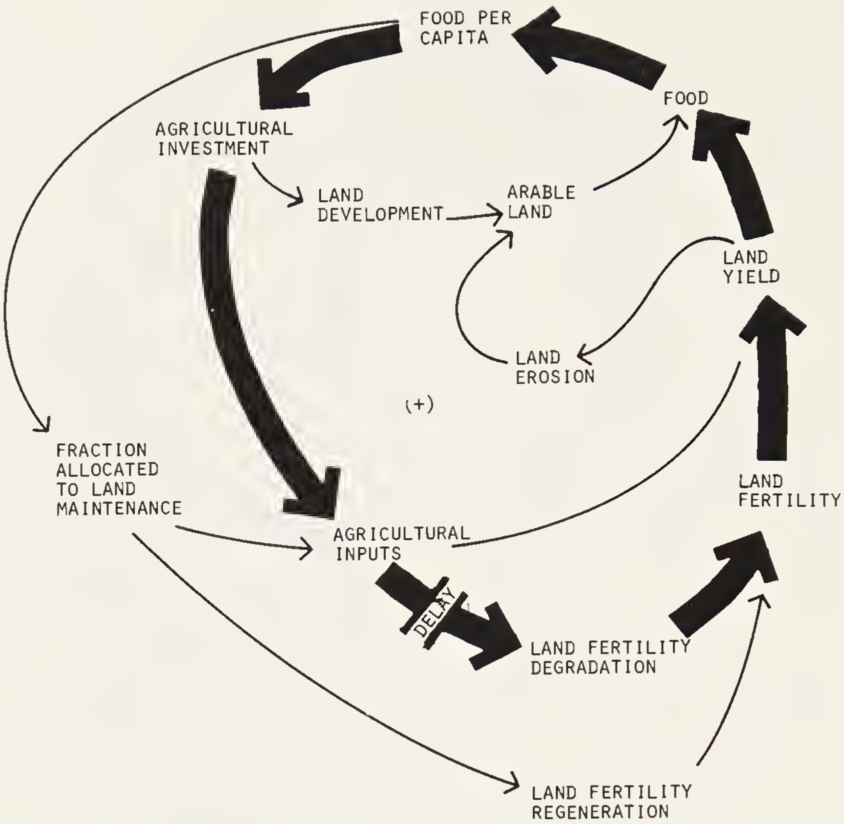


Figure 4-13 Loop 4: land fertility impairment

the microorganisms in the soil, to salinization, and to soil compaction, respectively—all of which we assumed to have unfavorable impacts on inherent land fertility. We also assumed in World3 that land fertility degradation can arise from a high level of industrial pollutants (heavy metals, radiation). A common characteristic of land fertility degradation due to agricultural inputs and industrial pollutants is that the effects do not occur until after a certain delay; the undesirable effects are not obvious immediately after the first use of the input or the first emission of a pollutant. Loop 4 (Figure 4-13) represents the assumed fertility degradation process. Food pressures result in higher investment in agricultural inputs as before. However, after a delay—assumed in the model to be twenty years—these inputs result in a reduction in land fertility and hence, ceteris paribus, in a lower land yield and less food.

Loop 4, like loop 3, is a positive feedback loop that will drive food output toward zero. However, the fertility degradation process is assumed to be much faster than the land erosion process; with no investment in soil maintenance, we assumed that it is possible to decrease the land fertility significantly in a few decades. On the other hand, soil fertility reductions are not irreversible, and land fertility regeneration can be speeded up by proper land maintenance techniques.

Loops 2 and 4 together explain why agricultural inputs are used despite their possible undesirable long-term effects. In the short run, the single result of increasing agricultural inputs is to increase land yield (through loop 2); it is only after a significant delay that the reduction in land fertility may ultimately depress land yield (through loop 4). Thus increases in agricultural inputs appear to have only beneficial effects in the short run.

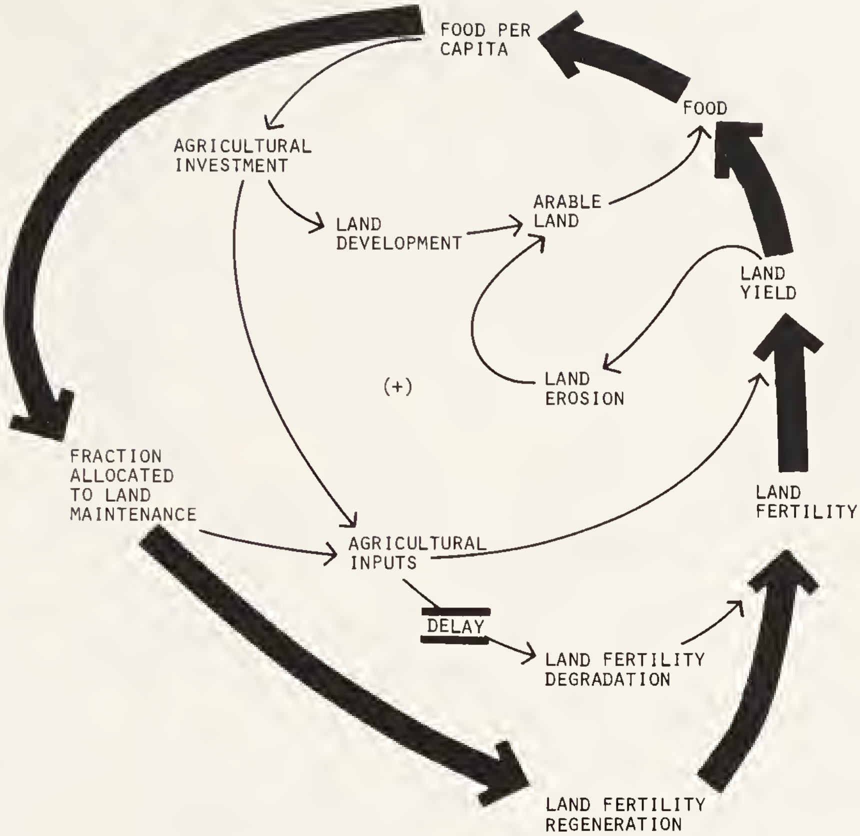


Figure 4-14 Loop 5: land fertility regeneration

Loop 5: Land Fertility Regeneration

When left fallow, land will recover lost fertility through the action of natural processes. The natural growth of grass and new forests on the soil will ultimately restore its content of nutrients, organic material, and useful microorganisms. These restorative processes normally go on continuously and can be enhanced by man-induced means, such as fertilization, mulching, proper irrigation and drainage, or planting leguminous green manures. This enhancement of the normal land fertility regeneration process is routinely undertaken by any farmer to prevent his land from losing its fertility.

Loop 5 (Figure 4-14) represents this process in World3. As long as the food available to the population is adequate, we assumed that a certain fraction of the annual agricultural investment will be devoted to land maintenance, even though that expenditure has no immediate visible return. This investment is assumed to be capable of enhancing the land fertility regeneration process to such an extent that normal rates of land fertility degradation can be counteracted and land fertility can remain at high levels.

Loop 6: Immediate Food Increase from Discontinuing Land Maintenance

If the food supply becomes very inadequate over several years, so that mass starvation and death are likely to result, we hypothesized that long-term investments in soil maintenance programs would no longer be made. In the short run, more agricultural inputs would thereby become directly available for producing more

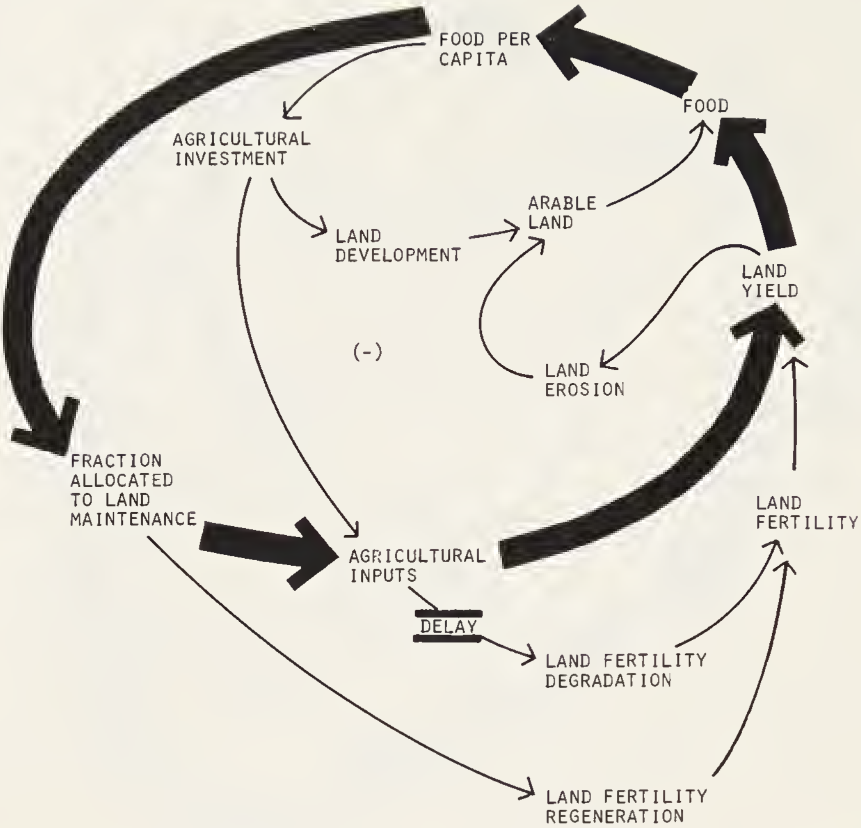


Figure 4-15 Loop 6: immediate food increase from discontinuing land maintenance

food. In the longer run, however, this diversion of land maintenance investment will result in a depletion of the soil fertility and hence in a decrease of the food output generated by the agriculture sector. Even with later ample allocations to land maintenance we assumed that it will take years for the soil to regain its fertility.

Loop 6 (Figure 4-15) represents the short-run gain in food output that can be achieved through the elimination of land maintenance programs. Loop 6 is a negative loop: food pressures act to terminate land maintenance programs and thus to increase the immediately productive agricultural inputs. More inputs give a higher yield and ultimately more food.

Loops 5 and 6 represent another trade-off between the long term and the short term in World3; the immediate benefits of discontinuing land maintenance in loop 5 are only obtained at the cost of depleting the land fertility in the long run through loop 6.

4.5 DESCRIPTION OF EQUATIONS

The causal structure outlined in section 4.4 can be formalized, and made less ambiguous by formulating a DYNAMO flow diagram (Figure 4-16). This section explains why the displayed structure was chosen and expresses each relationship in a mathematical equation. The discussion is organized around the major causal loops identified in section 4.4.

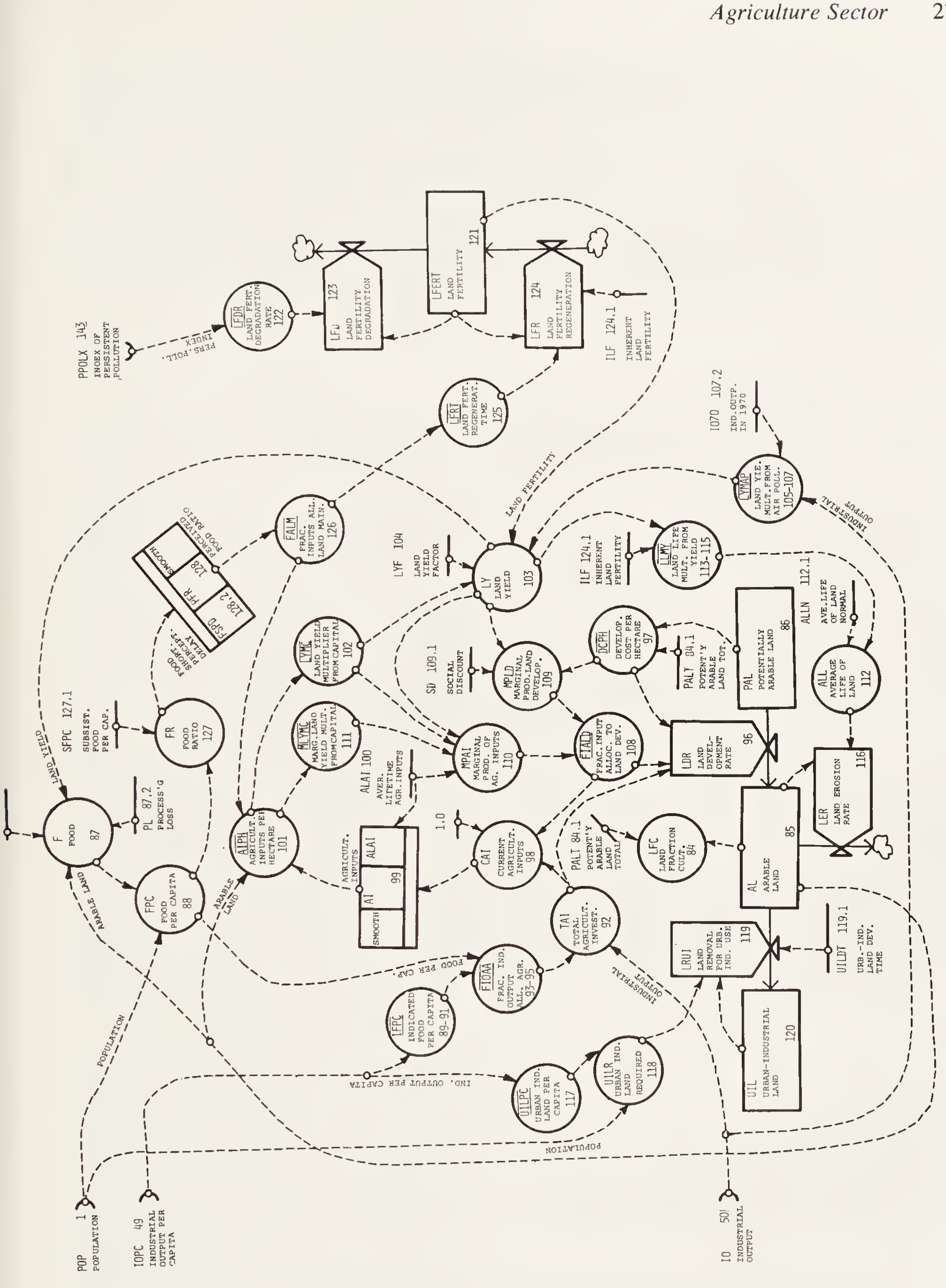


Figure 4-16 DYNAMO flow diagram for the agriculture sector

Loop 1: Food from Investment in Land Development

Arable land AL The world land area, which comprises about one-third of the total surface of the earth, amounts to about 13.1 billion hectares (excluding ice-covered areas). This total area can be divided into three major categories (Figure 4-17). As shown, only 24 percent of the world's total land area, or 3.2 billion hectares, is suitable for cultivation. We call this upper limit to the amount of cultivable land the potentially arable land total PALT. Then the fraction of land actually cultivated LFC at any time equals the arable land AL divided by the total potentially arable land area (PALT).

```
LFC.K=AL.K/PALT                                    84, A
PALT=3.2E9                                         84.1, C
    LFC    - LAND FRACTION CULTIVATED (DIMENSIONLESS)
    AL     - ARABLE LAND (HECTARES)
    PALT   - POTENTIALLY ARABLE LAND TOTAL (HECTARES)
```

Several inconsistent statistics can be found in the literature with regard to arable and potentially arable land and to annual crop production totals. Presumably, the differences arise from differing definitions of "crop" and "arable." Since the concept of "food" used in World3 is quite inclusive, we chose to use the broadly defined estimate of potentially arable land total PALT made by the President's Science Advisory Committee (PSAC 1967). Differing assumptions about prices and technology will also alter this estimate, but probably by only a small factor.

In World3, land is considered to be arable when it is used from time to time or full time to grow crops. This land "includes soils considered to be cultivated and acceptably productive of food crops adapted to the environment" (PSAC 1967). But not all of this land is highly productive. Its agricultural capability varies widely and depends on

1. the physical, chemical, and biological composition of the soil;
2. the range and the seasonality of temperature;
3. the annual amount and seasonal distribution of precipitation relative to evapotranspiration.

Land Category	**Area** (billion hectares)	**Percentage of Total**
Land suitable for cultivation[1] (potentially arable land total)	3.2	24.2
Nonarable land with grazing potential	3.6	27.8
Nonarable land with no grazing potential	6.3	48.0
Total	13.1	100.0

[1] In the original table appearing in PSAC (1967), this category was termed "potentially arable land." We chose to reserve that term for land that is suitable for cultivation but not yet cultivated.

Figure 4-17 World land area in different agricultural categories
Source: PSAC 1967, vol. 2, p. 428.

The arable land level in the world model embodies the average characteristics of all land under cultivation around the world.

```
AL.K=AL.J+(DT)(LDR.JK-LER.JK-LRUI.JK)                    85, L
AL=ALI                                                   85.1, N
ALI=.9E9                                                 85.2, C
    AL      - ARABLE LAND (HECTARES)
    DT      - TIME INTERVAL BETWEEN CONSECUTIVE
                CALCULATIONS (YEARS)
    LDR     - LAND DEVELOPMENT RATE (HECTARES/YEAR)
    LER     - LAND EROSION RATE (HECTARES/YEAR)
    LRUI    - LAND REMOVAL FOR URBAN-INDUSTRIAL USE
                (HECTARES/YEAR)
    ALI     - ARABLE LAND INITIAL (HECTARES)
```

The amount of arable land AL at any time equals the amount at a previous time, plus the amount of new land that has been developed through the land development rate LDR, minus the land that has been lost through the land erosion rate LER and land removal for urban-industrial use LRUI. It is estimated that the area of arable land in the year 1900 (ALI, the initial value of AL) was about 0.9 billion hectares (Doane 1957).

```
PAL.K=PAL.J+(DT)(-LDR.JK)                                86, L
PAL=PALI                                                 86.1, N
PALI=2.3E9                                               86.2, C
    PAL     - POTENTIALLY ARABLE LAND (HECTARES)
    DT      - TIME INTERVAL BETWEEN CONSECUTIVE
                CALCULATIONS (YEARS)
    LDR     - LAND DEVELOPMENT RATE (HECTARES/YEAR)
    PALI    - POTENTIALLY ARABLE LAND INITIAL (HECTARES)
```

The amount of potentially arable land (land that could be but has not yet been brought under cultivation) is steadily decreased as the land development rate LDR moves land from the potentially arable to the arable category. Since the area of arable land was about 0.9 billion hectares in 1900, and since the total cultivable area is estimated to be about 3.2 billion hectares, we may assume that the potentially arable but undeveloped land in 1900 must have totaled 2.3 billion hectares (neglecting losses to erosion and urban-industrial use).

The geographic distribution of arable land shown in Figure 4-18 indicates that approximately half the potentially arable land total PALT had been moved into the arable category by 1967. Thus the total world acreage of arable land can still be increased by a factor of two, but the potentially arable land left undeveloped is generally assumed to be less productive than the land already in use. In developed as well as in developing regions, good land is becoming a scarcer resource. The *Provisional Indicative World Plan for Agricultural Development* published by the FAO states:

> In Southern Asia, which contains a very large part of the population of the developing regions, some countries in Eastern Asia, in the Near East and North Africa and in certain parts of Latin America and Africa (e.g., the Andean highlands and the Savannah Zone of West Africa) there is almost no scope for expanding the arable land. [FAO 1970*a*, vol. 1, p. 41]

Continent	1 Total Land	2 Total Potentially Arable Land	3 Arable Land	4 Land Fraction Cultivated
		(billion hectares)		(3/2)
Africa	3.02	0.73	0.16	.22
Asia	2.74	0.63	0.52	.83
Australia and New Zealand	0.81	0.15	0.02	.13
Europe	0.48	0.17	0.15	.88
North America	2.11	0.47	0.22	.47
South America	1.75	0.68	0.09	.13
USSR[1]	2.24	0.36	0.23	.64
Total	13.15	3.19 =PALT	1.39 =AL (1967)	.44 =LFC (1967)

[1]The USSR is treated here as its own continent, and China is not included in the figures for Asia.

Figure 4-18 The geographic distribution of the potential for expansion of agricultural land
Source: PSAC 1967, vol. 2, p. 434.

Food Output F ‘‘Food’’ in World3 is the total direct output of the world’s arable land. The relatively small output from the oceans and from grazing land, as noted earlier, is neglected. Food is measured in vegetable-equivalent kilograms per year. Some of this total crop is fed to animals before the animals are consumed by man. We measure the ‘‘food content’’ of meat in vegetable equivalents—the amount of (fodder) crops needed to produce the meat. The conversion factor from fodder to meat is roughly 7:1 (CRAM 1969, p. 78), so the world’s meat output can be multiplied by 7 for an approximate measure of the crop output it represents.

In World3 the total annual food output was assumed to be a function of land and agricultural inputs. Labor is not included as an explicit factor in the production function because we assumed there will be a surplus of labor over the period studied. Thus the food output is calculated simply as the output per hectare of harvested land times the total cultivated land area.

```
F.K=LY.K*AL.K*LFH*(1-PL)                                87, A
LFH=.7                                                  87.1, C
PL=.1                                                   87.2, C
    F      - FOOD (VEGETABLE-EQUIVALENT KILOGRAMS/YEAR)
    LY     - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
               HECTARE-YEAR)
    AL     - ARABLE LAND (HECTARES)
    LFH    - LAND FRACTION HARVESTED (DIMENSIONLESS)
    PL     - PROCESSING LOSS (DIMENSIONLESS)
```

The land yield LY is the average amount of crops produced per hectare of arable land AL in the year when it is harvested. Typically, LY varies from 600 vegetable-equivalent kilograms per hectare-year in a traditional agricultural society to 5,000 vegetable-equivalent kilograms per hectare-year in highly intensive and mechanized modern agriculture (see the discussion of land yield later in this section).

Region	**Arable Land** (billion hectares)	**Area Harvested Annually**[1] (billion hectares)	**Cropping Intensity**[2] (percent)
Africa south of the Sahara	0.152	0.064	42
Asia and the Far East	0.211	0.211	100
Latin America	0.130	0.071	54
Near East and Northwest Africa	0.070	0.039	56
Total or average	0.563	0.385	68

[1]Figures for area actually planted are not available for many countries; thus those for the area harvested give closest approximation. In some countries a significant proportion of cereal crops may be grazed off, or flood and other damage may reduce the harvested area compared with the planted area.

[2]Cropping intensity is calculated by dividing the harvested area by arable area and expressing it as a percentage. Both arable land and harvested area include permanent crops.

Figure 4-19 Average cropping intensities in developing countries, 1961–1963
Source: FAO 1970*a*, p. 44.

All arable land AL is not harvested every year; typically, one-third of the land is left fallow for lack of irrigation or as a consequence of established cropping practices. The cropping intensity (= land fraction harvested LFH) can also surpass 100 percent under circumstances where double-cropping is possible. On the basis of the data in Figure 4-19, we set LFH as a constant equal to 0.7.

The effective edible food output F was also assumed to be somewhat smaller than the total agricultural production because some areas are used for the cultivation of nonedible crops (e.g., cotton, and because loss and spoilage are inevitable in the processing and storage of the food product. In the real world the loss factor is small—of the order of 1 percent (U.N. 1970*a*, p. xxxi). The spoilage factor however, is more important since large amounts of grain can spoil. We took these effects into account by choosing the processing loss PL as a constant equal to 0.1.

Food per Capita FPC The total annual food output F divided by the total population POP gives the average food per capita FPC.

```
FPC.K=F.K/POP.K                                       83, A
    FPC     - FOOD PER CAPITA (VEGETABLE-EQUIVALENT
                KILOGRAMS/PERSON-YEAR)
    F       - FOOD (VEGETABLE-EQUIVALENT KILOGRAMS/YEAR)
    POP     - POPULATION (PERSONS)
```

Since world food output is expressed in World3 in units of vegetable-equivalent kilograms per year, food per capita must be expressed in vegetable-equivalent kilograms per person-year. A more common measure of human nutritional requirements is in terms of energy—kilocalories per person-day—with a minimum requirement for normal health of about 2,200 kilocalories per person-day (see Chapter 2 for further discussion and references). The conversion factor between kilocalories and vegetable-equivalent kilograms is roughly 3,500 kilocalories per kilogram for grain crops, as illustrated in Figure 4-20. This number varies widely for different crops and is particularly high for low-protein crops such as potatoes and sugar beets. However,

Crop	**Kilocalories per Kilogram of Crop** (millions)
Soybean	3.3
Corn	3.7
Rice	3.6
Wheat	3.3
Potato	8.2
Sugar beet	8.2

Figure 4-20 Caloric content of several crops (harvested weight)
Source: Data from Borgstrom 1970*b*, p. 45.

3,500 kilocalories per kilogram was used in World3 as an average conversion factor because, to sustain life, low-protein foods must be supplemented with high-protein animal products.

Thus the minimum requirement of 2,200 kilocalories per person-day is equivalent to

$$\frac{2200 \text{ kilocalories}}{\text{person-day}} \times \frac{1 \text{ vegetable-equivalent kilogram}}{3500 \text{ kilocalories}} \times \frac{365 \text{ days}}{\text{year}}$$
$$= \frac{230 \text{ vegetable-equivalent kilograms}}{\text{person-year}}$$

We define this minimum value of 230 vegetable-equivalent kilograms per person-year or 2,200 kilocalories per person-day as the subsistence food per capita SFPC, a constant that is used both in the definition of the lifetime multiplier from food LMF (see Chapter 2) and in the food ratio FR, discussed later in this chapter.

Indicated Food per Capita IFPC In World3 the total investment in agriculture is primarily determined by the total demand for food. We assumed that the total agricultural investment TAI is increased (decreased) when the available food per capita FPC is below (above) the per capita food demand. As will be discussed, this per capita demand for food, which we termed the indicated food per capita IFPC, was assumed to increase when industrial output per capita IOPC increases (that is, when a higher ''economic level'' is reached).

Figure 4-21 illustrates the great variation in national per capita food consumption as a function of income in 1968. A similar graph, using 1957–1961 data (Figure 4-22), also shows the shifting pattern from the direct consumption of vegetable crops to the use of vegetable crops for fodder as income increases. In poor countries, nearly all the available grain is consumed directly by the population; very little is fed to animals. With rising income, the total amount of grain consumed per person increases steadily, but much of this additional grain consumption is indirect consumption in the form of milk, meat, and eggs. Whereas the annual amount of grain used directly as food decreases after reaching a maximum, total grain consumption continues to rise. This growing indirect use of grain makes possible the rise in the consumption of

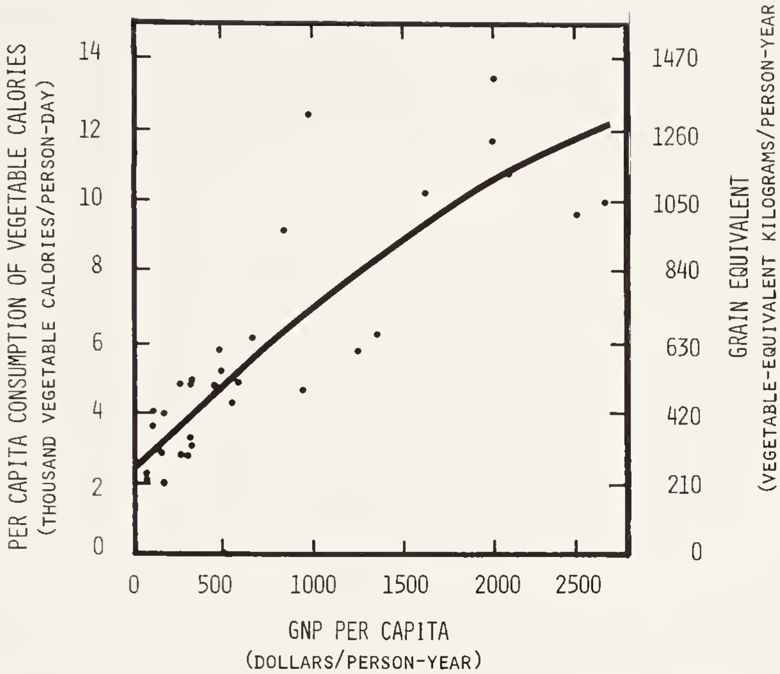


Figure 4-21 Per capita consumption of vegetable calories and GNP per capita for several countries, 1968

Sources: Food consumption data from U.N. 1970*a*; GNP per capita from IBRD 1970.

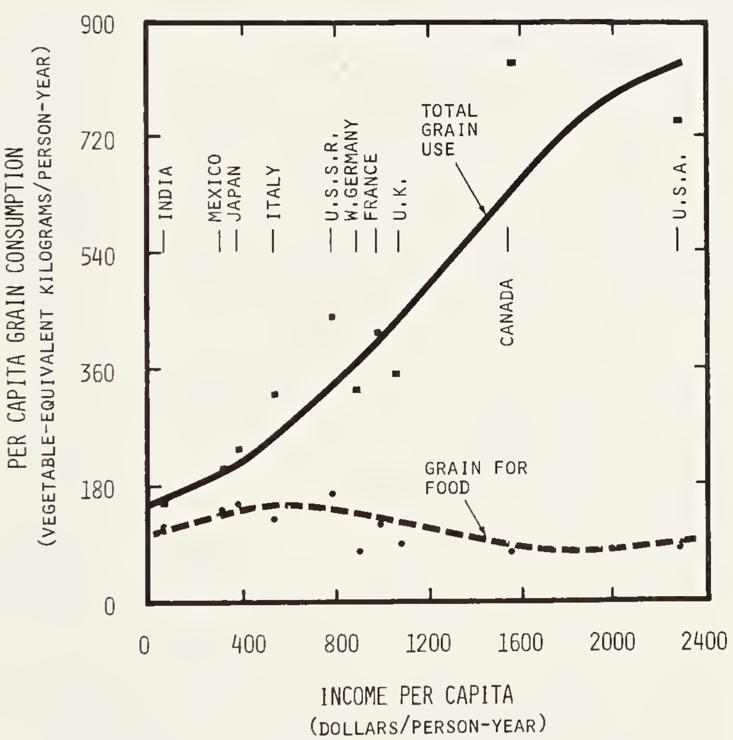


Figure 4-22 Income and per capita grain consumption

As a country becomes wealthier, less grain is used directly for consumption. The strong increase in total use is due to the growth in the indirect use of grain, for example, as feed for meat-producing animals.

Source: Lester R. Brown, *Seeds of Change: The Green Revolution and Development in the 1970's* (New York: Praeger Publishers, 1970), p. 143. Copyright © 1970 by Praeger Publishers, Inc. Excerpted and reprinted by permission.

vegetable-equivalent calories and especially protein in wealthier countries. Eventually, the food-consumption curve levels off, as the demand for food eventually becomes saturated at high income levels. There is evidence that a diminishing fraction of per capita income is spent on food as income increases even in relatively poor countries (Figure 4-23).

Figures 4-21 and 4-22 seem to indicate a fairly regular relationship between a country's level of economic activity (as measured by GNP per capita) and its per capita consumption of grain equivalents. We used this relationship to indicate the historical development of per capita food consumption demand at different levels of industrialization. The relationship we chose to use in World3 is shown in Figure 4-24. Note that industrial output per capita IOPC is used as the index of industrial development, as is the case throughout the model. To translate the available data, which were in terms of GNP per capita, to the model units of industrial output per capita IOPC, we used the relationship described in Figure 3-19. The four points indicated by dots in Figure 4-24 were calculated from total world food production figures in four different years, as indicated in Figure 4-25. Notice that the value of indicated food per capita IFPC never falls below the subsistence value of 230 vegetable-equivalent kilograms per person-year.

This relationship, represented in World3 as the indicated food per capita table IFPCT (Figure 4-26), is essentially a description of the relative value put on food production by societies in the past. It therefore represents the shift in socioeconomic values as economic development proceeds. Societal value judgments may of course continue to change through time. Hence there is little reason to describe the curve in Figure 4-26 as a "normal" or "desired" curve. Given actual food distribution patterns, the curve does not even necessarily generate adequate food for the total population. The curve simply generates the food per capita historically generated with the societal value structure that seemed to pertain in most countries of the world over the period 1900–1970. To simulate a world with a different value structure after 1970

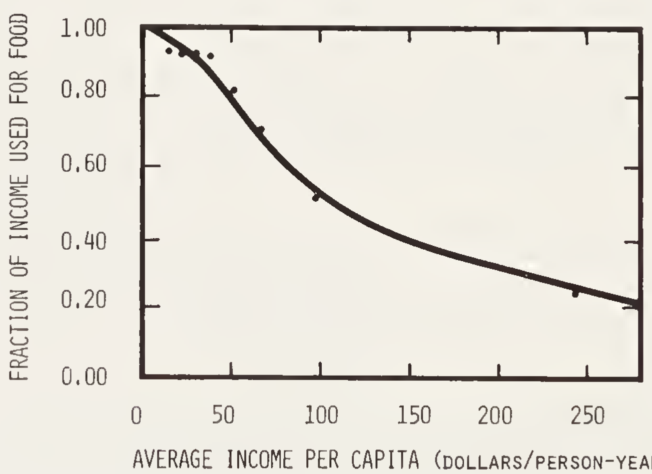


Figure 4-23 Fraction of income used for food at different income levels in Madras, India
Source: PSAC 1967, vol. 3, p. 49.

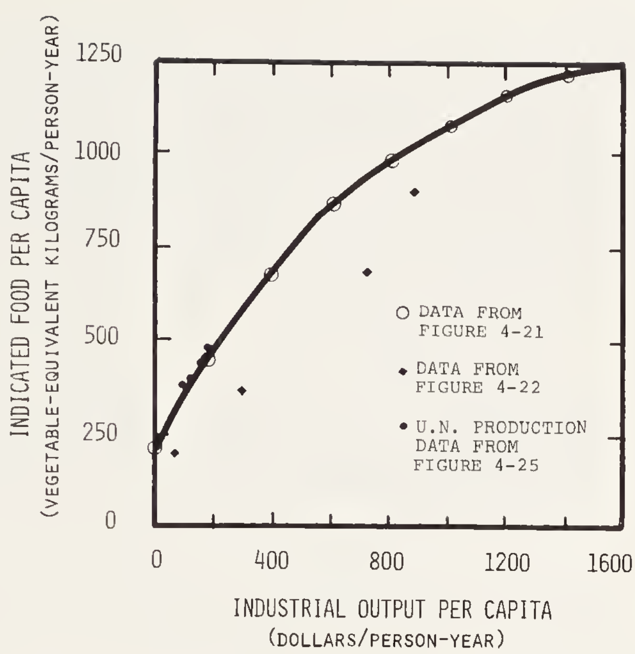


Figure 4-24 Indicated food per capita as a function of industrial output per capita

	1938	**1948**	**1960**	**1968**
	(billion kilograms)			
Cereals	640	673	951	1179
Pulses	—	29	34	44
Potatoes	221	262	285	314
Sweet potatoes	—	57	112	134
Oilseed	48	47	75	101
Soybeans	14	13	27	43
Total grain	923	1081	1484	1815
Total minus 10 percent processing loss	830	970	1,340	1,630
Population (million persons)	2,250	2,473	3,005	3,483
Food per capita (vegetable-equivalent kilograms per person-year)	370	390	450	470

Figure 4-25 World production of major commodities, selected years

Note: All major commodities are included so that the final numbers can be viewed as a good approximation of the total food output.

Source: U.N. 1970*a*, p. xxxi.

(for instance, one in which a higher value is put on food relative to industrial output), one would simply shift the indicated food per capita IFPC curve by setting new values for the table IFPC2T in the following equations:

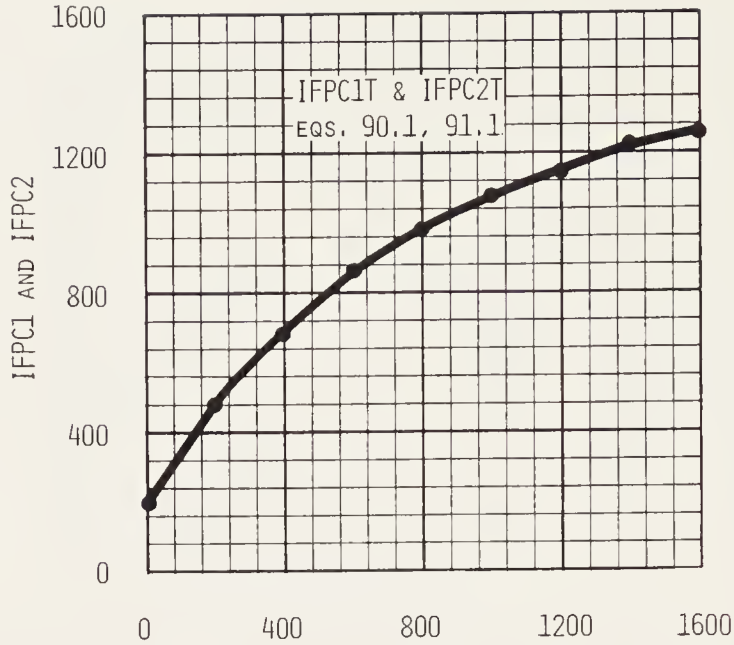


Figure 4-26 Indicated food per capita table

```
IFPC.K=CLIP(IFPC2.K,IFPC1.K,TIME.K,PYEAR)               89, A
    IFPC   - INDICATED FOOD PER CAPITA (VEGETABLE-
               EQUIVALENT KILOGRAMS/PERSON-YEAR)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    IFPC2  - IFPC, VALUE AFTER TIME=PYEAR (VEGETABLE-
               EQUIVALENT KILOGRAMS/PERSON-YEAR)
    IFPC1  - IFPC, VALUE BEFORE TIME=PYEAR (VEGETABLE-
               EQUIVALENT KILOGRAMS/PERSON-YEAR)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

IFPC1.K=TABHL(IFPC1T,IOPC.K,0,1600,200)                 90, A
IFPC1T=230/480/690/850/970/1070/1150/1210/1250          90.1, T
    IFPC1  - IFPC, VALUE BEFORE TIME=PYEAR (VEGETABLE-
               EQUIVALENT KILOGRAMS/PERSON-YEAR)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    IFPC1T - IFPC1 TABLE
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
               PERSON-YEAR)

IFPC2.K=TABHL(IFPC2T,IOPC.K,0,1600,200)                 91, A
IFPC2T=230/480/690/850/970/1070/1150/1210/1250          91.1, T
    IFPC2  - IFPC, VALUE AFTER TIME=PYEAR (VEGETABLE-
               EQUIVALENT KILOGRAMS/PERSON-YEAR)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    IFPC2T - IFPC2 TABLE
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
               PERSON-YEAR)
```

Total Agricultural Investment TAI In World3, portions of the annual industrial output IO are invested in capital for increasing agricultural, industrial, and service output in the future. To the extent that resources and capital are available, the demands for agricultural, service, and industrial output will be satisfied in that order of priority. The total agricultural investment TAI represents the value in dollar equivalents of that portion of the world's industrial output allocated to agriculture each year. Although the unit of TAI is dollars, the variable actually represents the manufactured physical goods (fertilizers, tractors, pesticides, roads, dams, and bull-dozers) used to increase arable land, land fertility, or land yield in any given year. The value of the total agricultural investment TAI is calculated from the total year's industrial output IO and the fraction of the industrial output allocated to agriculture FIOAA.

```
TAI.K=IO.K*FIOAA.K                                        92, A
    TAI     - TOTAL AGRICULTURAL INVESTMENT (DOLLARS/
                YEAR)
    IO      - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    FIOAA   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                AGRICULTURE (DIMENSIONLESS)
```

Fraction of Industrial Output Allocated to Agriculture FIOAA The relative supply of and demand for food determine the fraction of industrial output allocated to agriculture FIOAA. The food supply in any year is represented by the average food per capita FPC, and the demand for food is determined by the indicated food per capita IFPC discussed earlier. The ratio of the two (FPC/IFPC) is the driving factor causing a change in the allocation of industrial output to agriculture. A low ratio (FPC/IFPC<1) indicates that the food demand is not being satisfied, which causes an increase in the fraction of industrial output allocated to agriculture FIOAA. A high ratio indicates an overabundance of food, which reduces the investment in agriculture. The postulated numerical relationship between FPC/IFPC and FIOAA is shown in Figure 4-27 and in the following equations:

```
FIOAA.K=CLIP(FIOAA2.K,FIOAA1.K,TIME.K,PYEAR)              93, A
    FIOAA   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                AGRICULTURE (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    FIOAA2  - FIOAA, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    FIOAA1  - FIOAA, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

FIOAA1.K=TABHL(FIOAA1T,FPC.K/IFPC.K,0,2.5,.5)             94, A
FIOAA1T=.4/.2/.1/.025/0/0                                 94.1, T
    FIOAA1  - FIOAA, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FIOAA1T- FIOAA1 TABLE
    FPC     - FOOD PER CAPITA (VEGETABLE-EQUIVALENT
                KILOGRAMS/PERSON-YEAR)
    IFPC    - INDICATED FOOD PER CAPITA (VEGETABLE-
                EQUIVALENT KILOGRAMS/PERSON-YEAR)

FIOAA2.K=TABHL(FIOAA2T,FPC.K/IFPC.K,0,2.5,.5)             95, A
FIOAA2T=.4/.2/.1/.025/0/0                                 95.1, T
    FIOAA2  - FIOAA, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FIOAA2T- FIOAA2 TABLE
    FPC     - FOOD PER CAPITA (VEGETABLE-EQUIVALENT
                KILOGRAMS/PERSON-YEAR)
    IFPC    - INDICATED FOOD PER CAPITA (VEGETABLE-
                EQUIVALENT KILOGRAMS/PERSON-YEAR)
```

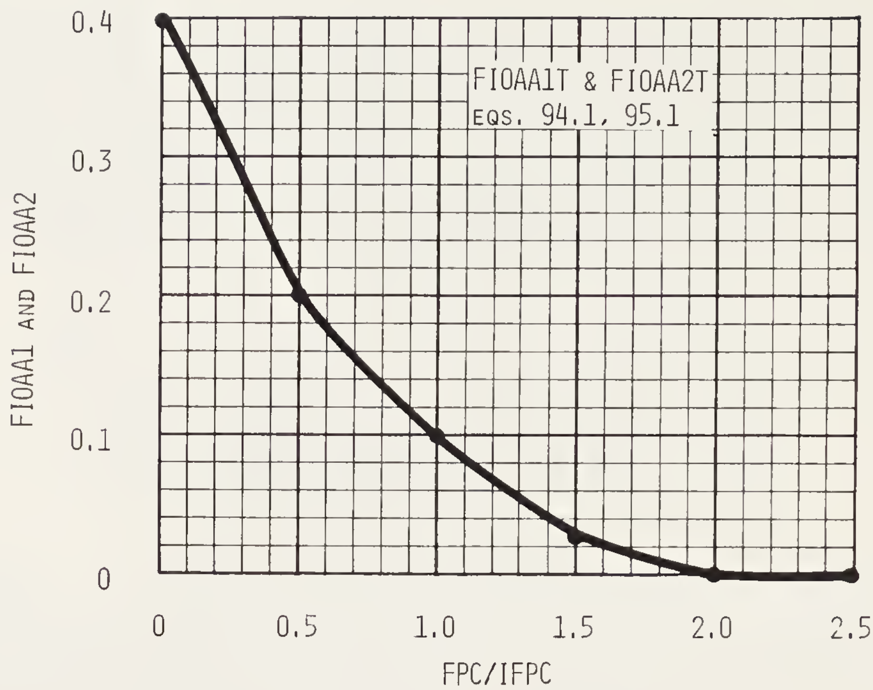


Figure 4-27 Fraction of industrial output allocated to agriculture table

Since the curve shown in Figure 4-27 is hypothetical, a CLIP function is included in the equations to allow it to be changed at any time during the model runs. We set the value of FIOAA at 0.1 when actual and indicated food per capita are equal (FPC/IFPC = 1) to suggest that a normal allocation to keep food production equal to demand is about 10 percent of annual industrial output. The main significance of the curve lies in its shape: a steeper slope represents a faster and stronger response to food shortage or surplus. A rough approximation of the slope is obtained from assumptions about possible extreme values. We assumed in World3 that the fraction allocated to agriculture FIOAA will not exceed 40 percent even in the case of extreme hunger, leaving only about one-half of the industrial output for consumption plus investment in service or industrial capital. Similarly, we assumed that a large surplus of food (twice the desired amount) will reduce the additional investment in agriculture to zero—in fact not even replacing the depreciation in the agriculture sector.

The resulting graph is only an assumption, and its values should ultimately be determined more rigorously, although the sensitivity runs shown later indicate that different graphs do not lead to any significant differences in the dynamic behavior of the overall model.

Land Development Rate LDR The total agricultural investment TAI can be allocated in two ways in the agriculture sector: to develop new arable land or to increase the yield on land already developed. The mechanism by which the allocation decision is made will be described under loop 2, the loop that acts to increase land yield. For the moment it is sufficient to recognize that the capital investment available for land development is expressed as the total agricultural investment TAI times the fraction of that investment allocated to land development FIALD. Then the amount of land, in hectares, that can be developed each year (the land development rate LDR) simply equals the total investment available (TAI×FIALD) divided by the development cost per hectare DCPH.

```
LDR.KL=TAI.K*FIALD.K/DCPH.K                                  96, R
    LDR    - LAND DEVELOPMENT RATE (HECTARES/YEAR)
    TAI    - TOTAL AGRICULTURAL INVESTMENT (DOLLARS/
               YEAR)
    FIALD  - FRACTION OF INPUTS ALLOCATED TO LAND
               DEVELOPMENT (DIMENSIONLESS)
    DCPH   - DEVELOPMENT COST PER HECTARE (DOLLARS/
               HECTARE)
```

Development Cost per Hectare DCPH The relatively large amount of potentially arable land PAL still remaining in the world does not imply that any increase in the amount of arable land will be easy or cheap. Land expansion is a function of opportunities (potentially arable land), pressures (food needs or population growth), and constraints (capital, water supply, and technological capability). For example, in Africa south of the Sahara, the high cost of clearing forests, the presence of the tsetse fly, and the relative lack of population make a rapid land expansion program extremely difficult. A plan for increasing food supplies in the less industrialized areas proposes an increase of 20 percent over the 1962 level of arable land in those areas by 1985 (FAO 1970*a*, vol. 1). This expansion would increase the land fraction cultivated LFC in nonindustrialized countries from 45 to 53 percent.

The cost of developing new land is often the strongest constraint on agricultural land expansion. Development costs in World3 are assumed to include the costs of clearing the land, draining or irrigating (including the construction of dams and pipes), and building access roads—in short, all the costs necessary to make the land ready for the first crop. Development costs differ widely from region to region; they may also change with technology. Any technological variation probably affects money costs more than the physical costs (man-hours, tons of steel, energy) of developing land. In World3 we are interested in the physical resource costs, not the money costs.

The costs of land clearing are strongly dependent on local physical conditions, such as the original topography and vegetation, as well as on local economic conditions. In South America, land-clearing costs vary from 14 dollars per hectare to 550 dollars per hectare (PSAC 1967, vol. 2, p. 438). Similar cost distributions exist for irrigation, including water supply, water distribution, and water application to the land, and for drainage to improve aeration. A sample of the resulting total development costs is given in Figure 4-28.

Country	Acreage (hectares)	Development Cost per Hectare (dollars per hectare)	Cost per Family (dollars per family)	Total Cost (millions of dollars)
Kenya[1]	12,000	2,432	—	29.2
Morocco[2]	—	1,430	—	—
Ceylon[3]	—	767	—	—
Sudan[4]	36,000	545	3,270	19.6
Nigeria[5]	—	285	8,400	—
Guatemala I[6]	98,800	227	4,527	22.2
Guatemala II[7]	98,800	80	1,617	8.1
United States[8]	402,800	1,520	—	—

[1]Kano Plain Irrigation Project. Includes dams, reservoirs, canals, flood control, land preparation, power distribution. Source: U.S. Bureau of Reclamation, preliminary draft of Kano Plain Reconnaissance Study, April and May 1966.

[2]Lower Moulouya Irrigation Project. Includes dams, canals, power, pumps, distribution, drainage, land preparation. Source: USAID, Preliminary Project Lower Moulouya Irrigation Project, Washington, D.C.

[3]Project unknown. Irrigation 490 dollars per hectare; clearing 277 dollars per hectare. Excludes domestic water, sanitation, fencing, homes. Source: B.H. Farmer, *Pioneer Peasant Colonization in Ceylon: A Study in Asian Agrarian Problems* (London: Oxford University Press, 1957), p. 387.

[4]Kasha-el-Guba Settlement. Includes dams, canals, laterals, infrastructure. Source: USAID, Sudan Desk File, Washington, D.C.

[5]Source: O. O. Okediji, "Some Socio-Cultural Problems in the Western Nigeria Land Settlement Scheme: A Case Study," *Nigerian Journal of Economics and Social Studies* 7, no. 3 (November 1965), pp. 301–310.

[6]Sebol-Chinaja. Includes surveying, drainage, roads, houses, population nuclei, family transportation. Source: United Nations draft document, based on Government of Guatemala estimates.

[7]Ibid. Includes surveying, drainage, and roads only.

[8]Garrison Diversion, Missouri River. Includes storage, canals, drainage, roads for providing irrigation water to currently cultivated land. Source: U.S. Bureau of Reclamation.

Figure 4-28 Sample land development costs
Source: PSAC 1967, vol. 2, p. 436.

On a global scale, the development costs increase as a larger fraction of the land is brought under cultivation. The first hectares of land developed require very low development investments. But as less convenient areas come into cultivation, clearing becomes more and more difficult and costly; and when natural precipitation is no longer sufficient, additional investments are needed for irrigation. At the extreme, when only very little land is available, the development cost will be heavy and the land supply will be highly inelastic. In other words, "the long run supply curve would be affected by the ease or difficulty of clearing and draining land. Not all land can be cleared with equal ease. The least cost land would be cleared first" (Hoover 1970). Technological change tends to shift the entire cost curve, making land development less expensive, but it does not change the curve's basic characteristic: increasing costs as the stock of potentially arable land steadily decreases.

The current real-world average development cost has been very roughly estimated at 1,000 dollars per hectare (PSAC 1967, vol. 2, p. 461), this average cost occuring at a point when 56 percent of the total potentially arable land remained uncultivated. Current average development costs in the United States are estimated at 1,500 dollars per hectare, with about 49 percent of the potentially arable land stock still undeveloped. Australia, with only 2 percent of its potentially arable land currently under cultivation, has recently completed two projects at a cost of around 60 dollars per hectare. Using those figures as a guideline, we hypothesized the relationship shown in Figure 4-29. For constant technology, the cost curve represents the assumption that the cost of development will be on the order of 100,000 dollars per hectare as the potentially arable land PAL approaches zero.* A higher value was not chosen because, at such high development costs, the distinction between potentially arable land and land judged unsuitable for cultivation is not very sharp.

```
DCPH.K=TABHL(DCPHT,PAL.K/PALT,0,1,.1)                    97, A
DCPHT=1E5/7400/5200/3500/2400/1500/750/300/150/75/  97.1, T
  50
    DCPH    - DEVELOPMENT COST PER HECTARE (DOLLARS/
                HECTARE)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    DCPHT   - DCPH TABLE
    PAL     - POTENTIALLY ARABLE LAND (HECTARES)
    PALT    - POTENTIALLY ARABLE LAND TOTAL (HECTARES)
```

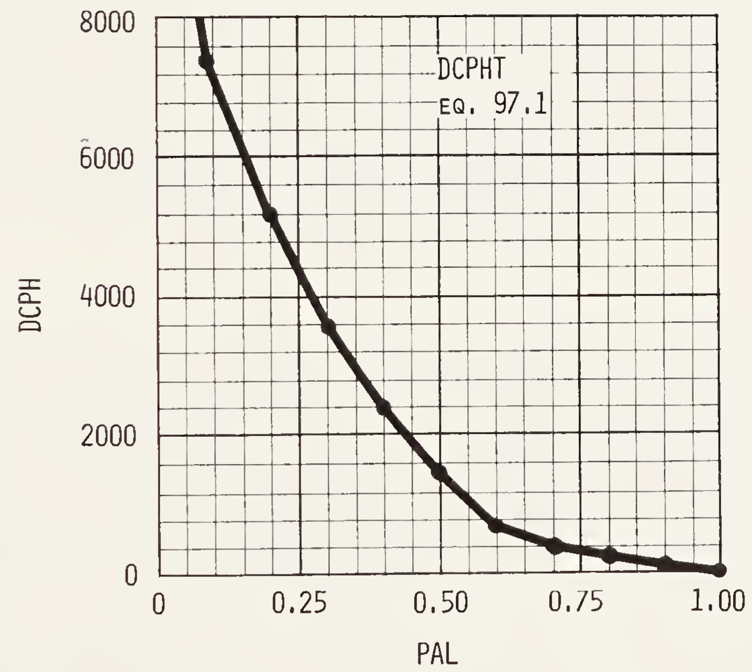


Figure 4-29 Development cost per hectare table

*Under certain extreme circumstances the funds allocated for land development may be sufficient to pay the finite cost (100,000 dollars per hectare) of repeatedly developing the last remaining hectares of potentially arable land PAL. That will occur when total agricultural investment TAI reaches extremely high values and when the fraction of investment allocated to land development FIALD is nonzero. Thus potentially arable land PAL may go negative. This problem is easily eliminated by increasing the first entry in the table of development costs per hectare DCPHT.

Loop 2: Food from Investment in Agricultural Inputs

The agricultural production function in World3 contains just two basic inputs: arable land and capital. In the last subsection we described the equations representing the generation of arable land by investment of a fraction of industrial output in land development. We now discuss the equations representing a parallel process: the investment in "agricultural inputs," which we define as manufactured capital goods intended to increase land yield (for example, fertilizers, pesticides, farm machinery, and irrigation systems). This second process may well be the primary means of increasing the world's food output in the future.

> . . . IWP favours intensification of land and water use over the addition of new land as the major policy, in most of the regions studied. For some countries, where land reserves are limited, such as India or the countries in N. W. Africa, there is little choice with respect to intensification, but even in those countries *where a choice was permitted by unutilized land resources, intensification was chosen as the main component of increases in agricultural production.* [FAO 1970*a*, vol. 1, p. 51]

Agricultural Inputs AI Every year the world's farmers invest in a certain volume of agricultural inputs. We call this yearly investment the current agricultural inputs CAI (measured in dollars per year); it is equal to the part of the total agricultural investment TAI that is not allocated to land development.

```
CAI.K=TAI.K*(1-FIALD.K)                              98, A
    CAI    - CURRENT AGRICULTURAL INPUTS (DOLLARS/YEAR)
    TAI    - TOTAL AGRICULTURAL INVESTMENT (DOLLARS/
               YEAR)
    FIALD  - FRACTION OF INPUTS ALLOCATED TO LAND
               DEVELOPMENT (DIMENSIONLESS)
```

The majority of these inputs are short-lived, normally lasting for only one growing season (fertilizer, seed, pesticides, operating costs for machinery, housing, and irrigation systems). The rest have a lifetime of several years (acquisition costs for machinery and farm buildings). On the average, agricultural inputs AI are useful for somewhat more than a year. Consequently, the effective amount of agricultural inputs AI available at any time to increase the actual food output depends not only on the current agricultural inputs CAI but also to some extent on past values of CAI. We made the assumption that the effective agricultural inputs AI can be approximated by a first-order exponential smoothing of current agricultural inputs CAI with a time constant (the average life of agricultural inputs ALAI) equal to 2 years.

```
AI.K=SMOOTH(CAI.K,ALAI.K)                            99, A
AI=5E9                                               99.1, N
    AI     - AGRICULTURAL INPUTS (DOLLARS/YEAR)
    SMOOTH - FIRST-ORDER EXPONENTIAL INFORMATION DELAY
    CAI    - CURRENT AGRICULTURAL INPUTS (DOLLARS/YEAR)
    ALAI   - AVERAGE LIFETIME OF AGRICULTURAL INPUTS
               (YEARS)
```

```
ALAI.K=CLIP(ALAI2,ALAI1,TIME.K,PYEAR)                   100, A
ALAI1=2                                                 100.1, C
ALAI2=2                                                 100.2, C
    ALAI    - AVERAGE LIFETIME OF AGRICULTURAL INPUTS
                (YEARS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    ALAI2   - ALAI, VALUE AFTER TIME=PYEAR (YEARS)
    ALAI1   - ALAI, VALUE BEFORE TIME=PYEAR (YEARS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
```

Since to our knowledge no estimate exists of the 1900 value of agricultural inputs AI for the entire world, we had to rely on a very rough assessment of this value. The 1900 level of arable land AL was 0.9 billion hectares (see the discussion under loop 1). The agricultural inputs per hectare AIPH in 1900 must have been relatively small, given that most of the modern inputs had not yet been invented or were only rarely available. Figure 4-30 indicates how small the total use of such inputs was in the United States in 1910 compared with 1960, although the land base over which they were used had changed only slightly. In World3 we assumed that the global average AIPH in 1900 was about one-half of what it is today in the nonindustrialized areas of the world, or about 5 dollars per hectare-year (Figure-32). Thus the 1900 level of agricultural inputs AI (=AIPH times AL) becomes roughly 5×10^9 dollars per year (approximately equal to 5 dollars per hectare-year times 0.9×10^9 hectares). Although this estimate is probably correct only to within a factor of two, the possible error is not very important, since the feedback loops in the agriculture sector quickly adjust the agricultural inputs and hence the food production to the level required by the indicated food per capita IFPC table shown in Figure 4-26.

Resource Category	**1910**	**1920**	**1930**	**1940**	**1950**	**1960**
Farm labor	135	143	137	122	90	62
Machinery and power	28	44	55	58	118	142
Farm buildings	99	116	111	98	106	128
Fertilizer and lime	20	28	36	48	118	192
Tractors	—	9	32	55	119	133
Combines	—	1	12	37	137	205
Cornpickers	—	—	17	36	151	251
Feed, seed, and livestock purchased	22	32	37	63	101	149
Miscellaneous capital operating items	71	85	96	93	108	138
Cropland	87	95	103	100	100	92

Figure 4-30 Changing patterns of input use in U.S. agriculture, 1910–1960
Note: These entries represent an index of major categories of inputs (1947–1949=100).
Source: Heady and Tweeten 1963, p. 15.

	Fertilizers		Seed		Irrigation	
	1962*	**1985**	**1962***	**1985**	**1962***	**1985**
Africa south of Sahara	14.2	180.4	295.0	412.1	—	—
Asia	335.0	5,180.9	868.6	1,258.7	750.7	1,186.0
Latin America	218.3	1,861.3	276.4	355.7	479.6	896.9
Near East[1]	78.7	470.7	108.1	145.7	264.4	350.8
North Africa[2]	18.0	145.0	51.4	72.1	—	—
Total	664.2	7,838.3	1,599.5	2,244.3	1,494.7	2,433.7

*1961–1963 average.
[1]10 countries only, excluding Kuwait and Yemen Arab Republic.
[2]1962*=1965* (1964–1966 average).
[3]Same quantities used also for livestock.
[4]South America only.

Figure 4-31 Value of agricultural inputs in 1962 and proposed levels for 1985, selected developing regions (millions of 1962 dollars)
Source: FAO 1970*a*, p. 180.

Agricultural Inputs per Hectare AIPH The intensity of use of agricultural inputs is the important determinant of land yield. To measure the average intensity of use (the agricultural inputs per hectare AIPH), the variable AI must be divided by the arable land AL over which the inputs are used.

We assumed in World3 that a certain fraction of AI is not used to obtain immediate increases in land yield but is instead spent on land maintenance, or the conservation of land fertility LFERT. The purpose of this expense is to secure a high land yield for the future. This fraction allocated to land maintenance FALM, the equation for which is described under loop 6, includes resources spent on crop rotation, drainage, and similar practices. The annual average global use of productive agricultural inputs per hectare AIPH is then given as

```
AIPH.K=AI.K*(1-FALM.K)/AL.K                          101, A
    AIPH    - AGRICULTURAL INPUTS PER HECTARE (DOLLARS/
                HECTARE-YEAR)
    AI      - AGRICULTURAL INPUTS (DOLLARS/YEAR)
    FALM    - FRACTION OF INPUTS ALLOCATED TO LAND
                MAINTENANCE (DIMENSIONLESS)
    AL      - ARABLE LAND (HECTARES)
```

Global figures for agricultural inputs per hectare in terms of money equivalents are difficult to find. Figure 4-31 gives total values of the different agricultural inputs in the developing world for 1962 and proposed values for 1985. On the basis of these values and data on the arable land in these countries, one can arrive at the estimates of agricultural inputs per hectare AIPH values given in Figure 4-32. The estimate of AIPH in nonindustrialized areas of the order of 10 dollars per hectare-year is compatible with the scant information available on other countries (U.S.D.A. 1965, p. 77). The value of AIPH in the industrialized areas of the world is undoubtedly much higher.

Crop Protection 1962*	Crop Protection 1985	Mechanization[3] 1962*	Mechanization[3] 1985	Total Inputs 1962*	Total Inputs 1985	Total Input as Percent of Crop Output 1962*	Total Input as Percent of Crop Output 1985
13.6	309.0	27.0	101.2	349.8	1,002.7	6.4	9.1
20.4	1,215.8	200.9	1,153.9	2,175.6	9.995.3	9.8	18.9
110.0[4]	397.2[4]	438.5	1,031.8	1,522.8	4,542.9	17.1	25.7
25.0	116.4	36.7	117.3	512.9	1,200.9	18.6	19.2
11.0	38.5	94.0	206.0	174.4	461.6	20.3	25.2
180.0	2,076.9	797.1	2,610.2	4,735.5	17,203.4	11.8	19.2

Figure 4-31 (continued)

Land Yield Multiplier from Capital LYMC The ability of agricultural inputs to enhance the yield from each hectare of land is expressed by a variable called the land yield multiplier from capital LYMC. This factor multiplies the yield that would otherwise be expected, given the basic land fertility, by an amount that varies as the use of agricultural inputs per hectare AIPH varies. The value of LYMC is always 1.0 or larger; it is assumed that the application of agricultural inputs never decreases the yield that might have been obtained on the same land by traditional methods.

The increases in grain yields over time in various parts of the world are shown in Figures 4-3, 4-33, and 4-34. Since the primary agricultural change in these areas over the period was the introduction of modern agricultural inputs, these figures give a rough idea of the range over which the land yield multiplier from capital LYMC has varied.

As an estimate of the inherent land fertility ILF, which is defined as the land yield when no modern agricultural inputs are employed in the production process and when the land fertility is not impaired by earlier misuse of the soil, we chose 600 vegetable-equivalent kilograms per hectare-year. Since this value seemed to be the lower bound of most yield data we reviewed, we assumed that it could be considered

Region	Arable Land (billion hectares) 1962	Arable Land (billion hectares) 1985	Agricultural Inputs per Hectare (dollars per hectare-year) 1962	Agricultural Inputs per Hectare (dollars per hectare-year) 1985
Africa south of the Sahara	0.15	0.19	2.3	5.3
Asia	0.21	0.22	10.4	44.9
Latin America	0.13	0.17	11.4	26.7
Near East and Northwest Africa	0.07	0.08	9.8	21.3
Total	0.56	0.66	8.4	26.0

Figure 4-32 Agricultural inputs per hectare for selected developing regions, 1962, and proposed levels for 1985

Source: Data from FAO 1970*a*, p. 52.

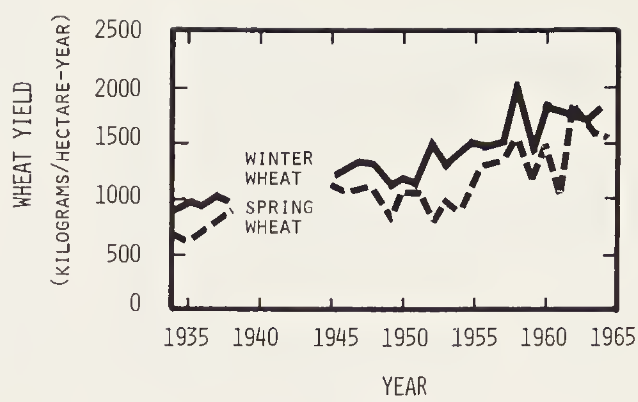


Figure 4-33 Historical wheat yields in the United States

Source: Georg Borgstrom, *Too Many: A Story of Earth's Limitations*, rev. ed. (New York: Macmillan Publishing Co., 1970), p. 46. (Copyright © 1969, 1971 by Georg Borgstrom. Copyright © 1969 by Macmillan Publishing Co., Inc.)

a typical yield in traditional agricultural societies. On the other hand, average land yields as high as 5,000–6,000 vegetable-equivalent kilograms per hectare-year may become attainable over large areas of arable land with exceedingly high levels of agricultural inputs per hectare AIPH. Thus the land yield multiplier from capital LYMC may increase preindustrial land yields around the world by a factor of about ten at very high values of AIPH (such yields are rare today but may become possible in the future). This upper limit of LYMC is of special significance; together with the limit of potentially arable land PALT, it defines the maximum value of global food production assumed in World3.

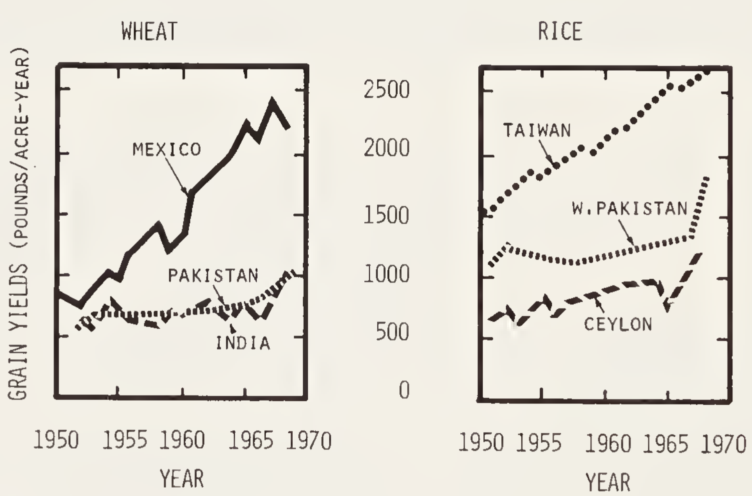


Figure 4-34 Yield "take-off" for wheat and rice

Source: Lester R. Brown, *Seeds of Change: The Green Revolution and Development in the 1970's* (New York: Praeger Publishers, 1970), pp. 37, 39. Copyright © 1970 by Praeger Publishers, Inc. Excerpted and reprinted by permission.

Why should we assume that there is any necessary limit to the yield increases attainable from adding capital inputs to the agricultural production function? From a biological point of view, there does seem to be an upper limit to the efficiency with which the photosynthetic process can fix incoming solar energy into vegetable matter edible to man. From an economic point of view, the diminishing marginal returns to agricultural inputs are already evident. The next few paragraphs discuss the present trends toward diminishing returns for several agricultural inputs: fertilizer, pesticides, new seed, and mechanization.

The use of fertilizer in various countries of the world and its relationship to land yield have already been shown in Figure 4-6. Since an increase in fertilizer use normally is accompanied by other improvements (better seeds, more pesticides, and better cultivation techniques), the graph should not be interpreted as more than a general demonstration of the relation between yield and fertilizer use. Decreasing marginal returns to both fertilizer and pesticide use are demonstrated more clearly by Figures 4-35 and 4-36. In addition, the data on which the graphs are based demonstrate a nearly perfect proportionality between fertilizer and pesticide use per hectare (PSAC 1967, vol. 3, pp. 140–143).

Figure 4-36 may give a misleading impression of the ability of pesticides *alone* to increase yields. In looking at the steep curve of the figure, it should be noted that the heavy use of pesticides is almost always accompanied by the heavy use of other inputs. Although global crop losses due to pests are large (Figures 4-37 and 4-38), perhaps of the order of 20 percent, even infinite expenditures on pesticides cannot do more than recover this 20 percent loss, that is, increase food production by one-fifth. Diminishing returns to pesticide use must occur fairly quickly as pesticide use increases.

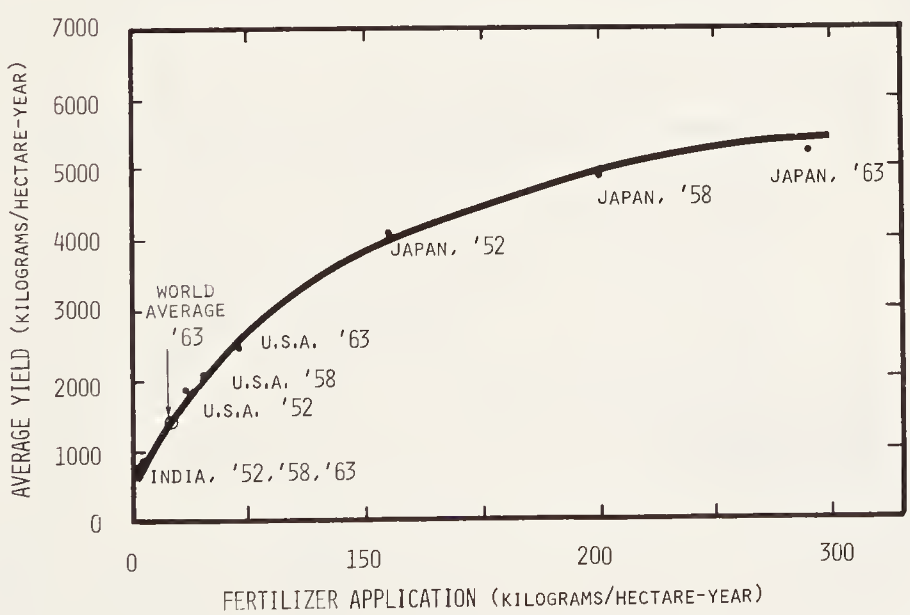


Figure 4-35 Yield and fertilizer use
Source: PSAC 1967, vol. 3, p. 143.

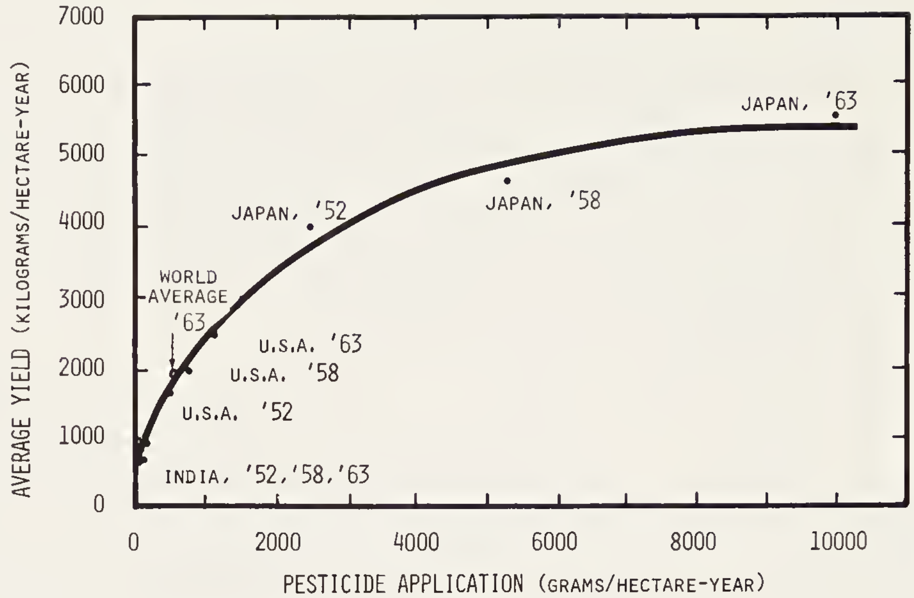


Figure 4-36 Yield and pesticide use
Source: PSAC 1967, vol. 3, p. 141.

Crop	Percentage of Loss[1] from Insects	Diseases	Weeds
Maize	12	12	10
Wheat	6	14	12
Rice	4	7	17
Grain sorghum	9	9	13
Soybean	8	14	17
Potato	14	19	3

[1]Estimate based on full production with causes eliminated.

Figure 4-37 Estimated losses to insect, disease, and weed pests in production of selected crops in the United States, 1951–1960
Source: PSAC 1967, vol. 2, p. 205.

	Corn	Wheat	Rice
Harvested crop (million metric tons)	218	266	232
Total preharvested losses (million metric tons)	121	86	207
Loss percentages			
by weed	37	37	22.5
by insects	36	25	58.0
by disease	27	38	19.5

Figure 4-38 Global preharvested losses of corn, wheat, and rice, 1965
Source: Cramer 1967.

In extreme cases one may even observe a negative marginal return to more use of fertilizer. Very high inputs of fertilizer may cause the head of the grain to grow so large that the stalk will break before harvesting, or the concentration of salts in the soil may become sufficient to damage the plants. Both processes will result in lower yields (see curves a, b, and c in Figure 4-39). The achievement of plant geneticists over the last twenty years, in what is called the Green Revolution, has been to develop new seed varieties that produce stalks capable of supporting heavy grain heads, which are thus more responsive to fertilizer than traditional varieties (see curves I, II, and III in Figure 4-39). In a sense, the new varieties have "postponed" the decreasing returns to agricultural inputs.

Because the new crop varieties have a much higher yield ceiling and mature more quickly than those formerly available, wheat and rice production can be doubled or even tripled in areas where enough irrigation water, fertilizers, and pesticides are available. In Mexico, where dwarf wheat was first introduced, production increases were spectacular and made the country independent of wheat imports. The yield increases shown in Figure 4-34 were primarily due to the introduction of the new varieties. Figure 4-40 indicates the extent to which these new seeds have been adopted around the world.

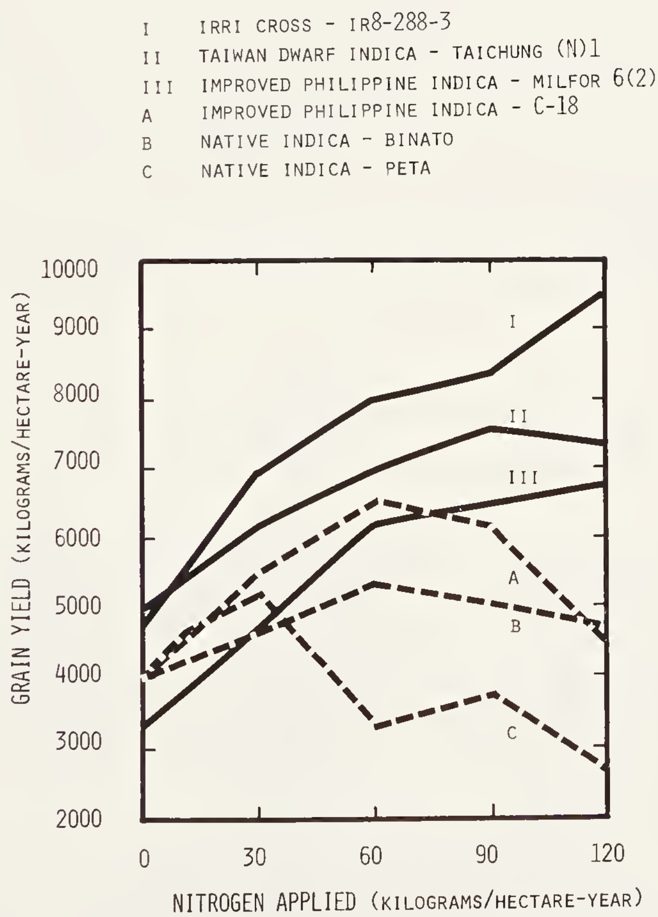


Figure 4-39 Yield responses of different seed varieties to fertilizer use
Source: FAO 1970*a*, p. 97.

Commodity and Country	Seed Status[a] (rating)	Proportion of Crop Area In Improved Varieties (percent)	Yields per Hectare 1948–1952 (100 kilograms per hectare-year)	1960–1962	Change (percent)
Rice					
Japan	1	100	40.0	50.5	26
Taiwan	1	95	19.1	25.4	33
Venezuela	2	90	11.4	15.1	33
Chile	3	65	29.0	27.0	−7
United Arab Republic	3	35	37.9	52.8	39
Pakistan	4	5	13.8	15.9	15
Iran	4	3	19.3	19.6	2
Wheat					
Japan	1	100	18.5	26.1	41
Netherlands	1	100	36.5	43.8	20
Mexico	1	85	8.8	16.7	90
Chile	2	80	11.9	13.7	15
Pakistan	2	7	8.7	8.1	−7
United Arab Republic	3	30	18.4	25.1	36
Colombia	3	20	7.2	9.1	26
Iran	3	10	9.0	7.8[b]	−13
Jordan	4	15	7.0	5.4	−23
Maize					
Venezuela	2	20	11.4	11.0	−4
Pakistan	2	8	9.8	10.0	2
Chile	3	50	13.8	20.7	50
Colombia	3	20	10.7	11.2	5
United Arab Republic	3	7	20.9	24.1	15

[a]Index of present efficiency in the chief factors influencing development,production, distribution, and use of better seeds, using rating of 1 to 4 with quality highest for rating of 1.
[b]1960–1961.

Figure 4-40 Yield and proportion of crop in improved varieties 1948–1952 and 1960–1962
Source: U.S.D.A. 1965, p. 49.

But new seed does not lead to such phenomenal results without costs: to perform well, the new crop varieties need considerably more fertilizer, pesticides, and water than traditional varieties. Further expansion in their use will probably be constrained by the amount of adequately irrigated land than can be made available. Currently, only 11 percent of the world's arable land is irrigated (PSAC 1967, vol. 2, p. 440), and it is estimated that about 10 percent of this land, or 16 million hectares is already planted with high-yield varieties (Shaw 1970, p. 11).

> The Mexican wheats have a pronounced yield advantage over local wheat only when they are grown under irrigated or high rainfall conditions. Under dry land farming conditions, where little or no fertilizers can be used, they offer little if any advantage. . . . Expansion of the area planted to high-yielding wheats is already slowing somewhat in both India and Pakistan, for example, as the additional land with suitable water supply diminishes. [Brown 1970, p. 21]

The expansion of the world's irrigated land area is expected to be small, amounting to an increase of about 50 percent in irrigated area in the developing world by 1985 (FAO 1970*a*, Vol. 1, p. 58). One important reason for the slow expansion is the high cost of getting water to the plants: "About one half the water provided for irrigation is lost in transportation, and less than half the water that reaches the fields is utilized by plants" (Revelle 1962).

Consequently, although the land yield can be increased significantly by introducing high-yielding seed varieties, this approach requires increasing amounts of capital to provide adequate irrigation, fertilizer, and pesticides. Diminishing returns thus seem to be active also with respect to the use of new seed varieties.

Finally, Figure 4-41 indicates decreasing returns to farm mechanization measured as horsepower employed per hectare. The relationship between agricultural yield and mechanization differs from that between yield and fertilizer. First, more horsepower does not necessarily result in higher yields. Second, mechanization is not a prerequisite for raising the productivity of farming as, for example, small landholdings in Asia illustrate. However, the importance of timely sowing, the elimination of fallow in sufficiently irrigated areas, and narrowing the interval between harvests by more intensive crop rotation schemes indicates that farm mechanization normally will be accompanied by increased yields.

How can increases in agricultural inputs per hectare be linked quantitatively to increases in yield through the land yield multiplier from capital LYMC? We began to answer this question by estimating how many times the 1963 world agricultural inputs per hectare AIPH must be increased to achieve a doubling or a tripling of world average yields, using the information from the figures already presented here as a base. The first step was to obtain the world average values of fertilizer use per hectare, pesticide use per hectare, and horsepower per hectare for 1963.

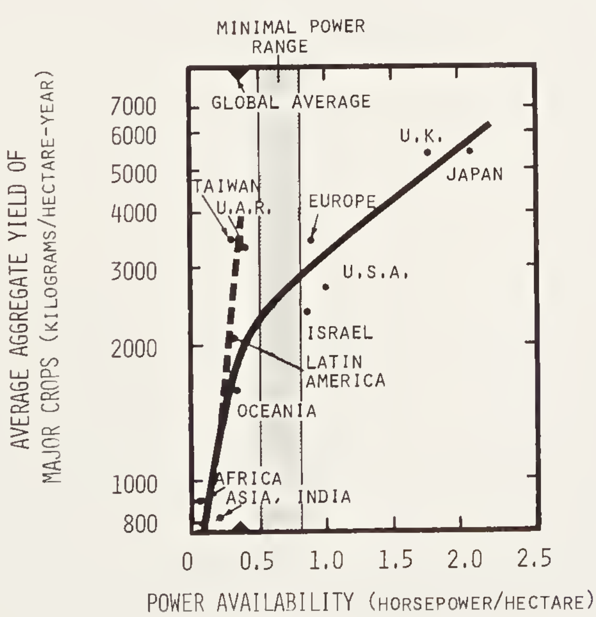


Figure 4-41 Yield and power availability
Source: PSAC 1967, vol. 3, p. 180.

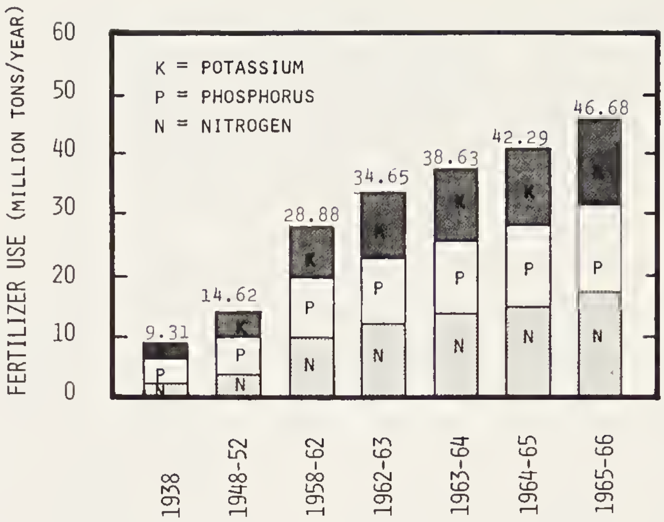


Figure 4-42 Global use of fertilizers (million tons per year)
Source: Georg Borgstrom, *Too Many: A Story of Earth's Limitations*, rev. ed. (New York: Macmillan Publishing Co., 1970), p. 27. (Copyright © 1969, 1971 by Georg Borgstrom. Copyright © 1969 by Macmillan Publishing Co., Inc.)

Our estimate of the global average fertilizer use of 28 kilograms per hectare-year was obtained by dividing the 1963 total of 39 million tons per year (Figure 4-42) by the estimated 1.4 billion hectares of cultivated arable land AL (PSAC 1967, vol. 2, p. 434). The estimated global pesticide use of 0.53 kilogram per hectare-year was obtained in a similar way from Figure 4-43 by taking the grand total of 750,000 tons and again dividing by the arable land. Finally, the global average horsepower consumption is given as 0.36 horsepower per hectare in Figure 4-44.

These global average values were then used to define the reference points on the graphs in Figures 4-6, 4-35, 4-36, and 4-41; using these reference points we then inferred how many times the respective inputs must be increased to obtain a doubling or a tripling of the reference yield. The results are shown on the right-hand side of Figure 4-45. On the basis of Figure 4-40, we assumed that to double the 1963 yield would require 6 times the 1963 agricultural inputs, and to triple the yield would require 20 times the amount of inputs used in 1963.

The overall development scenario for the developing world given by the President's Science Advisory Committee (PSAC 1967, vol. 3, pp. 95–174), summarized in Figure 4-46, arrives at conclusions similar to ours. As can be seen from the figure, that study found that to achieve a doubling of the average land yield LY in the nonindustrialized countries (from the 1966 value of 1,300 vegetable-equivalent kilograms per hectare-year) on 0.7 billion hectares of arable land would require 11 times the 1966 input of fertilizer (8.6 kilograms per hectare-year) and 6 times the 1966 input of pesticides (0.17 kilogram per hectare-year). In addition, significantly improved new seeds would be required. On the basis of this information about the developing world, we assumed that their (lower than global average) land yield would double in response to a tenfold increase in agricultural inputs per hectare.

Pesticide—Class and Type	Asia (except mainland China)	Africa	Latin America	Oceania	Europe (except U.S.S.R.)	United States	Class and Type Totals
Insecticides:							
Chlorinated hydrocarbons	27,052	8,278	6,038	114	15,733	64,375	121,590
Organophosphorus compounds	4,004	2,258	2,105	4	12,106	34,437	54,914
Arsenicals	3,283	*n*	286	200	952	4,950	9,671
Mineral oils and dinitro compounds	8,888	619	246	500	8,759	—	19,012
Botanical insecticides	153	178	6	22	141	2,490	2,990
Total insecticides	43,380	11,333	8,681	840	37,691	106,252	208,177
Fungicides:							
Sulfur and compounds	21,185	17,540	2,971	540	109,739	78,250	230,225
Copper compounds	13,617	48	3,210	1,850	74,724	15,974	109,423
Mercury compounds	1,691	—	18	12	2,775	884	5,380
Carbamates and others	3,300	73	4,526	150	35,527	3,854	47,430
Total fungicides	39,793	17,661	10,725	2,552	222,765	98,962	392,458
Fumigants	7,704	14	48	84	1,621	7,890	17,361
Herbicides	37,767	934	887	784	16,832	62,644	119,848
Rodenticides	202	*n*	2	8	2,569	—	2,781
Other pesticides and dips	798	3,038	830	2,656	2,434	—	9,756
Area totals	129,644	32,980	21,173	6,924	283,912	275,748	750,381

n = negligible quantity (500 kg or less).

Figure 4-43 Pesticide usage in metric tons of active ingredients, by class and geographic area, 1963
Source: PSAC 1967, vol. 3, p. 144.

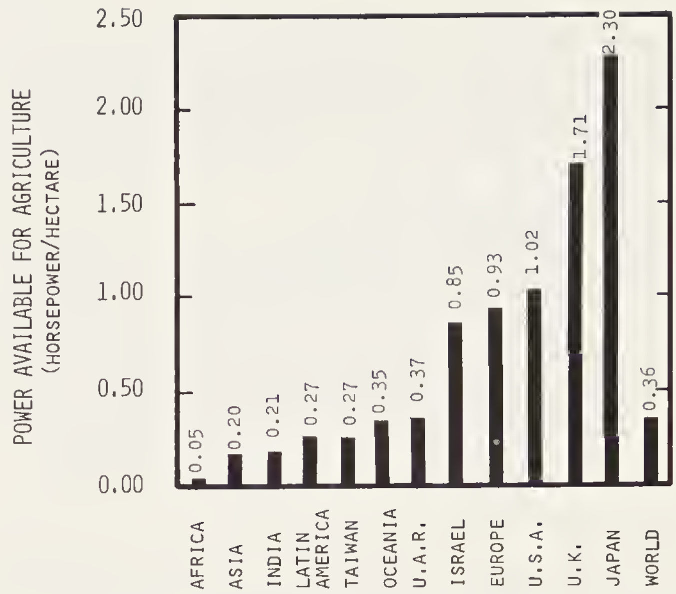


Figure 4-44 Power availability by geographic area, 1964–1965
Source: PSAC 1967, vol. 3, p. 177.

Thus we assumed that a sixfold (twentyfold) increase in world average agricultural inputs per hectare would lead to a doubling (tripling) of the 1963 global average land yield. We also established that a tenfold increase in agricultural inputs per hectare would lead to a doubling of the 1966 nonindustrialized world average land yield. To be able to use both these estimates in the construction of an average relation between land yield and agricultural inputs, we had to make assumptions about the relative size of the 1963 global average land yield and the 1966 developing country average land yield—and similarly relate the average global and developing world agricultural inputs.

We chose to express the land yields in multiples of the inherent land fertility ILF (equal to 600 vegetable-equivalent kilograms per hectare-year). We assumed that the 1966 average land yield of the developing world was 1,300 vegetable-equivalent kilograms per hectare-year (PSAC 1967, vol. 3, p. 174) and that the 1963 global average land yield was 2,000 vegetable-equivalent kilograms per hectare-year (on the basis of

Input	Average Global Use in 1963	Inputs Needed to Double Yield above the 1963 Value	Inputs Needed to Triple Yield above the 1963 Value	Multiple Needed to Double Yield above the 1963 Value	Multiple Needed to Triple Yield above the 1963 Value
Fertilizer (kilograms per hectare-year)	28	170	560	6	20
Pesticide (kilograms per hectare-year)	0.53	3	10	6	20
Power (horsepower per hectare)	0.36	1.3	2.1	3	6

Figure 4-45 Inputs needed to increase average yield
Sources: Compiled from Figures 4-6, 4-35, 4-36, and 4-41.

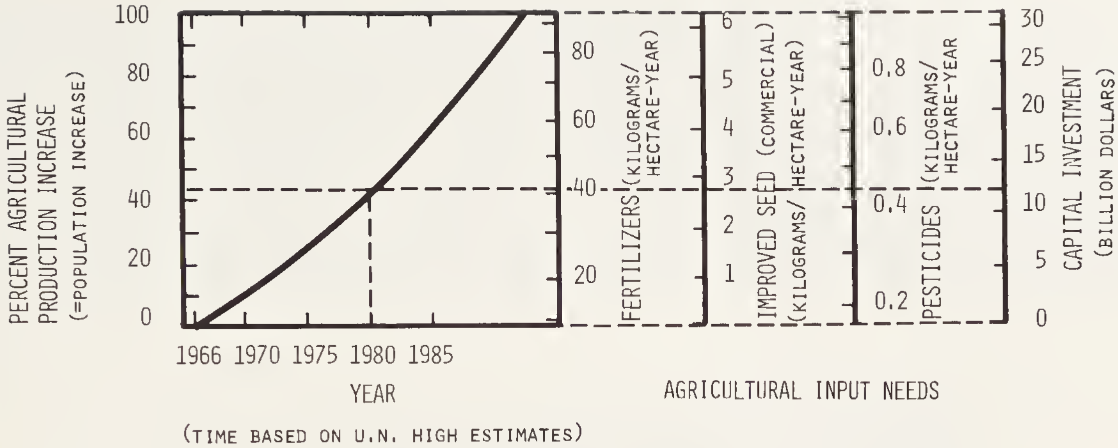


Figure 4-46 Proposed future yield and input consumption for the developing world
Source: PSAC 1967, vol. 3, p. 174.
Note: The 1966 production corresponds to an average yield of 1,300 kilograms per hectare-year on 700 million hectares of land. The area includes Asia (except mainland China and Japan), Africa, and Latin America.

Figures 4-35, 4-36, and 4-41). These yields are, respectively, about two and three times the inherent land fertility ILF. Further, we assumed that the 1963 global average agricultural inputs per hectare AIPH was four times the 1966 average agricultural inputs per hectare AIPH in the developing world. The multiple of four seems reasonable, considering the indicated differences in fertilizer and pesticide use, assuming that the other agricultural inputs are used approximately in the same proportion. Using all these figures, we were able to draw a general relationship between agricultural inputs per hectare (expressed in multiples of the 1966 developing-world value) and the resulting land yield (expressed in multiples of the inherent land fertility) as shown in Figure 4-47.

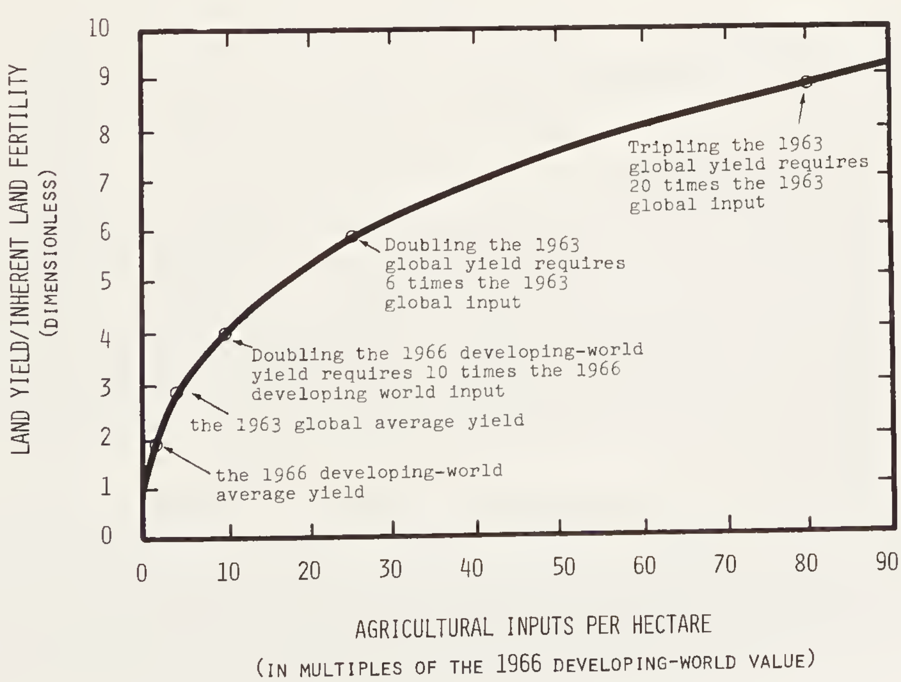


Figure 4-47 Relation between land yield and agricultural inputs per hectare

Then, to obtain the land yield multiplier from capital LYMC, it was only necessary to convert the horizontal axis of Figure 4-47 from multiples of the 1966 value of agricultural inputs per hectare AIPH in the developing world to dollar equivalents. Our calculated approximate dollar values of AIPH in various developing areas of the world are shown in Figure 4-32. Assuming from that figure a value of 12 dollars per hectare for the developing world in 1966, we obtained the relationship for LYMC shown in Figure 4-48 and expressed in the following equations:

```
LYMC.K=TABHL(LYMCT,AIPH.K,0,1000,40)                     102, A
LYMCT=1/3/3.8/4.4/4.9/5.4/5.7/6/6.3/6.6/6.9/7.2/         102.1, T
  7.4/7.6/7.8/8/8.2/8.4/8.6/8.8/9/9.2/9.4/9.6/9.8/
  10
    LYMC   . - LAND YIELD MULTIPLIER FROM CAPITAL
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LYMCT   - LYMC TABLE
    AIPH    - AGRICULTURAL INPUTS PER HECTARE (DOLLARS/
               HECTARE-YEAR)
```

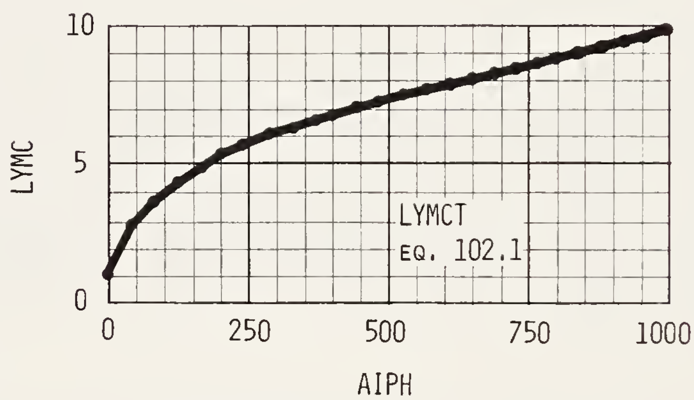


Figure 4-48 Land yield multiplier from capital table

As a rough check on the validity of this relationship, Taiwan in 1957 had "operating expenses" of 343 dollars for its average 1.6-hectare farm (Tsui 1959), or an agricultural inputs per hectare AIPH value of 215 dollars per hectare. According to Figure 4-48, Taiwan ought to have an average yield of approximately 3,000 (5 $\times$ 600) vegetable-equivalent kilograms per hectare-year, which compares reasonably well with the actual value of 2,540 vegetable-equivalent kilograms per hectare-year given in Figure 4-40.

As shown in Figure 4-48, World3 incorporates the assumption that yields will not continue to increase indefinitely as more and more capital is invested in agricultural inputs. The relationship chosen implies zero returns to additional inputs when agricultural inputs per hectare AIPH exceeds 1,000 dollars per hectare-year—a value roughly 30 times higher than the 1966 global average value.

Land Yield LY The land yield LY is the average total weight of crops (in kilograms) produced on a hectare of land in one year. In World3 the land yield LY is partly determined by the land fertility LFERT, which is defined as the weight of crops the land will produce in a traditional setting, using only traditional inputs such as human or animal energy and natural fertilizers such as manure. The land yield LY can be increased significantly above the land fertility LFERT by the use of modern agricultural inputs. The extent to which these inputs can raise yield is indicated by the land yield multiplier from capital LYMC.

```
LY.K=LYF.K*LFERT.K*LYMC.K*LYMAP.K                         103, A
    LY      - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
                HECTARE-YEAR)
    LYF     - LAND YIELD FACTOR (DIMENSIONLESS)
    LFERT   - LAND FERTILITY (VEGETABLE-EQUIVALENT
                KILOGRAMS/HECTARE-YEAR)
    LYMC    - LAND YIELD MULTIPLIER FROM CAPITAL
                (DIMENSIONLESS)
    LYMAP   - LAND YIELD MULTIPLIER FROM AIR POLLUTION
                (DIMENSIONLESS)

LYF.K=CLIP(LYF2,LYF1,TIME.K,PYEAR)                        104, A
LYF1=1                                                    104.1, C
LYF2=1                                                    104.2, C
    LYF     - LAND YIELD FACTOR (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    LYF2    - LYF, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)
    LYF1    - LYF, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
```

The land yield factor LYF is simply a multiplier (normally equal to one and therefore inoperative) that allows the entire land yield calculation to be altered by a constant factor at any time chosen by the modeler.

Land Yield Multiplier from Air Pollution LYMAP A final factor affecting land yield LY is air pollution, which operates through the land yield multiplier from air pollution LYMAP. Pollution (defined in Chapter 6) interacts with the agriculture sector in two ways. The persistent pollutants (heavy metals, pesticide residues, and radioactive isotopes) represented in the pollution sector of World3 are assumed to affect land yield LY indirectly through land fertility LFERT after a long delay (described later in this chapter). But other pollutants that would disappear instantaneously (within a year) if their production ceased, most notably air pollution, are not included in the persistent pollution sector. Because the effects of air pollution on land yield can be significant, they are represented separately in the agriculture sector of the model.

The level of air pollution is closely related to industrial output IO (given a constant level of air pollution control technology) because the residence time for a particle in the atmosphere is only of the order of weeks. This air pollution may affect food output in two different ways: by actually reducing plant growth or by making food inedible because of its content of aerially supplied poisons.

The reduction of plant growth by photo-induced smog is well documented in local areas. It occurs partly because the decrease in sunlight penetration reduces the photosynthesis taking place in the leaves. In addition, toxic substances deposited on the leaves can damage or destroy them. Examples of these substances are hydrofluoric acid, sulfur dioxide, ozone, and ethylene, which are released into the air as by-products of industrial processes.

> Smog in the Log Angeles basin contributes to the slow decline of citrus groves south of the city and damages trees in the San Bernardino National Forest 50 miles away. Fluoride and sulfur oxides, released into the air by phosphate fertilizer processing in Florida, have blighted large numbers of pines and citrus orchards. Livestock grazing on fluoride-tainted vegetation develop a crippling condition known as fluoresis. In New Jersey, pollution injury to vegetation has been observed in every county and damage reported to at least 36 commercial crops. [CEQ 1970]

The loss of crops due to air pollution is not a new phenomenon in local areas. It is well recorded in the Los Angeles basin. Figure 4-49 shows losses as early as in 1949. The scale of the problem has been rising; currently in the United States the direct costs of air pollution on both (construction) materials and vegetation are estimated at 4.9 billion dollars annually, or 0.5 percent of the GNP (CEQ 1972, p. 107).

Because of the high mobility of materials in the atmosphere, the effects of air pollution are not necessarily constrained to the area close to the source. The air pollution load is heaviest in densely populated (and hence usually industrialized) areas, but the air pollution from urban areas also affects nonurban areas. The data in Figure 4-50 show that in the United States the urban air pollution level increases with urban population size and that the nonurban pollution levels, although lower, are far from zero. Similarly, Figure 4-51 shows the extent to which sulfur dioxide originating in Germany and England makes precipitation acidic even as far away as northern Norway.

Crop	Total Acres Planted	Acres Affected	Percentage of Total Affected	1949 Average Yield per Acre	Percent Loss	Dollar Value per Unit	Total Dollar Loss
Alfalfa	53,400	9,000	17	5.3 tons	15	$24.00	$171,720
Spinach	3,350	1,000	30	5.1 "	50	33.50	85,425
Parsley	300	300	100	500 crates	25	1.50	56,250
Celery	2,300	200	4	950 "	25	2.00	47,500
Romaine	500	300	60	300 "	25	1.50	33,750
Endive	350	275	79	300 "	20	1.40	23,100
Radish	750	500	67	400 "	10	1.10	23,100
Turnip	750	300	40	500 "	10	1.00	15,000
Table beets	700	250	36	300 "	10	1.50	11,250
Mustard greens	600	200	33	400 "	10	1.00	8,000
Chard	50	40	80	450 "	25	1.00	4,500
Total							$479,495

Figure 4-49 Economic loss of crops caused by air pollution in Los Angeles County, 1949

Source: Middleton, Kendrick, and Schwalm 1950.

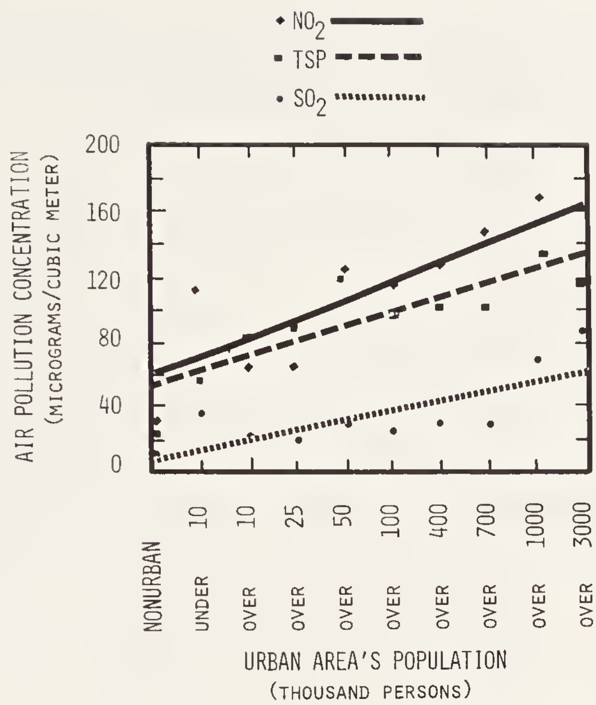


Figure 4-50 Air pollution levels in nonurban and different sized urban areas in the United States, 1969–1970
Source: CEQ 1972, p. 215.

We assumed in World3 that air pollution is uniformly distributed over agricultural land. We also chose the global total industrial output IO as the most reasonable indicator of the level of air pollution. Although much has been said and written about the effects of air pollution on land yields, we could only speculate about how much an increasing air pollution load might depress agricultural output. Our assumption about the value of the land yield multiplier from air pollution LYMAP is represented in Figure 4-52. This figure expresses the rather conservative assumption that industrial output must increase to more than ten times its 1970 value before air pollution will begin to decrease land yield LY on a global scale. We also recognize that the load of air pollutants can be reduced with proper control methods, so we tested the effect of making this relationship even less severe in some of the model simulation runs.

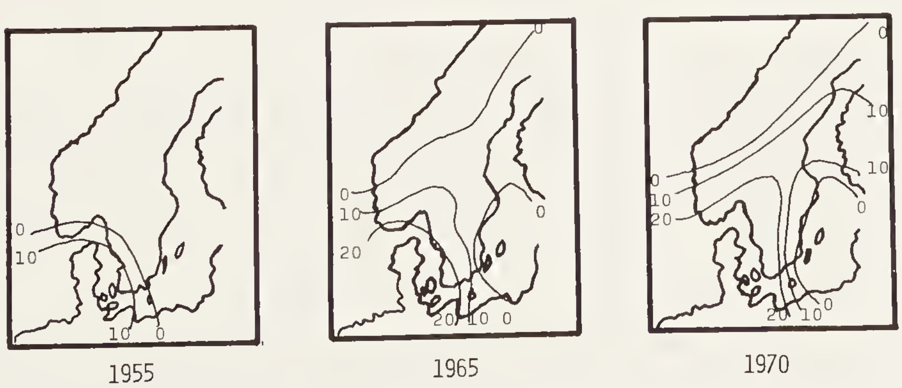


Figure 4-51 The development through time in Scandinavia of the deposition of excess acid through precipitation during one year (in milligrams of hydrogen ions per square meter)
Source: SMFA-SMA 1971, p. 28.

```
LYMAP.K=CLIP(LYMAP2.K,LYMAP1.K,TIME.K,PYEAR)        105, A
    LYMAP  - LAND YIELD MULTIPLIER FROM AIR POLLUTION
               (DIMENSIONLESS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    LYMAP2 - LYMAP, VALUE AFTER TIME=PYEAR
               (DIMENSIONLESS)
    LYMAP1 - LYMAP, VALUE BEFORE TIME=PYEAR
               (DIMENSIONLESS)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

LYMAP1.K=TABHL(LYMAP1T,IO.K/IO70,0,30,10)            106, A
LYMAP1T=1/1/.7/.4                                    106.1, T
    LYMAP1 - LYMAP, VALUE BEFORE TIME=PYEAR
               (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LYMAP1T- LYMAP1 TABLE
    IO     - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    IO70   - INDUSTRIAL OUTPUT IN 1970 (DOLLARS/YEAR)

LYMAP2.K=TABHL(LYMAP2T,IO.K/IO70,0,30,10)            107, A
LYMAP2T=1/1/.7/.4                                    107.1, T
IO70=7.9E11                                          107.2, C
    LYMAP2 - LYMAP, VALUE AFTER TIME=PYEAR
               (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LYMAP2T- LYMAP2 TABLE
    IO     - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    IO70   - INDUSTRIAL OUTPUT IN 1970 (DOLLARS/YEAR)
```

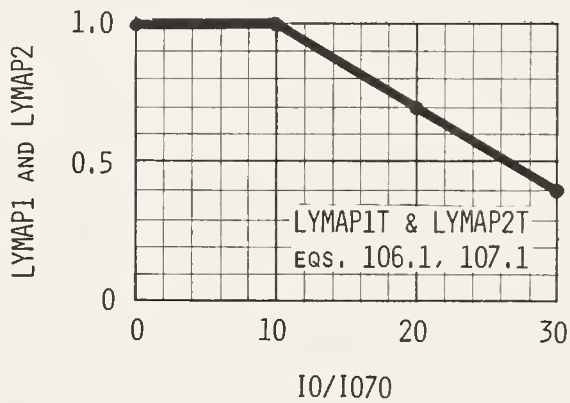


Figure 4-52 Land yield multiplier from air pollution table

Loops 1 and 2: The Investment Allocation Decision

At any point in time, society can choose to employ its total agricultural investment TAI either to develop new land or to increase the intensity with which existing arable land is cultivated. We assumed that this choice can be adequately represented by marginal productivity considerations: in World3 more agricultural investment is allocated to land development if the marginal (physical) productivity of land development MPLD (measured in vegetable-equivalent kilograms per dollar) is higher than the marginal (physical) productivity of agricultural inputs MPAI (also in vegetable-equivalent kilograms per dollar). In other words, we assumed that the next food dollar tends to be invested in the activity that will result in the larger additional crop.

Fraction of Investment Allocated to Land Development FIALD   If every society operated as a perfect profit-maximizer and had access to all the information needed to do so, all agricultural investment would be allocated to the activity with the highest marginal productivity. However, institutional constraints, communication problems, and different traditions tend to force social systems into economically suboptimal positions. Such imperfections are represented in Figure 4-53 by the relationship between the fraction of agricultural investment allocated to land development FIALD and the ratio of the marginal productivity of land development MPLD and the marginal productivity of agricultural inputs MPAI.

As Figure 4-53 indicates, we assumed imperfect market operations to the extent that 15 percent of the total agricultural investment TAI is allocated to land development even when MPAI is twice as large as MPLD. The curve in Figure 4-53 is also meant to include in an admittedly rough way the imperfections that arise in the real world through the uneven geographic distribution of fertile land and agricultural capital—imperfections compounded by complications arising from international politics. It must be stressed that the curve in Figure 4-53 represents a hypothesis that is acceptable only because it produces a realistic model behavior and because sensitivity testing (see section 4.6) reveals that the overall dynamic model behavior is not very sensitive to the exact form of the graph.

```
FIALD.K=TABHL(FIALDT,(MPLD.K/MPAI.K),0,2,.25)          108, A
FIALDT=0/.05/.15/.30/.50/.70/.85/.95/1                 108.1, T
    FIALD  - FRACTION OF INPUTS ALLOCATED TO LAND
                DEVELOPMENT (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FIALDT - FIALD TABLE
    MPLD   - MARGINAL PRODUCTIVITY OF LAND DEVELOPMENT
                (VEGETABLE-EQUIVALENT KILOGRAMS/DOLLAR)
    MPAI   - MARGINAL PRODUCTIVITY OF AGRICULTURAL
                INPUTS (VEGETABLE EQUIVALENT KILOGRAMS/
                DOLLAR)
```

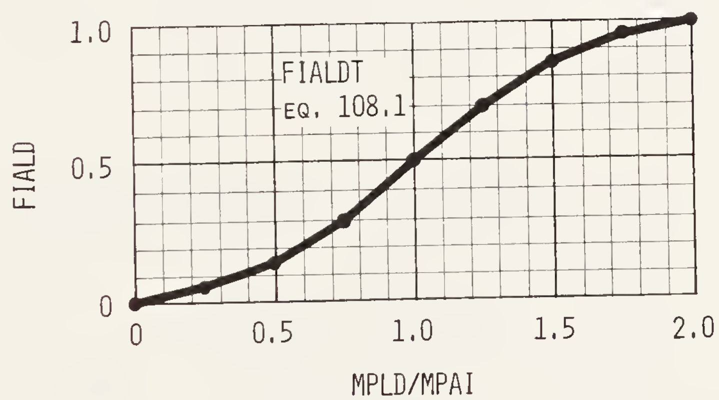


Figure 4-53 Fraction of investment allocated to land development table

Marginal Productivity of Land Development MPLD The marginal (physical) productivity of land development MPLD is the additional amount of crops that will be produced from the next dollar invested in land development. Once developed, the new arable land will produce an additional crop every year—unless the land is taken out of production to be kept fallow or to make room for construction, or because of irreversible erosion. We assumed that such land withdrawal is not anticipated by society when the decision is made to invest and hence that society plans on a constant yield LY from the land over a long period of time T. We further assumed that the net present value to society of this sequence of crops can be found by ordinary discounting, using a social discount rate SD. We assumed that the newly developed land enters production at the current average land yield LY. Thus the societal value assigned to this new land is

$$\int_0^T LY \times e^{-SD \times t} \quad dt$$

which can be approximated as LY/SD, since typically $SD \times T \gg 1$ ($SD = 0.07\ (\text{year})^{-1}$ and $T \geqslant 50$ years, implying $SD \times T \geqslant 3.5$).

The current marginal productivity of land development MPLD can then be computed from the perceived social benefit, LY/SD, and from the present development cost per hectare DCPH:

```
MPLD.K=LY.K/(DCPH.K*SD)                                    109, A
SD=.07                                                     109.1, C
    MPLD    - MARGINAL PRODUCTIVITY OF LAND DEVELOPMENT
                (VEGETABLE-EQUIVALENT KILOGRAMS/DOLLAR)
    LY      - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
                HECTARE-YEAR)
    DCPH    - DEVELOPMENT COST PER HECTARE (DOLLARS/
                HECTARE)
    SD      - SOCIAL DISCOUNT (1/YEAR)
```

Marginal Productivity of Agricultural Inputs MPAI Similarly, the marginal (physical) productivity of agricultural inputs MPAI is the additional amount of crops that will arise from the next dollar invested in agricultural inputs. The immediate increase in food output arising from investment in agricultural inputs can be computed as the partial derivative of food output F with respect to agricultural inputs AI, holding arable land AL constant:

$$\begin{aligned}
\left(\frac{\partial F}{\partial AI}\right)_{AL} &= \frac{\partial(LY*AL)}{\partial AI} \\
&= \frac{\partial LY}{\partial AIPH} \\
&= LFERT \times LYMAP \times \frac{\partial LYMC}{\partial AIPH} \\
&= \frac{LY}{LYMC} \times MLYMC,
\end{aligned}$$

where

AI	=	agricultural inputs (dollars per year)
AIPH	=	agricultural inputs per hectare (dollars per hectare-year)
AL	=	arable land (hectares)
F	=	food (vegetable-equivalent kilograms per year)
LFERT	=	land fertility (vegetable-equivalent kilograms per hectare-year)
LY	=	land yield (vegetable-equivalent kilograms per hectare-year)
LYMAP	=	land yield multiplier from air pollution (dimensionless)
LYMC	=	land yield multiplier from capital (dimensionless)
MLYMC	=	marginal land yield multiplier from capital (hectares per dollar)

The marginal land yield multiplier from capital MLYMC (Figure 4-54) is defined as ∂LYMC/∂AIPH (that is, the derivative of the LYMC graph in Figure 4-48). Again, since some agricultural inputs increase food output beyond one growing season, discounting is necessary to find the present value of the crop increase. In this case the longevity of the agricultural inputs—the average life of agricultural inputs ALAI—is much shorter than the societal planning horizon (T≈50 years). Thus the present value of a crop increase Δ F is

$$\int_0^{ALAI} \Delta F \times e^{-SD \times t}\ dt,$$

which can be approximated by $\Delta F \times ALAI$ since, typically, $SD \times ALAI \ll 1$ (SD= 0.07 (years) $^{-1}$, ALAI = 2 years, implying $SD \times ALAI = 0.14$).

The marginal productivity of agricultural inputs MPAI consequently appears as:

```
MPAI.K=ALAI.K*LY.K*MLYMC.K/LYMC.K                        110, A
    MPAI    - MARGINAL PRODUCTIVITY OF AGRICULTURAL
                INPUTS (VEGETABLE EQUIVALENT KILOGRAMS/
                DOLLAR)
    ALAI    - AVERAGE LIFETIME OF AGRICULTURAL INPUTS
                (YEARS)
    LY      - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
                HECTARE-YEAR)
    MLYMC   - MARGINAL LAND YIELD MULTIPLIER FROM CAPITAL
                (HECTARES/DOLLAR)
    LYMC    - LAND YIELD MULTIPLIER FROM CAPITAL
                (DIMENSIONLESS)

MLYMC.K=TABHL(MLYMCT,AIPH.K,0,600,40)                    111, A
MLYMCT=.075/.03/.015/.011/.009/.008/.007/.006/.005/ 111.1, T
  .005/.005/.005/.005/.005/.005/.005
    MLYMC   - MARGINAL LAND YIELD MULTIPLIER FROM CAPITAL
                (HECTARES/DOLLAR)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    MLYMCT  - MLYMC TABLE
    AIPH    - AGRICULTURAL INPUTS PER HECTARE (DOLLARS/
                HECTARE-YEAR)
```

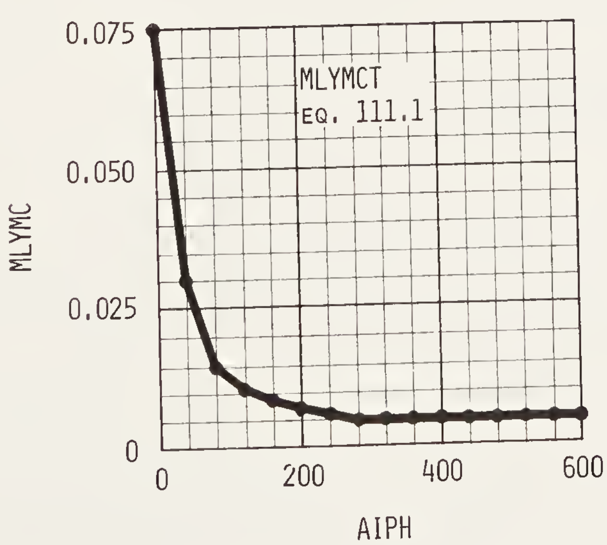


Figure 4-54 Marginal land yield multiplier from capital table

In World3 when the development cost per hectare DCPH increases (as potentially arable land PAL gets scarce), the marginal productivity of land development MPLD decreases relative to the marginal productivity of agricultural inputs MPAI. This leads to a smaller fraction of agricultural investment allocated to land development FIALD—in other words, a greater emphasis on intensifying the cultivation of existing land. This sequence of events has already taken place in Asia, leading the President's Science Advisory Committee to state:

> We have carefully considered the basic question of whether the developing world can continue to attempt to meet food needs largely through extension of traditional agriculture and increasing imports or whether it will be necessary to shift to the far more difficult method of increasing production by intensifying agriculture and improving yields. Our analysis indicates that future food needs cannot be provided by imports, either concessional or commercial and at least in Asia, not by cultivation of new lands. They must, of necessity, be provided by increased yields in the developing countries. [PSAC 1967, vol. 1, p. 40]

Loop 3: Land Erosion and Urban-Industrial Use

Erosion is the process of detachment and transportation of earth materials (rock, soil) by geologic agents (water, wind, gravity). A distinction is often made between geologic (natural) and accelerated (man-induced) erosion and between water and wind erosion.

Water erosion is a very common geologic process. It is caused by such factors as the amount and seasonal distribution of rainfall, the general topography of the land, the type of vegetation, and the nature of soils and subsoils (Buckman and Brady 1960). Water erosion is responsible for many significant changes in the earth's surface over long periods of time. Water has leveled mountains and has created deserts as well as fertile valleys and deltas. This erosion process generally occurs over millions of years, however, and the land-destructive forces are in general balance with geologic land-creating occurrences. The intervention of man has often disturbed this equilibrium by affecting the determinants of erosion (type of vegetation, condition of soil, shape of surface). The process of cultivation removes natural ground cover and replaces it by soil-exposing crops, a process that has tended to enhance the washing away of soil.

Whereas water erosion is a problem in areas with high rainfall, wind erosion is more common in arid and semiarid regions. Wind erosion is closely related to the moisture content of the soil, wind velocity, soil surface conditions, and soil characteristics. Again, cultivation has often aggravated the destructive forces of nature; mismanagement of plowed lands, as well as overgrazing, has encouraged wind erosion.

From a short time perspective, erosion may not appear to be an important determinant of global food production. Over a two-hundred-year period, however, the loss of arable land through erosion could become a significant dynamic force. Evidence of erosion from mankind's past activities covers large areas of land from the American great plains to the once-forested coast of the Mediterranean. Many of

	1882 (billion hectares)	Percent	1952 (billion hectares)	Percent	Change 1882–1952 (billion hectares)	Percent
Forest	5.2	45.4	3.3	29.6	−1.9	− 36.8
Desert and wasteland	1.1	9.4	2.6	23.3	+1.5	+140.6
Built-on land	0.87	7.7	1.6	14.6	+0.73	+ 85.8
Pastures	1.5	13.4	2.2	19.5	+0.7	+ 41.9
Tilled land	0.86	7.6	1.1	9.2	+0.24	+ 24.5
	9.53	83.5	10.8	96.2	+1.27	+ 12.9
Area not especially utilized	1.81	16.5	0.27	3.8	−1.54	− 79.9
Total	11.34	100	11.07	100	−0.27	− 2.4

Figure 4-55 Changes in land utilization, 1882–1952
Source: Abridged and adapted from "Changes in the World's Land-Use Balance Sheet, 1882–1952" in *World Balance Sheet* by Robert R. Doane (Harper & Row, 1957), p. 24.

the world's large deserts—the Kalahari and the Sahara, for example—are currently expanding into surrounding areas at rates of several miles per year. Between 1882 and 1952, world deserts grew by an average of 25 million hectares per year (Doane 1957)—though not only at the expense of arable land. By cutting down forests and exhausting land by too intensive use, man has actually wasted almost as much land as he has developed. In fact, one estimate is that the net addition of arable land between 1882 and 1952 was only 240 million hectares, or one-fifth of the total arable land in 1952 (Figure 4-55). Another estimate puts the present global erosion loss at perhaps 10 million hectares per year (Borgstrom 1970*b*). All such estimates are uncertain, since virtually no studies of erosion on a global scale have been conducted.

Average Life of Land ALL To calculate the erosion rate of arable land AL in World3 we began by determining the average time constant of erosion under traditional agricultural practices. We call this time constant the average life of land normal ALLN.

In its natural state the surface of the earth is being eroded at a rate of 1 centimeter every 80 to 200 years (Bear 1965). Using an estimated average global topsoil depth of 40 centimeters (the depth of soil can vary from a few centimeters to 30 meters or more), we assumed that under natural ground cover the global soil stock would erode significantly over a period of roughly 10,000 years. Under traditional agriculture, which usually involves minor disruption of the natural ground cover, we assumed that erosion proceeds somewhat faster. We therefore chose the average life of land normal ALLN (the time constant for the exponential decay of arable land under traditional agriculture) as 6,000 years.

Soil Treatment	**Runoff from Land as Percent of Rainfall on Land** (percent)	**Soil Lost** (tons per hectare-year)	**Erosion Rate** (centimeters per 100 years)
No crop, but tilled regularly	31	114	71
Corn grown continuously	29	49	34
Wheat grown continuously	24	25	17
Crop rotation (corn, wheat, clover)	14	7.0	4.6
Bluegrass sod grown continuously	12	0.85	0.6

Figure 4-56 Soil losses due to water erosion under different soil treatments
Source: Miller and Krusekopf 1932.

The average life of land ALL decreases significantly when the protective cover of grass and forest is replaced by an intensively cultivated monoculture. For example, intertilled crops such as corn and potatoes tremendously augment water erosion. Oats and wheat, which are species of grass, offer a better obstruction to surface wash, but their soil-holding capability is still lower than that of the original soil protective agencies. Figure 4-56 gives the losses due to water erosion on a shelly, silt, loam soil at a Missouri agricultural station.The data indicate that cropped land may be denuded at a rate of 0.3 meter or more per century, that is, up to one hundred times faster than the "natural erosion rate."

We represented this acceleration of erosion under conditions of intensive cultivation by making the average life of land ALL a variable that is dependent on cultivation intensity. The average life of land normal ALLN is multiplied by a modifier called the land life multiplier from yield LLMY, which can reduce the average life of land as intensity, and therefore yield, increases.

```
ALL.K=ALLN*LLMY.K                                          112, A
ALLN=6000                                                  112.1, C
    ALL     - AVERAGE LIFE OF LAND (YEARS)
    ALLN    - AVERAGE LIFE OF LAND NORMAL (YEARS)
    LLMY    - LAND LIFE MULTIPLIER FROM YIELD
                (DIMENSIONLESS)
```

Land Life Multiplier from Yield LLMY As already mentioned in the discussion of the causal loops of the agriculture sector, we assumed that there is usually an underallocation of resources for controlling erosion. This underallocation occurs for two reasons:

1. The costs of erosion control are immediate, but the benefits are not usually realized for several generations.
2. It is very difficult to monitor processes as slow as land erosion and therefore difficult to judge how much effort should be devoted to controlling the process.

We also assumed that erosion occurs more quickly as the vegetation departs further from natural mixed ecological systems and toward machine-cultivated, high-yield monoculture. Therefore, more erosion control is needed when cultivation is more intense but, for the two reasons already cited, we assumed that that need is not immediately recognized or satisfied. These two assumptions led us to the conclusion that more intensive use of the soil will lead to an erosion rate that is faster than the ''normal'' rate, although still very slow in terms of human generations.

It would be most desirable to link the erosion rate with intensive cropping practices through some objective index of the extent to which each modern agricultural development alters the soil structure and its exposure to eroding agents. Unfortunately, such an index does not exist, nor does there seem to be enough knowledge about erosion rates to create one. In the absence of a better index of the disturbance of natural soil ecology, we made the (oversimplified) assumption that the land yield, an indirect measure of cropping intensity, provides some indication of the probable additional exposure of soil to erosion.*

Over the past, there has been a correlation between the land yield and the disruptive interference needed to bring forth unnatural amounts of food from the land, but the relation is certainly not absolute. If society desires to do so, it can probably avoid the increased erosion rates, even while obtaining high yields, by setting aside sufficient resources to accomplish this task. Future agricultural models should formally recognize and incorporate this possibility. The extent of erosion in the world does seem to indicate, however, that human societies in recent history have not felt sufficient responsibility for the future to expend much serious effort on soil conservation.

As shown in Figure 4-57 we hypothesized the following relationship between the land life multiplier from yield LLMY and land yield LY:

```
LLMY.K=CLIP(LLMY2.K,LLMY1.K,TIME.K,PYEAR)               113, A
    LLMY    - LAND LIFE MULTIPLIER FROM YIELD
                (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    LLMY2   - LLMY, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    LLMY1   - LLMY, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

LLMY1.K=TABHL(LLMY1T,LY.K/ILF,0,9,1)                    114, A
LLMY1T=1.2/1/.63/.36/.16/.055/.04/.025/.015/.01         114.1, T
    LLMY1   - LLMY, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LLMY1T  - LLMY1 TABLE
    LY      - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
                HECTARE-YEAR)
    ILF     - INHERENT LAND FERTILITY (VEGETABLE-
                EQUIVALENT KILOGRAMS/HECTARE-YEAR)
```

*An undesirable side effect of this assumption is the following: in World3, higher levels of pollution lead to lower land yield. We also assumed that higher land yields lead to faster erosion. Hence in World3 an increase in the level of air pollution, among other things, leads to a *reduction* of the land erosion rate. We accepted this anomaly only because the coupling between air pollution and the erosion rate is rather weak. It might have been better to make the land life multiplier depend on agricultural inputs per hectare AIPH rather than on land yield LY.

```
LLMY2.K=TABHL(LLMY2T,LY.K/ILF,0,9,1)                    115, A
LLMY2T=1.2/1/.63/.36/.16/.055/.04/.025/.015/.01         115.1, T
    LLMY2  - LLMY, VALUE AFTER TIME=PYEAR
               (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LLMY2T - LLMY2 TABLE
    LY     - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
               HECTARE-YEAR)
    ILF    - INHERENT LAND FERTILITY (VEGETABLE-
               EQUIVALENT KILOGRAMS/HECTARE-YEAR)
```

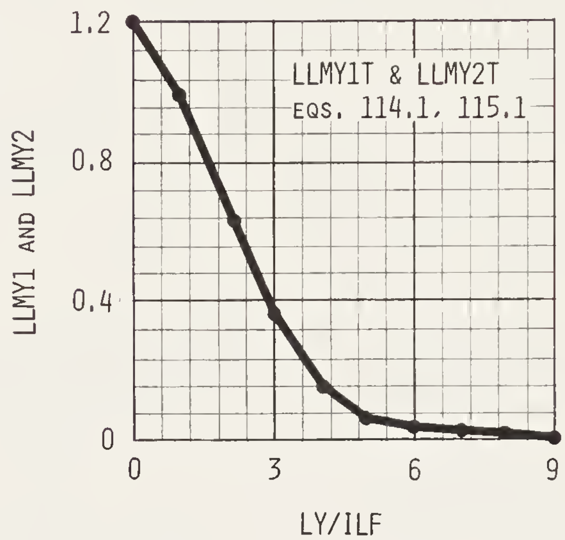


Figure 4-57 Land life multiplier from yield table

The average life of land ALL is assumed to decrease by a factor of 1/100 (to 60 years) as the land yield LY is forced up to nine times the natural inherent land fertility ILF of 600 vegetable-equivalent kilograms per hectare-year. Again, the importance of this curve lies in its negative slope rather than in the exact values it generates, which are only hypothetical. The sensitivity of the model to changes in the curve is demonstrated in section 4.6.

Land Erosion Rate LER The rate at which arable land is lost through erosion —the land erosion rate LER—is finally calculated as the level of arable land AL divided by the average life of land ALL:

```
LER.KL=AL.K/ALL.K                                       116, R
    LER    - LAND EROSION RATE (HECTARES/YEAR)
    AL     - ARABLE LAND (HECTARES)
    ALL    - AVERAGE LIFE OF LAND (YEARS)
```

This equation, given the postulated land life multiplier from yield LLMY curve of Figure 4-57, generates an erosion rate that would reduce the level of arable land to one-half (one-tenth) of its initial value in about 1,400 (4,600) years at the current average global land yield—roughly 2,000 vegetable-equivalent kilograms per hectare-year.

Urban-Industrial Land per Capita UILPC Large areas of land, including arable and potentially arable land, are being covered every year by expanding human settlements. Arable land is lost to dwellings and industrial plants; to roads, waste-disposal sites, and airports; to strip mines and power lines; and to recreational use of land (sports fields, golf courses, and parks). In World3 this urban-industrial use of land is assumed to be caused by the pressures of large populations and high industrial activity. Thus it occurs in both industrialized and nonindustrialized nations, but more in the former than in the latter.

In a study of California land usage, it was found "that by 1960, 3 million acres (1.2 million hectares) of arable land has been converted to non-agricultural use, which amounted to about 0.2 acres per person (0.08 hectares per person)" (Arkley 1969). "If this rate were to remain constant, half the state's productive farmland would be destroyed within 30 years. If it continues to accelerate as it has in recent years, 80 percent of the farmland will be gone" (Prestbo 1971). California is an extreme example, but it very clearly demonstrates the implications of an accelerating urban-industrial land use.

According to estimates of the U.S. Department of Agriculture, the United States, whose land area per capita almost exactly equals the world's average, is losing about 0.6 million hectares of farmland per year by housing subdivisions, factories, highways, and other forms of urban sprawl. That loss is equivalent to only about 0.3 percent of the total land area per year (Prestbo 1971), giving the impression that very large expansions of the urban area can still take place without serious impact. But the removal of land for urban-industrial use is accelerating and may create farmland shortages even in the United States within 50 to 100 years if the present growth rates continue.

Figure 4-58 shows the past growth trends of U.S. population and urban areas and their projections to the year 2000. Urban land in 1900 amounted to only about 1 percent of the agricultural area of the United States. It is expected to increase to approximately 8 percent in the year 2000 (Clawson, Held, and Stoddard 1965).

Figure 4-58 also indicates that urban land *per capita* increased from 0.04 hectares per person in 1920 to 0.05 hectare per person in 1970; it is projected to reach 0.06 hectare per person in the year 2000. The land taken from agriculture is more than twice as great if areas for highways, road systems, railroads, airports, sport fields, and parks are included, as in Figure 4-59.

The use of arable land for urban-industrial purposes is not only an American problem. In England and Wales arable land was lost to urban and industrial development at an approximate rate of 16,000 hectares per year between 1945 and 1966. Between the two world wars, this rate was even higher (Ministry of Agriculture, Fisheries, and Food 1968). The amount of urban land per capita increased from 0.024 hectare per person in 1925 to 0.035 hectare per person in 1960 (Best and Coppock 1962).

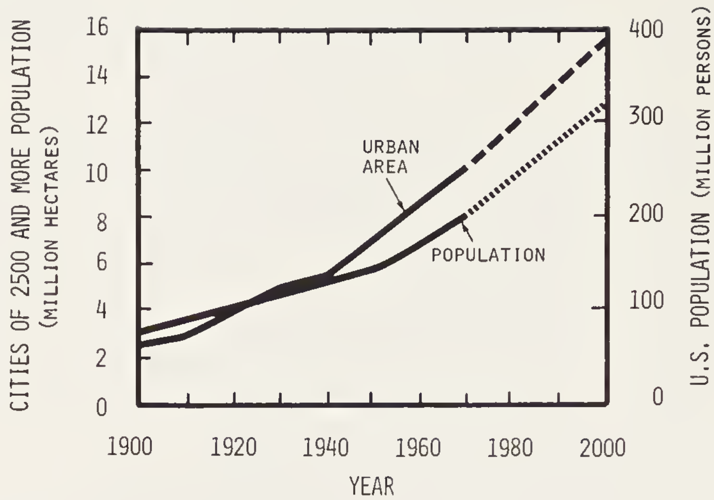


Figure 4-58 U.S. population and urban area
Source: M. Clawson, B. Held, and C. H. Stoddard, *Land for the Future* (Baltimore: The Johns Hopkins University Press for Resources for the Future, 1965), p. 102. Copyright © by The Johns Hopkins University Press.

Year	GNP per Capita (dollars per person-year)	Industrial Output per Capita[1] (dollars per person-year)	Urban-Industrial Land per Capita (hectares per person)
1910	1,500	570	0.093
1920	1,700	650	0.091
1930	1,900	720	0.086
1940	2,200	850	0.093
1950	2,500	980	0.100
1960	2,900	1,160	0.102

[1]GNP data converted to industrial output as shown in Figure 3-3.

Figure 4-59 Urban-industrial land per capita in the United States
Source: U.S.D.A. 1962.

At the present rate of disappearance, several of the Swiss cantons will have lost all tilled land before the end of the century. And Denmark now sees the end to the breaking of new land on the poor marshlands of Jutland in compensation for the good, fertile soils lost to urbanization, etc., on the islands of Fyn and Sjaelland. [Borgstrom 1970*b*, p. 312]

In World3 we hypothesized that the amount of urban industrial land per capita UILPC is a function of the industrial output per capita IOPC. We assumed that most, but not all, of this land is taken from arable land rather than from land without agricultural potential, since cities almost always arise at the heart of an agricultural region, and roads and airports are most cheaply built on level ground. In drawing the relation between urban industrial land per capita UILPC and the industrial output per capita IOPC shown in Figure 4-60, we also assumed that land use is less extravagant in the world as a whole than in the United States. Further, we assumed that urban-industrial land per capita UILPC in a primitive society amounts to 50 square meters per person or 0.005 hectare per person. This figure is the hypothesized minimum land use, more or less the area of a simple dwelling.

```
UILPC.K=TABHL(UILPCT,IOPC.K,0,1600,200)              117, A
UILPCT=.005/.008/.015/.025/.04/.055/.07/.08/.09      117.1, T
    UILPC   - URBAN-INDUSTRIAL LAND PER CAPITA (HECTARES/
                PERSON)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    UILPCT  - UILPC TABLE
    IOPC    - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                PERSON-YEAR)
```

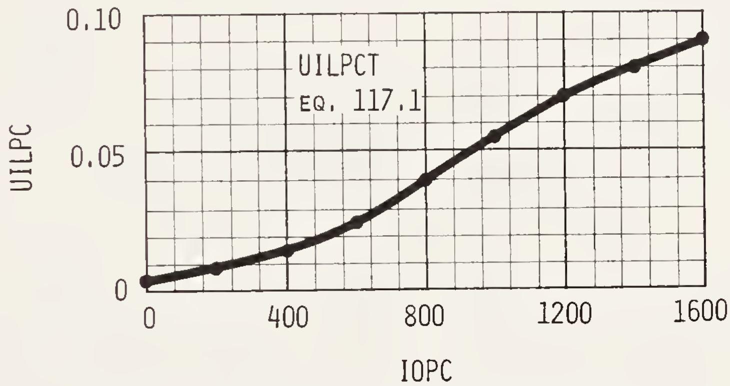


Figure 4-60 Urban-industrial land per capita table

Land Removal for Urban-Industrial Use LRUI The total area of urban-industrial land required UILR by the population POP at any given level of economic development is obtained by multiplying the required per capita use by the population:

```
UILR.K=UILPC.K*POP.K                                   118, A
    UILR    - URBAN-INDUSTRIAL LAND REQUIRED (HECTARES)
    UILPC   - URBAN-INDUSTRIAL LAND PER CAPITA (HECTARES/
                PERSON)
    POP.    - POPULATION (PERSONS)
```

The variable UILR expresses a goal: the amount of land needed by the world's population for urban-industrial use. It will increase if either the population or the industrial output per capita increases. We further assumed that the economic system will work to adjust the actual urban-industrial land UIL to the urban-industrial land required UILR goal within a ten-year time period. This adjustment delay of ten years, called the urban-industrial land development time UILDT, represents average planning and construction delays. The assumption was also made that arable land, once used for urban-industrial purposes, cannot be returned to agricultural production (at least not within the 100–200 year time horizon of this study).

The adjustment of urban-industrial land UIL to the current need UILR defines the rate of land removal for urban industrial use LRUI, which is the number of hectares removed from the stock of arable land for urban-industrial purposes every year:

```
LRUI.KL=MAX(0,(UILR.K-UIL.K)/UILDT)                    119, R
UILDT=10                                               119.1, C
    LRUI   - LAND REMOVAL FOR URBAN-INDUSTRIAL USE
               (HECTARES/YEAR)
    UILR   - URBAN-INDUSTRIAL LAND REQUIRED (HECTARES)
    UIL    - URBAN-INDUSTRIAL LAND (HECTARES)
    UILDT  - URBAN-INDUSTRIAL LAND DEVELOPMENT TIME
               (YEARS)
```

Urban-Industrial Land UIL Finally, the total urban-industrial land UIL level is arrived at by accumulating the land removal for urban-industrial use LRUI over time:

```
UIL.K=UIL.J+(DT)(LRUI.JK)                              120, L
UIL=UILI                                               120.1, N
UILI=8.2E6                                             120.2, C
    UIL    - URBAN-INDUSTRIAL LAND (HECTARES)
    DT     - TIME INTERVAL BETWEEN CONSECUTIVE
               CALCULATIONS (YEARS)
    LRUI   - LAND REMOVAL FOR URBAN-INDUSTRIAL USE
               (HECTARES/YEAR)
    UILI   - URBAN-INDUSTRIAL LAND INITIAL (HECTARES)
```

To arrive at an estimate of the global urban-industrial land area UIL in the year 1900, we made the assumption that UIL in 1900 was growing at the same rate as the steadily increasing urban-industrial land required UILR. In other words, we chose the 1900 level of UIL so that the rate of land removal for urban-industrial land LRUI in 1900 exactly matched the annual increase in urban-industrial land required UILR at that time. In World3 we assumed the global average industrial output per capita IOPC to be 40 dollars per person-year in 1900 (see Chapter 3), indicating UILR of 9.3 million hectares (from Figure 4-60) for the 1.65 billion people living at that time. Using the average global population growth rate of 1.2 percent per year between 1900 and 1970 as an approximation to the growth rate of urban land required, the equation for LRUI requires that the 1900 level of UIL be 8.2 million hectares.

Loop 4: Land Fertility Degradation

It is well known that yields from arable land can be greatly increased by the use of modern agricultural inputs, as represented in loop 2 of the agriculture sector. It is not known whether modern inputs are free from undesirable side effects when they are used intensively over long periods of time—they have not yet been used intensively for long periods. The long-term viability of the very intensive use of modern agricultural inputs is being questioned, however (see Borgstrom 1970*a* and *b*; Brown 1970*b*, p. 170). It is argued that the same inputs that increase yield in the short run may, in the long run, depress the intrinsic ability of the soil to support vegetation. The mechanisms by which this may happen include salinization of the soil by irrigation, the destruction of nitrogen-fixing bacteria by fertilizers, the evolution of pesticide-resistant insects, the compaction of the soil by heavy machinery, and the poisoning of soil microorganisms by persistent pollutants. On the other hand, proponents of modern agricultural inputs argue that no such damage will occur if the inputs are used in the proper manner—that is, in accordance with present knowledge about soils and their cultivation.

Unfortunately, present land yield data cannot be used to resolve this argument unambiguously, for land yields represent a composite index of the processes of short-term artificial enrichment and possible long-term reduction of soil fertility. As pointed out earlier, in our terminology the land yield LY is equal to the land fertility LFERT multiplied by the land yield multiplier from capital LYMC, which is assumed to increase when more agricultural inputs are employed per hectare. Neglecting for a moment the yield-depressing effect from air pollution:

$$\mathrm{LY} = \mathrm{LFERT} \times \mathrm{LYMC}$$

Thus it is possible that land *yields* may increase while land *fertility* decreases; LYMC may go up faster than LFERT goes down. Some writers believe that is what has actually happened in the world during this century:

> The fact that crop yields are rising does not necessarily mean that the basic capacity of soils to produce also is going up or even is unimpaired. There is some evidence that the inherent productiveness of many field soils has been on the down grade. [Buckmann and Brady 1960, p. 541]

Since the existing information is not sufficient to resolve this dispute, and since it is very unlikely that either of the extreme views is the correct one, we chose to include in World3 a representation of a weak fertility-reducing effect of long-term, intensive use of agricultural inputs. If the effect is included in the model structure, it becomes very simple to test the implications of the more extreme points of view —very strong fertility-reducing side effects or no side effects at all—through the variation of a single set of model parameters.

Land Fertility LFERT The land fertility LFERT is defined as the average ability of one hectare of arable land AL to produce crops without the use of any modern agricultural inputs. Hence LFERT is the output a traditional farmer would obtain from the land using only traditional seed, natural compost or manure, hand or animal labor, and natural water supply. The land fertility LFERT is measured in vegetable-equivalent kilograms per hectare-year. We assumed that the average value of LFERT for virgin land, that is, the inherent land fertility ILF, is equal to 600 vegetable-equivalent kilograms per hectare-year. (See the discussion of land yield LY under loop 2.)

The fertility of any land area is a complex function of the organic and inorganic content of the soil, the climate, and the incident solar radiation, the last two of which we assume to be invariant. Apart from the macronutrients of carbon, hydrogen, and oxygen that can be obtained from air and water, plants also depend on a large number of other nutrients—phosphorus, potassium, calcium, iron, and perhaps some other elements that have not yet been identified by plant physiologists. Most of these nutrients are made available to plants by the natural weathering of rocks and especially by the microorganisms in the soil that break down insoluble organic matter and release acids that can dissolve mineral nutrients from rock particles. Essential nitrogen compounds are also generated from the air by nitrogen-fixing bacteria or supplied from manure or rotting vegetable wastes, called humus. The transfer of nutrients from humus and rocks to plants through the action of microorganisms is a slow process. It is most efficient when the soil is porous and well aerated, with a moderate ability to hold moisture. A surprisingly large quantity of soil organisms must be present to maintain a high fertility (see Figure 4-61).

Any process that interferes with soil microorganisms, soil chemistry, or the aeration and water-holding properties of soils is likely to change the soil fertility. There are many such processes, some with a positive influence tending to regenerate soil fertility, and some tending to degrade it. Thus we may think of a continuous competition between the degenerating and regenerating forces, at all times producing some resultant value of the land fertility LFERT:

```
LFERT.K=LFERT.J+(DT)(LFR.JK-LFD.JK)                          121, L
LFERT=LFERTI                                                 121.1, N
LFERTI=600                                                   121.2, C
    LFERT  - LAND FERTILITY (VEGETABLE-EQUIVALENT
               KILOGRAMS/HECTARE-YEAR)
    DT     - TIME INTERVAL BETWEEN CONSECUTIVE
               CALCULATIONS (YEARS)
    LFR    - LAND FERTILITY REGENERATION (VEGETABLE-
               EQUIVALENT KILOGRAMS/HECTARE-YEAR-YEAR)
    LFD    - LAND FERTILITY DEGRADATION (VEGETABLE-
               EQUIVALENT KILOGRAMS/HECTARE-YEAR-YEAR)
    LFERTI - LAND FERTILITY INITIAL (VEGETABLE-
               EQUIVALENT KILOGRAMS/HECTARE-YEAR)
```

We assumed that the average land fertility LFERT of the arable land AL in 1900 was 600 vegetable-equivalent kilograms per hectare-year, identical to the inherent land fertility ILF of virgin land.

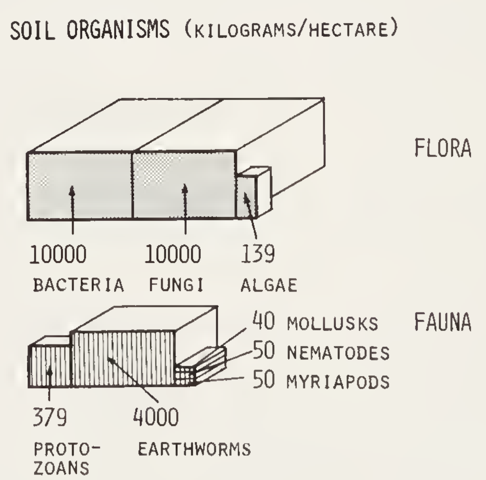


Figure 4-61 Soil organisms in well-cultivated soil

Source: Georg Borgstrom, *Too Many: A Story of Earth's Limitations*, rev. ed. (New York: Macmillan Publishing Co., 1970), p. 94. (Copyright ©1969, 1971 by Georg Borgstrom. Copyright ©1969 by Macmillan Publishing Co., Inc.)

Land Fertility Degradation Rate LFDR The land fertility degradation rate LFDR is the fraction of the current land fertility LFERT that is lost through degradative processes in a year. We made two assumptions about the land fertility degradation rate LFDR: it is increased by the same industrial and agricultural practices that lead to the accumulation of persistent pollution, and its increase appears only after a significant delay.

Chapter 6 contains a definition of persistent pollution and a description of how it is generated in World3. One of the determinants of the persistent pollution generation rate is the total amount of agricultural inputs used each year; another is the total use of nonrenewable resources. Of the many different kinds of persistent pollutants generated by agricultural and industrial activities, we assumed that some feed back to influence human health, and others influence soil fertility. The possible effects of pollutants on soil fertility are many. The soil microorganisms that fix nitrogen and break down humus are sensitive to and sometimes nearly eliminated by a heavy use of nitrogen fertilizers, by pesticides, and by accumulations of heavy metals (lead, mercury) in the soil (see Tyler 1972). The natural mechanisms for pest control by predatory species are almost invariably interrupted by the use of broad-spectrum pesticides. The extensive use of irrigation without proper drainage may eventually cause deposits of salts in the soil at levels that are toxic to plants. In other words, many of the persistent pollutants that are harmful to higher organisms are probably also harmful to the complex system of drainage patterns and to the insects, bacteria, molds, earthworms, and other small but important organisms that create and maintain soil fertility.

We assumed that this interruption of the ecological systems in the soil by pollutants does not create an immediate decrease in soil fertility but instead becomes obvious only after a fairly long delay, as the polluting material works its way through the ecosystem. The delay is contained in the pollution sector of the model, where it is called the persistent pollution transmission delay PPTD and is assigned a value of twenty years.

The assumed relationship between pollution and the land fertility degradation rate LFDR is shown in Figure 4-62. The horizontal axis in this figure shows the persistent pollution index PPOLX, which is equal to the total pollution load of the world's ecosystem at any time, divided by the total load in 1970. This total pollution load is a function of total resource usage and total agricultural inputs, delayed twenty years, as explained in Chapter 6. The graph in Figure 4-62 indicates that with zero pollution we assumed that negligible degradation forces act to reduce the existing land fertility. In other words, the land can be cultivated indefinitely at low intensities because the naturally occurring regeneration forces can keep up with the ongoing degradation—as exemplified by the 2,000-year-long cultivation of England or of the Punjab in India. At any higher intensity, based on the value of modern agricultural inputs per hectare AIPH, the rate of land fertility degradation LFD is higher.

```
LFDR.K=TABHL(LFDRT,PPOLX.K,0,30,10)                    122, A
LFDRT=0/.1/.3/.5                                       122.1, T
    LFDR   - LAND FERTILITY DEGRADATION RATE (1/YEAR)
```

```
TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
LFDRT  - LFDR TABLE
PPOLX  - INDEX OF PERSISTENT POLLUTION
           (DIMENSIONLESS)
```

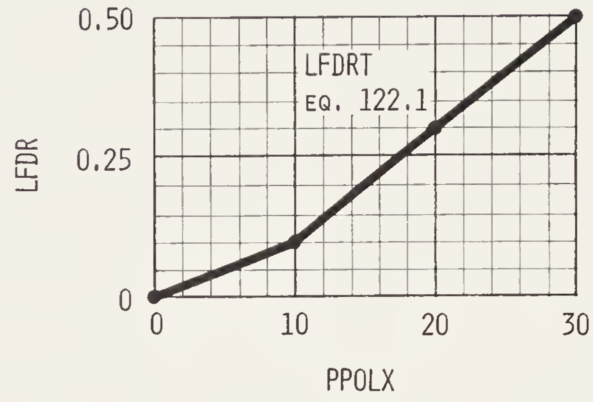


Figure 4-62 Land fertility degradation rate table

The total amount of land fertility degradation LFD occurring in one year, measured in vegetable-equivalent kilograms per hectare-year-year, is obtained by multiplying the current land fertility LFERT by the land fertility degradation rate LFDR:

```
LFD.KL=LFERT.K*LFDR.K                                    123, R
    LFD    - LAND FERTILITY DEGRADATION (VEGETABLE-
               EQUIVALENT KILOGRAMS/HECTARE-YEAR-YEAR)
    LFERT  - LAND FERTILITY (VEGETABLE-EQUIVALENT
               KILOGRAMS/HECTARE-YEAR)
    LFDR   - LAND FERTILITY DEGRADATION RATE (1/YEAR)
```

It is not easy to determine how fast fertility will degrade if no land fertility regeneration efforts are undertaken. The experiment illustrated in Figure 4-63 does indicate land fertility degradation rates of the order of 0.7 percent per year at the intensity used in Illinois in the first half of the twentieth century. This conclusion is based on the assumption that the organic content of soils is a good indicator of land fertility, so that land fertility degrades at the same rate as organic matter disappears. On the other hand, much higher degradation rates—of the order of 10 percent per year—were observed at a similar cultivation intensity in an experiment conducted under tropical conditions in Yambio, Africa, around 1970 (Figure 4-64). The differences in degradation rates may well be explained by differences in the soils, crops, and climate. We assumed an average land fertility degradation rate LFDR equal to 2 percent per year for the pollution level occurring in 1970. We also hypothesized that an agricultural and industrial intensity resulting in a pollution level 30 times the 1970 level will destroy the average land fertility at a rate of 50 percent per year if no efforts are made to counteract the destruction. As the discussion under loop 5 indicates, the natural land fertility regeneration rate assumed in World3 is sufficient to counterbalance some of the degradative forces. Thus, if sufficient funds are allocated to land maintenance, even at the maximum land fertility degradation rate the equilibrium land fertility can be maintained at one-half the inherent land fertility.

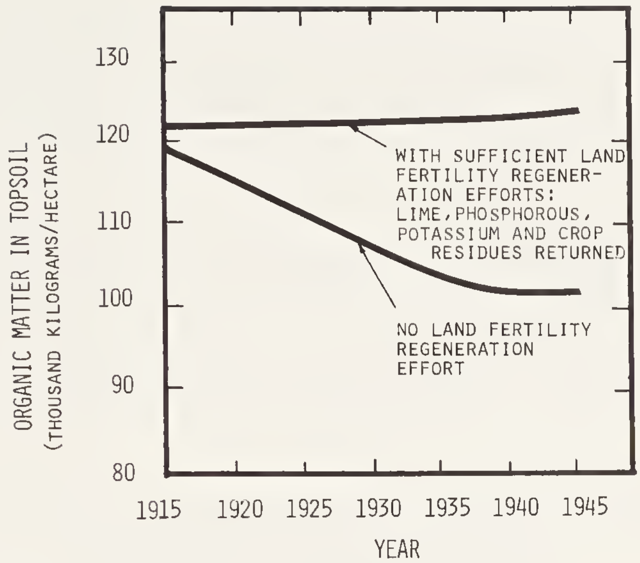


Figure 4-63 The influence of soil treatment on organic matter
Source: Snider 1950.

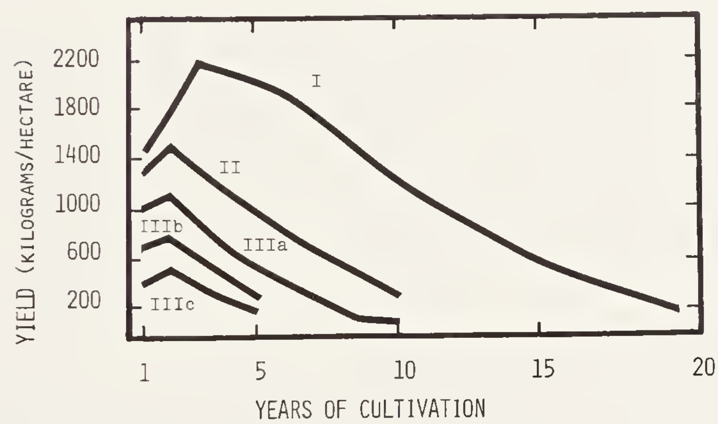


Figure 4-64 The decline of fertility of some Northern Rhodesian soils under continuous cultivation to maize without manure or fertilizers
I indicates stronger red earths and clays,
II indicates transitional soils, and
III indicates light soils.
Source: Allan 1965, p. 95.

Loop 5: Land Fertility Regeneration

We have already indicated that we believe the damage to soil fertility to be reversible; that is, given time, natural processes will restore fertility, and these processes can be enhanced by man. Historically, the regenerative processes seem to have been strong. Certain soils have been cultivated for thousands of years without appreciable reduction of soil fertility, and some may have even increased in fertility. Today, while the intensive use of soil may increase the fertility degradation forces, mankind is also equipped with an unprecedented ability to aid the natural regenerative processes. It is impossible to be certain about the outcome of this new balance of degradation and regeneration. We assumed in the model that the soil fertility will be appreciably reduced only under the most extreme conditions (very high levels of contamination of the soil and no attempts at enhancing the regenerative processes). We also assumed that the soil fertility does not keep on falling under increased degradative influences; it simply drops to a new, lower equilibrium level.

Land Fertility Regeneration LFR   The rate at which land fertility is regenerated LFR (measured in vegetable-equivalent kilograms per hectare-year-year) is assumed to be proportional to the difference between current and inherent (maximum) land fertility. The constant of proportionality is the inverse of the time constant of the regeneration process, which we called the land fertility regeneration time LFRT.

```
LFR.KL=(ILF-LFERT.K)/LFRT.K                              124, R
ILF=600                                                  124.1, C
    LFR    - LAND FERTILITY REGENERATION (VEGETABLE-
               EQUIVALENT KILOGRAMS/HECTARE-YEAR-YEAR)
    ILF    - INHERENT LAND FERTILITY (VEGETABLE-
               EQUIVALENT KILOGRAMS/HECTARE-YEAR)
    LFERT  - LAND FERTILITY (VEGETABLE-EQUIVALENT
               KILOGRAMS/HECTARE-YEAR)
    LFRT   - LAND FERTILITY REGENERATION TIME (YEARS)
```

Land Fertility Regeneration Time LFRT   The best data on the time necessary for the natural restoration of land fertility come from tropical areas. Such land fertility regeneration regularly occurs in the traditional slash-and-burn agricultural methods widespread in the tropics (Nye and Greenland 1960). Land is cleared by burning, which releases the nutrients formerly stored in the vegetation. Crops are then grown in the soil enriched by these nutrients. Free soil nutrients however, are rapidly lost through leaching and to a lesser extent taken up by crops; before long the land fertility is so much reduced that cultivation must move on to a newly cleared plot of land. The depleted land is allowed to return to natural forest, requiring a fallow of 10 to 20 years, before the land is again burned and new crops harvested. Figure 4-65 provides an estimate of the amount of nutrients stored in the soil and assimilated by crops in an 18-year-old forest in the Congo.

	N	**P**	**K**	**Ca and Mg**	
		(pounds per acre)			
Nutrients stored in:					
18-year-old secondary forest	499	65	361	502	
Total available or exchangeable nutrients in the forest soil (0–12 ins.)	≈ 2,500	17	320	89	47
Total	≈ 3,000	82	681	638	
Nutrients removed in the harvest of:					
Rice (1,000 lbs. paddy)	12	3.2	3.5	0.8	1.4
Peanuts (500 lbs. kernels)	25	2.2	2.7	0.3	0.9
Cassava (10,000 lbs.)	22	3.0	58.0	5.4	

Figure 4-65 Amount of nutrients in soil and vegetation
Source: Nye and Greenland 1960.

If the land fertility regeneration time in the tropical jungle is about 15 years, the time in colder climates must be somewhat longer, since ground cover develops and humus releases nutrients more slowly. It is likely that the regeneration time increases with the size of the exhausted land area and the degree to which the soil is impoverished when it is left to recover (Gomez-Pompa 1972). Recovery from fertility reduction due to compaction of the soil has been observed to require 4 to 15 or more years of grass coverage in Great Britain (Pilpel 1971). The recovery from imbalances in pest populations due to pesticides is probably achieved relatively quickly, although genetic changes may persist. Natural recovery from salinization may be impossible. On the basis of such observations, we assumed that a typical value for the land fertility regeneration time when only natural forces are at work is 20 years. However, this is not the time actually required for a piece of land to recover, since man can and does speed up the natural processes through artificial procedures. To represent the human enhancement of the regeneration process, the average value of 20 years is modified in World3 as follows.

Under current agricultural practices the natural regeneration process can be significantly enhanced by human efforts through the allocation of agricultural resources to land maintenance. Examples of this type of aid to natural regeneration are the restoration of nutrient levels through adding humus, draining salty areas, reforestation, planting hedges, and reducing the leaching process by mechanical means of soil control. History seems to indicate that farmers actually do care for the fertility of their land to the extent that they do not let the land fertility degrade significantly within their own lifetimes. In other words, land fertility seems to have been relatively constant in the real world at least during this century; consequently, it should also be constant in World3 over the same period.

The land fertility will remain constant in World3 only if the forces acting to degrade fertility are exactly balanced by the forces acting to regenerate fertility. Such a balance or equilibrium can occur at many different levels of land fertility, and at different regeneration and degradation rates, as long as the two rates are equal. In other words, it is possible in World3 to have a stable land fertility at high fertility or low fertility or anywhere between.

We postulated earlier that the rate of land fertility degradation LFD increases when the persistent pollution index PPOLX and land fertility LFERT increase. We also assumed that the rate of land fertility regeneration LFR increases with decreasing land fertility LFERT and with decreasing land fertility regeneration time LFRT. For given constant values of PPOLX and LFRT, one unique value of land fertility LFERT is stable, because it makes land fertility degradation LFD equal to land fertility regeneration LFR (Figure 4-66).

Here the rates of LFD and LFR are plotted against LFERT for given values of PPOLX and LFRT. Since the resulting straight lines must always cross, LFERT reaches an equilibrium value for any set of values of PPOLX and LFRT. This equilibrium fertility is always less than the inherent land fertility ILF, except when there is absolutely no pollution. The equilibrium fertility decreases when pollution increases, and it decreases when LFRT increases.

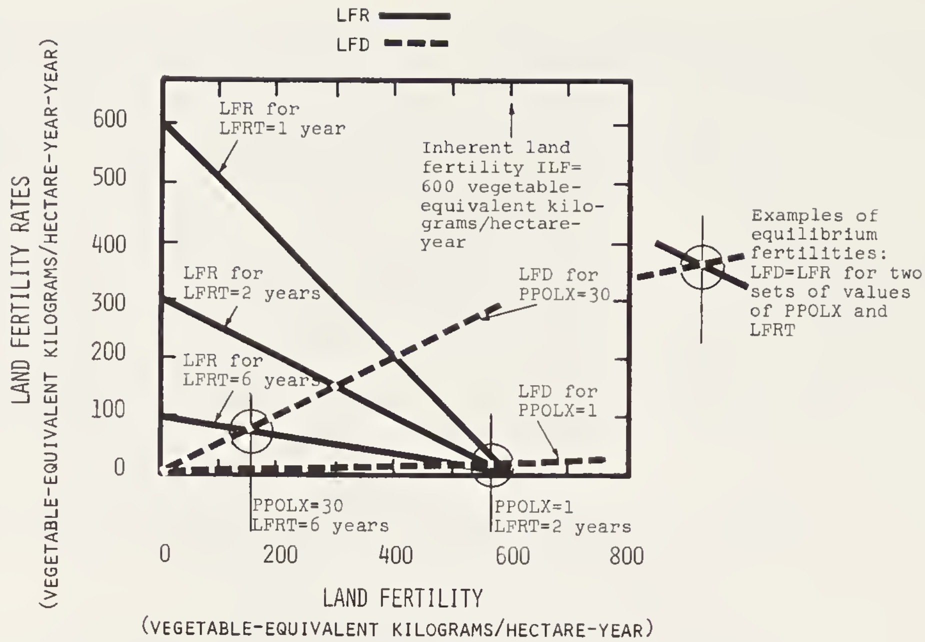


Figure 4-66 The adjustment of land fertility equilibria

ILF	= inherent land fertility (vegetable-equivalent kilograms per hectare-year)
LFD	= land fertility degradation (vegetable-equivalent kilograms per hectare-year-year)
LFERT	= land fertility (vegetable-equivalent kilograms per hectare-year)
LFR	= land fertility regeneration (vegetable-equivalent kilograms per hectare-year-year)
LFRT	= land fertility regeneration time (years)
PPOLX	= persistent pollution index (PPOL/PPOL70, dimensionless)

Even without active efforts (beyond leaving the land fallow) to speed up regeneration, traditional slash-and-burn societies could manage to maintain the land fertility because they were not faced with persistent pollution as defined in Chapter 6. When the persistent pollution index PPOLX is larger than zero, the equilibrium land fertility LFERT cannot be maintained close to the traditional, inherent value of 600 vegetable-equivalent kilograms per hectare-year unless the land fertility regeneration time LFRT is kept quite small—less than 4–6 years. In other words, constant fertility can be maintained in such situations only by enhancing the natural forces that tend to restore fertility. To achieve the relatively constant land fertility observed over the century before 1950, even in the face of some persistent pollution and population pressure, must have required sufficient allocations to land maintainance to make the land fertility regeneration time LFRT shorter than 5 years.

On this basis we assumed in World3 that farmers in the real world allocate some resources to land fertility maintenance. We hypothesized that the land fertility regeneration time LFRT is never decreased to less than 2 years by increased allocations to land maintenance. We also assumed that the regeneration time can be kept in this general order of magnitude by allocating 5–10 percent of the agricultural inputs per hectare AIPH to regeneration. Figure 4-67 shows the assumed relationship between the land fertility regeneration time LFRT and the fraction of agricultural inputs allocated to land maintenance FALM. If no inputs are allocated to land maintenance, LFRT equals its average natural value of 20 years. As allocations to land maintenance increase, LFRT continuously decreases and reaches a minimum value of 2 years.

```
LFRT.K=TABHL(LFRTT,FALM.K,0,.10,.02)                    125, A
LFRTT=20/13/8/4/2/2                                     125.1, T
    LFRT    - LAND FERTILITY REGENERATION TIME (YEARS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LFRTT   - LFRT TABLE
    FALM    - FRACTION OF INPUTS ALLOCATED TO LAND
                MAINTENANCE (DIMENSIONLESS)
```

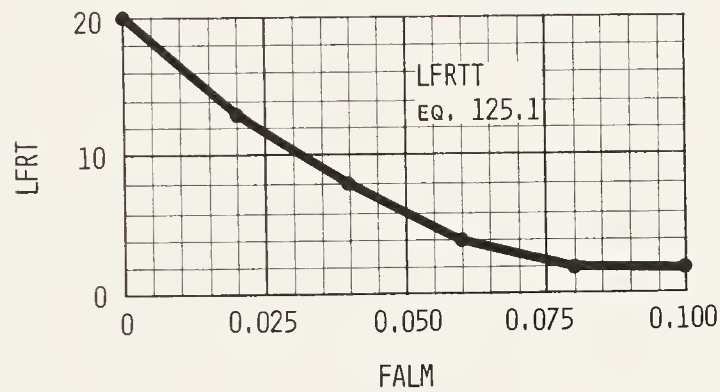


Figure 4-67 Land fertility regeneration time table

Thus in World3 the two ways of increasing the equilibrium land fertility LFERT are increasing land fertility regeneration through allocations to land maintenance, and lowering persistent pollution.

Loop 6: Discontinuing Land Maintenance

In the preceding subsection it was assumed that farmers under ordinary conditions allocate some resources to land fertility maintenance, although there are no immediate (say, within a year) benefits from such investments in terms of increased food output. On the other hand, if the same resources were spent on agricultural inputs, more food would result in the short run. Hence it is possible that land-maintaining activities are not kept up in times of extreme food shortages. Under famine conditions, would farmers still be farsighted and continue to allocate resources to land fertility maintenance or, to obtain the maximum amount of food in the short run, would they spend *all* their resources on productive activities?

Historically, extreme food shortages have seldom forced a clear-cut choice between land fertility maintenance and increased short-term productivity, perhaps because the hungry people were not usually the ones who owned the land. One possible example of this process is the hypothesis (see Harte and Socolow 1971) that the fall of the Mayan culture just before the year 1000 was due to widespread starvation following deterioration of the soils in the area. The Mayan society was based on slash-and-burn agriculture, and the reduction of land fertility may have occurred when population pressure was such that it was no longer possible to let the land lie fallow for the required 10–15 years between each cultivation period. It may have become necessary to shorten the period of fallow (in terms of World3 to reduce the resources allocated to land maintenance), with a resulting rapid reduction of land fertility. The dynamics of population pressure in a slash-and-burn society have been investigated by Shantzis and Behrens (1973). Modern-day examples of such short-sighted behavior under extreme pressure from food shortage have been cited by Allan (1965) and by Kunstadter (1972).

We chose to include a representation of this type of behavior in World3, although the resulting structure affects the model's behavior only in the few cases where prolonged food shortages occur. We assumed in World3 that very low ratios of average food per capita FPC to subsistence food per capita SFPC must be reached and sustained for several years before the global aggregate food production system is forced to abandon the practice of land fertility maintenance. The delay of several years is intended to represent the fact that constraints on trade and distributional inequalities act to preserve some land maintenance. But in a situation of prolonged food shortage, we assumed that land maintenance becomes of secondary importance compared with survival and is partially abandoned. Under these conditions societies may return fallow land to cultivation too frequently, build irrigation plants without proper (expensive) drainage systems, feed crop residues to animals rather than return them to compost, and even in extremes eat the grain that should be reserved for seed.

These assumptions are represented in the model by the relation shown in Figure 4-68. This figure relates the fraction of agricultural inputs allocated to land maintenance FALM to the perceived food ratio PFR, the latter being an averaged value of the ratio of actual to subsistence food per capita FPC/SFPC. The subsistence amount of food was set equal to 230 vegetable-equivalent kilograms per person-year (see the discussion under loop 2 in this section). We assumed that the food shortages must be extreme for a two-year period, as defined by the food shortage perception delay FSPD, before the allocation of capital to land maintenance changes significantly. If PFR is 1.0, implying just subsistence food per capita, we assumed that 4 percent of agricultural inputs per hectare AIPH would be invested each year in land maintenance (enough to reduce the land fertility regeneration time LFRT from 20 years to 8 years).

```
FALM.K=TABHL(FALMT,PFR.K,0,4,1)                         126, A
FALMT=0/.04/.07/.09/.1                                  126.1, T
    FALM   - FRACTION OF INPUTS ALLOCATED TO LAND
               MAINTENANCE (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FALMT  - FALM TABLE
    PFR    - PERCEIVED FOOD RATIO (DIMENSIONLESS)

FR.K=FPC.K/SFPC                                         127, A
SFPC=230                                                127.1, C
    FR     - FOOD RATIO (DIMENSIONLESS)
    FPC    - FOOD PER CAPITA (VEGETABLE-EQUIVALENT
               KILOGRAMS/PERSON-YEAR)
    SFPC   - SUBSISTENCE FOOD PER CAPITA (VEGETABLE-
               EQUIVALENT KILOGRAMS/PERSON-YEAR)
```

```
PFR.K=SMOOTH(FR.K,FSPD)                                    128, A
PFR=1                                                      128.1, N
FSPD=2                                                     128.2, C
     PFR    - PERCEIVED FOOD RATIO (DIMENSIONLESS)
     SMOOTH - FIRST-ORDER EXPONENTIAL INFORMATION DELAY
     FR     - FOOD RATIO (DIMENSIONLESS)
     FSPD   - FOOD SHORTAGE PERCEPTION DELAY (YEARS)
```

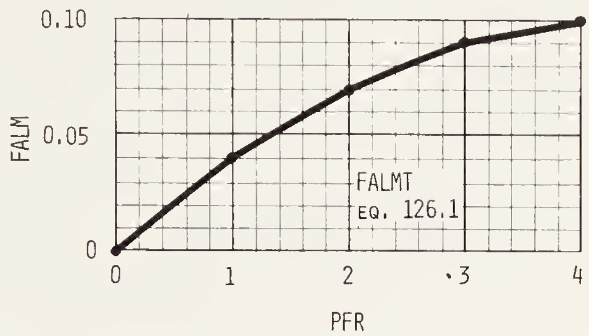


Figure 4-68 Fraction allocated to land maintenance table

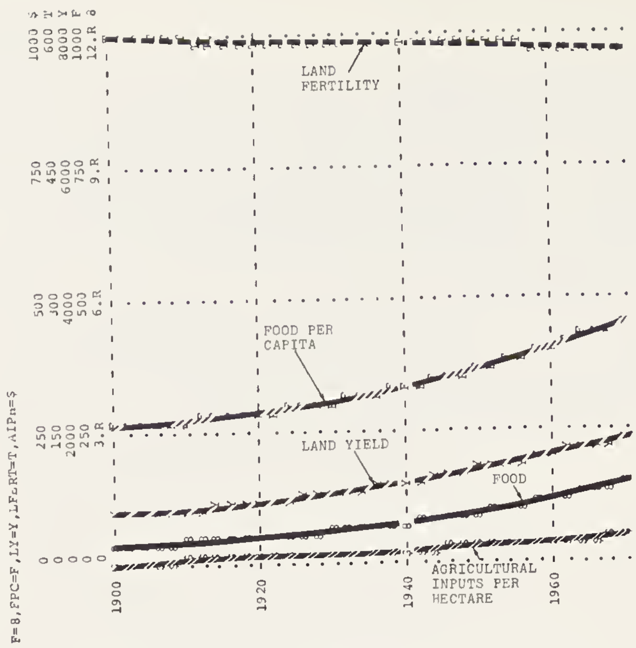
4.6 SIMULATION RUNS

This section describes the dynamic behavior of the agriculture sector as it is driven by exogenously determined inputs that represent possible patterns of influence from the other sectors of World3. These exogenous inputs are population POP, industrial output IO, and the index of persistent pollution PPOLX. The equations that generate these exogenous inputs are defined in the program listing in the appendix to this chapter. To promote a basic understanding of the possible behavior modes of the agriculture sector, the inputs are formulated as exponentially increasing functions in the first four parts of this section. The final part shows the behavior of the sector when, after a period of growth, the driving factors are held constant at different values. The behavior of the agriculture sector when it is embedded in the complete world model is discussed in Chapter 7.

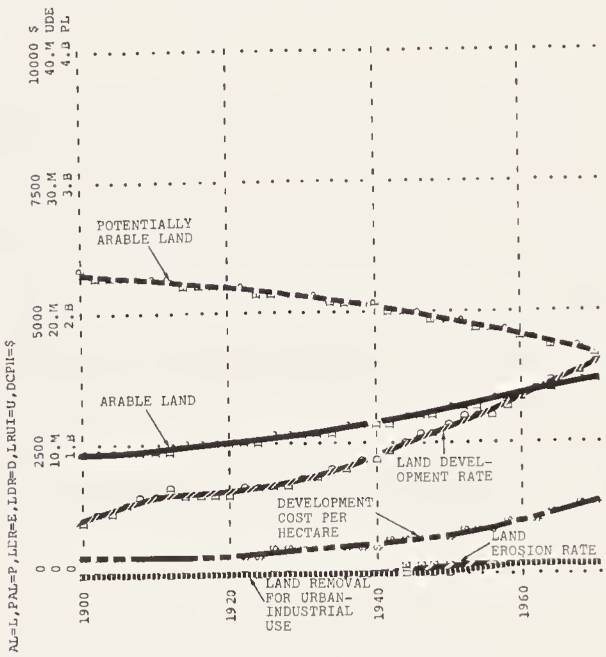
Historical Run

Run 4-1 (Figure 4-69) shows the behavior of the agriculture sector given initial values characteristic of the year 1900 and run to 1970. The four plots show the response of different variables during the same simulation. This run approximately reproduces world aggregate historical data for the period 1900–1970 as shown in section 4.2. The model generates reasonable 1970 values for arable land AL (1.4 billion hectares), development costs per hectare DCPH (1,000 dollars per hectare), agricultural inputs per hectare AIPH (40 dollars per hectare year-year) land yield LY (2,000 vegetable-equivalent kilograms per hectare-year), and food per capita FPC (500 vegetable-equivalent kilograms per person-year).

The growth in total food production F is caused by an increase in both arable land AL and land yield LY (Run 4-1A). Land yield LY grows primarily because of the increase in agricultural inputs per hectare AIPH. The increase in yield occurs in spite of a slight decrease in land fertility LFERT, the inherent capability of the land to produce food without additional agricultural inputs.



A. The behavior of land yields and food production

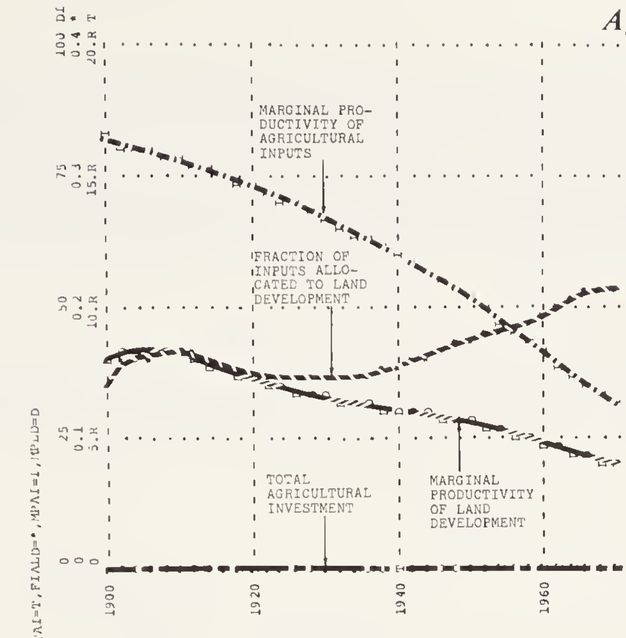


B. The behavior of arable land

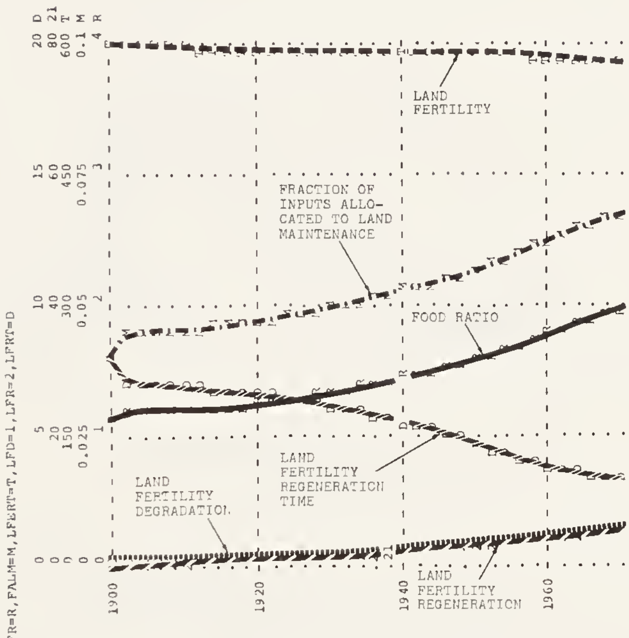
Figure 4-69 Run 4-1: historical run

Run 4-1B shows that arable land AL increases as more and more potentially arable land PAL is developed. As the level of PAL decreases, development costs per hectare DCPH increase, but not enough to stop the development of more land each year. The land erosion rate LER and land removal for urban-industrial use LRUI remain small during the historical period.

Run 4-1C shows how the model's decision to invest in land development or in more agricultural inputs was made over the historical period. Since the marginal productivity of agricultural inputs MPAI is greater than the marginal productivity of land development MPLD, a larger fraction of the total agricultural investment TAI is used for more intense cultivation of existing arable land rather than for land development. The marginal productivities of both agricultural inputs MPAI and land development MPLD fall slightly over the period, due to the onset of diminishing



C. The allocation mechanism



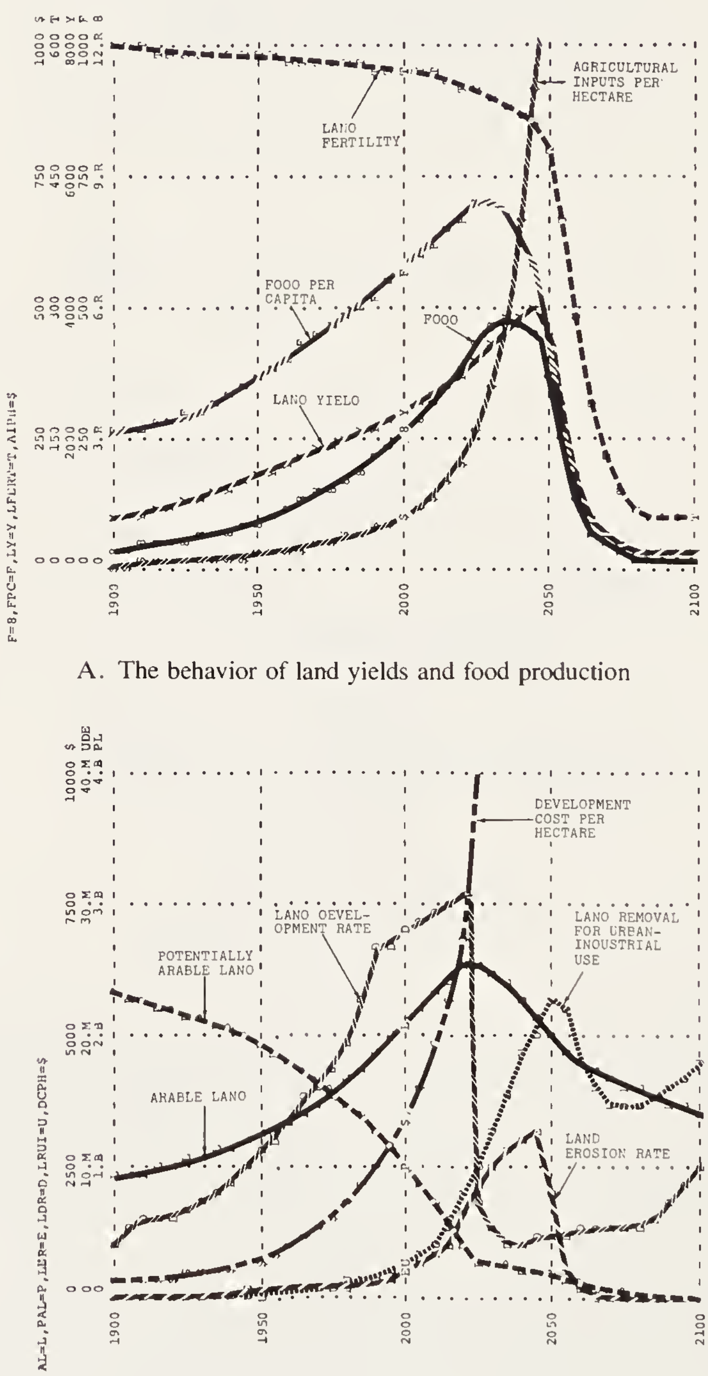
D. The behavior of land fertility

returns. The ratio of the two marginal productivities is not greatly changed, however, so that the fraction of investment allocated to land development FIALD changes only slightly (from 15 percent to 20 percent). Total agricultural investment TAI is actually growing exponentially, but the growth pattern is not evident in this plot because of the large vertical scale chosen for this variable.

Run 4-1D shows that the rate of land fertility regeneration LFR is always slightly lower than land fertility degradation LFD over the 70-year period. This discrepancy causes a small decrease in land fertility LFERT, despite the increasing fraction of agricultural inputs allocated to land maintenance FALM. The increase in FALM is caused by the rise in the food ratio FR—as food becomes more plentiful, farmers can afford to spend more of their agricultural capital on land maintenance. The land fertility regeneration time LFRT is cut in half by this increasing effort at land maintenance. Nevertheless, the exponentially growing index of persistent pollution PPOLX keeps land fertility degradation LFD just slightly ahead of land fertility regeneration LFR.

Standard Run

Run 4-2 (Figure 4-70) shows the behavior of different variables in the agriculture sector as it is simulated from 1900 to 2100, assuming that the exogenous inputs



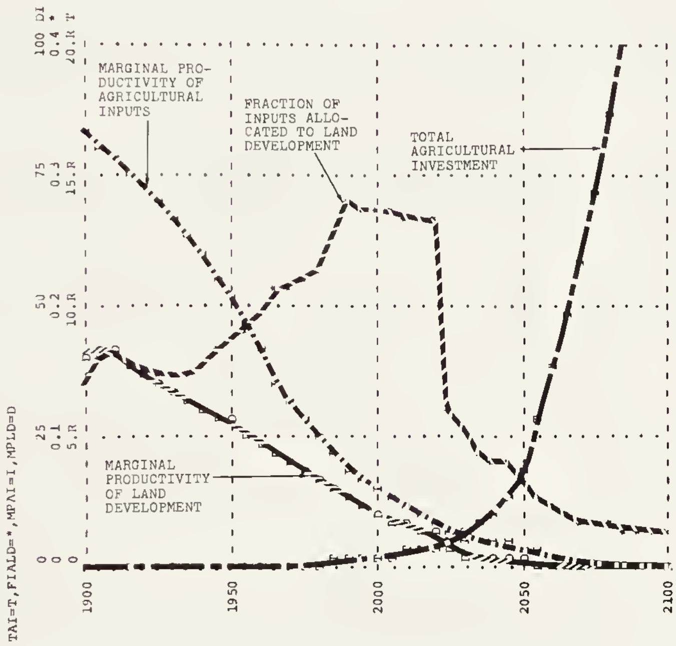
A. The behavior of land yields and food production

B. The behavior of arable land

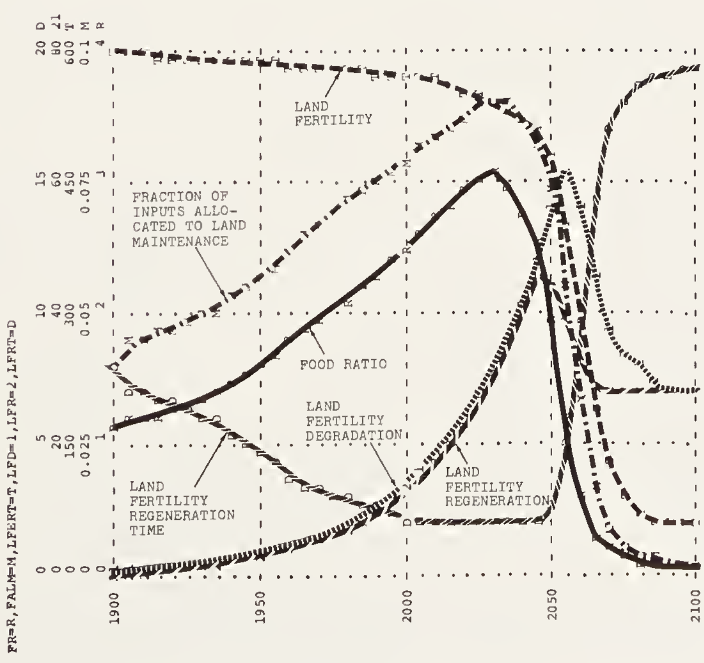
Figure 4-70 Run 4-2: standard run

continue to grow exponentially at fixed rates of growth. Population POP grows at 1.2 percent per year, industrial output IO at 3.6 percent per year, and the index of persistent pollution PPOLX at 3 percent per year. By the year 2100 the population level POP has reached 18 billion, industrial output per capita IOPC equals 4,900 dollars per person-year, and persistent pollution PPOLX reaches 50 times its 1970 level.

Several factors contribute to the overshoot and decline mode of behavior shown here. Since total food is the product of the number of hectares of arable land AL and the yield per hectare LY (minus small losses due to processing and harvesting), the



C. The allocation mechanism



D. The behavior of land fertility

decline in food production must be a result of a decline in either of these two variables. In the standard run, both arable land and land yields eventually decline.

Run 4-2A shows yield LY peaking around the year 2040. Its decline is due to falling land fertility LFERT and increasing air pollution (not plotted here). Run 4-2D demonstrates the mechanisms that cause the decline in land fertility LFERT. As in the historical run, (Figure 4-69) land fertility regeneration LFR lags slightly behind land fertility degradation LFD between 1900 and 2000. From 2000 to 2050 the land fertility regeneration time LFRT is reduced to its minimum value of two years by the growing fraction of agricultural inputs allocated to land maintenance FALM. Despite the success of land maintenance efforts in speeding up the land regenerative mechanisms, land fertility continues to fall because of the degrading effects of the continually increasing persistent pollution index PPOLX.

After the year 2050 the decline in land fertility LFERT is greatly exacerbated by the decline in the food ratio FR. When food per capita drops very low, the urgent short-term need for more food causes a smaller fraction of agricultural inputs to be allocated to land maintenance. As land maintenance is abandoned, the regenerative mechanisms slow down (LFRT increases toward 20 years), and land fertility LFERT falls sharply.

The decrease in LFERT, coupled with a falling land yield multiplier from air pollution LYMAP, causes land yield LY to fall after the year 2045 despite the sharp rise in agricultural inputs per hectare AIPH (Run 4-2A). As AIPH exceeds 1,000 dollars per hectare-year, the land yield multiplier from capital LYMC becomes saturated at its highest value—ten times the value possible without agricultural inputs.

Run 4-2B shows the mechanisms that lead to a decline in arable land AL. The growth in the land development rate LDR must eventually cease as potentially arable land PAL approaches zero and development costs per hectare DCPH become very high. Around the year 2020 almost all potentially arable land PAL is developed, and the marginal return to developing further land becomes so low that investment is diverted to agricultural inputs. As the fraction of investment allocated to land development FIALD decreases, (Run 4-2C) the rate of land development LDR drops sharply (institutional delays not represented in this simple model would make the investment transition less abrupt).

Meanwhile, land erosion LER and land removal for urban-industrial use LRUI continue to grow because of the exponential rise in population and industrial output, which causes arable land AL to decline. During the interval from 2050 to 2070, the annual amount of land removed for urban and industrial use LRUI decreases slightly, and then continues to increase after 2070. This behavior is caused by the first-order delay in the hypothesized relationship between the amount of land required for urban and industrial use per capita UILPC and the industrial output per capita IOPC. As IOPC grows, the required amount of UILPC eventually reaches a constant upper limit. From this point on, further growth in the *total* amount of urban industrial land required UILR is due only to the growth in population POP; therefore, its exponential growth rate is slower than it was before 2050. The rate of land removal for urban-industrial use LRUI responds to this changing rate of increase only after a first-order delay, with a delay time UILRDT of 10 years. The slight overshoot, decline, and then continued increase in the land removal rate LRUI illustrate its delayed adjustment to a slower rise in the demand for urban-industrial land.

The growth in land erosion LER is caused by the rise in land yield LY. As LY declines, LER also declines. One might expect erosion to continue to grow even after land yield LY declines, since one would expect overintensive cropping practices to continue in the face of rising food shortages (this undesirable side effect of the land erosion–land yield formulation is discussed in section 4.5).

Sensitivity Runs—Limits to Food Production

The upper limit to the production of food in World3 is determined by two constraints: the maximum amount of potentially arable land available (PALT) and the maximum yield obtainable from that land once it is developed (the maximum value of the land yield multiplier from capital LYMC). The sensitivity of the agriculture sector to possible errors in the estimates of these two constraints will be investigated here.

In section 4.5 we hypothesized a relationship between agricultural inputs per hectare AIPH and land yield LY. It was assumed in the standard run that increased inputs can increase yield by a maximum factor of 10 above the inherent land fertility. Figure 4-71 shows two other possible estimates of the land yield multiplier from

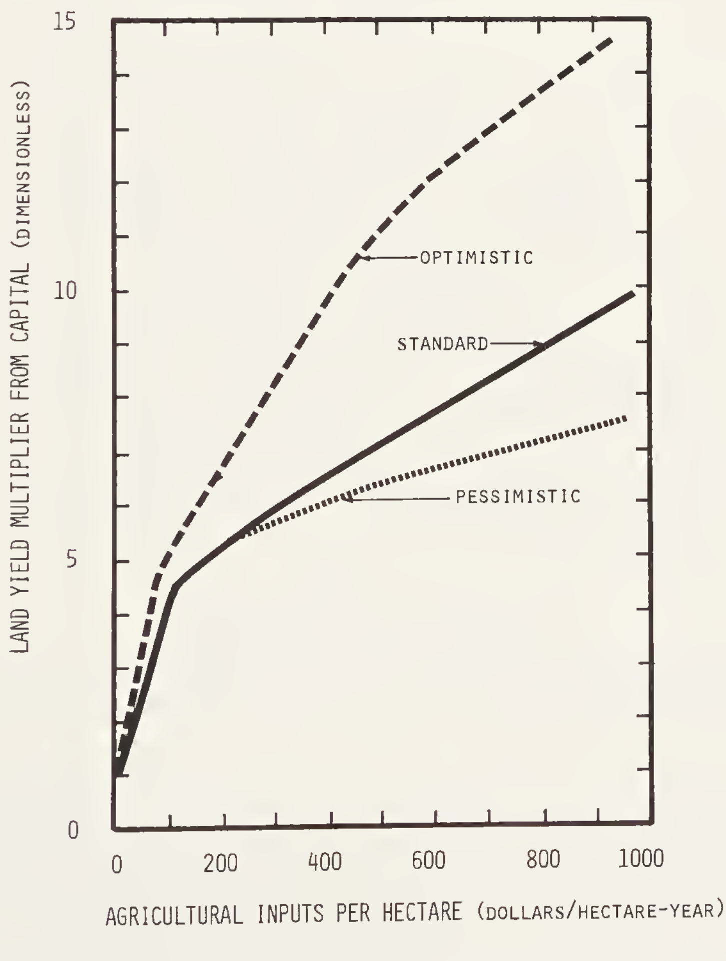
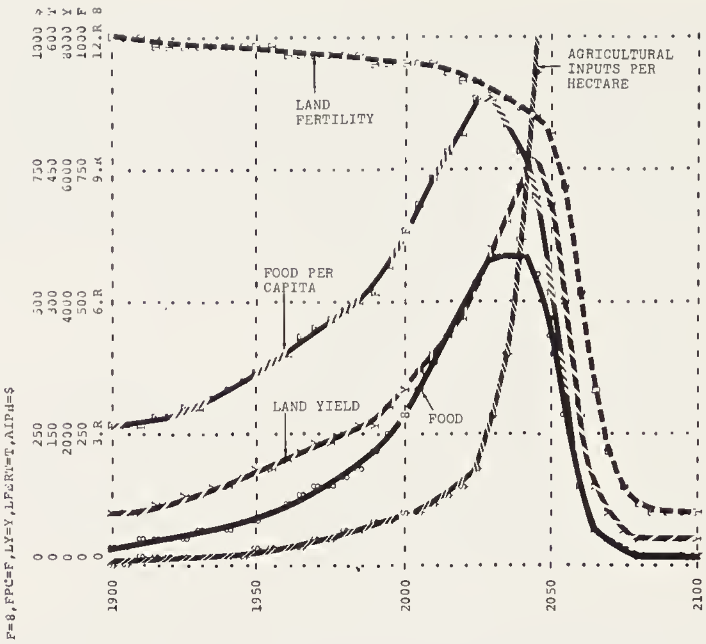
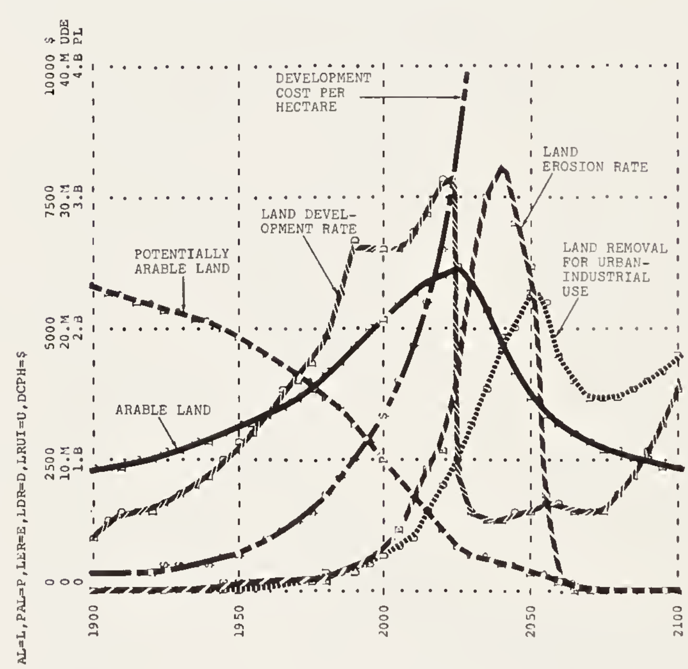


Figure 4-71 Standard, pessimistic, and optimistic estimates of the land yield multiplier from capital table



A. The behavior of land yields and food production



B. The behavior of arable land

Figure 4-72 Run 4-3: sensitivity test of the land yield multiplier from capital table, using the optimistic LYMCT

capital LYMC relationship, one that raises the upper limit by 50 percent and one that decreases it by 25 percent. These two curves will be used to investigate the sensitivity of the model's behavior to alternative assumptions of the upper limit to land yields.

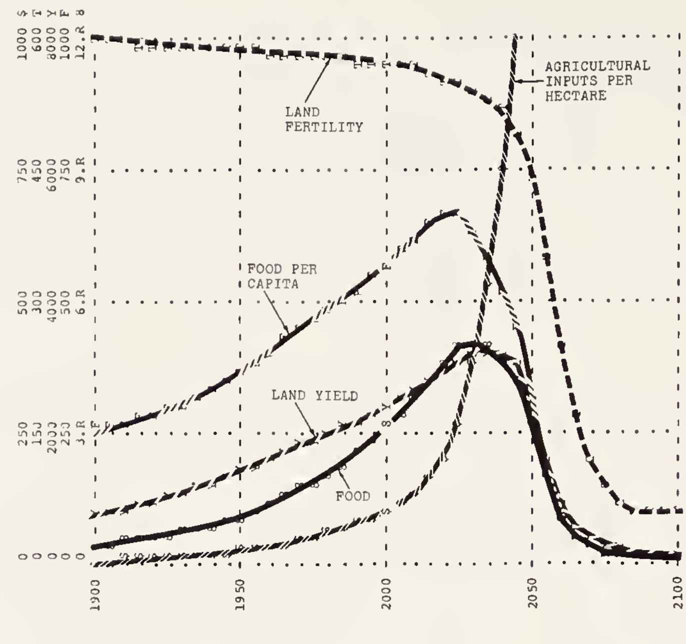
Run 4-3 (Figure 4-72) shows the results of a simulation using the "optimistic" curve from Figure 4-71. In this simulation, all other factors are the same as in the standard run, but agricultural inputs are now assumed to be capable of enhancing land yield LY by a maximum factor of 15. As might be expected, land yields LY peak higher, causing food production F to peak higher. The overshoot and decline mode of behavior remains, however, and the decline occurs only a few years later than in the standard run. The decline is caused by the same sequence of events that brought about the decline in the standard run—reduced land fertility from pollution, diminishing returns to both capital and land, and exponentially growing food demand from a growing population. Note that the decline is more severe here than it was in the standard run, since the higher land yield LY leads to an increased rate of erosion LER.

Run 4-4 (Figure 4-73) shows the results of a simulation using the ''pessimistic'' curve for the land yield multiplier from capital LYMC in Figure 4-71, which assumes a maximum enhancement of land yield LY of 7.5 times the inherent fertility ILF. Again, all other factors are the same as in the standard run. In this run, land yield LY and food production peak at values slightly lower than their maximums in the standard run. However, the decline still occurs at about the same time and for the same reasons. Arable land AL does not decline as rapidly as in the standard run, since lower yield leads to a lower erosion rate.

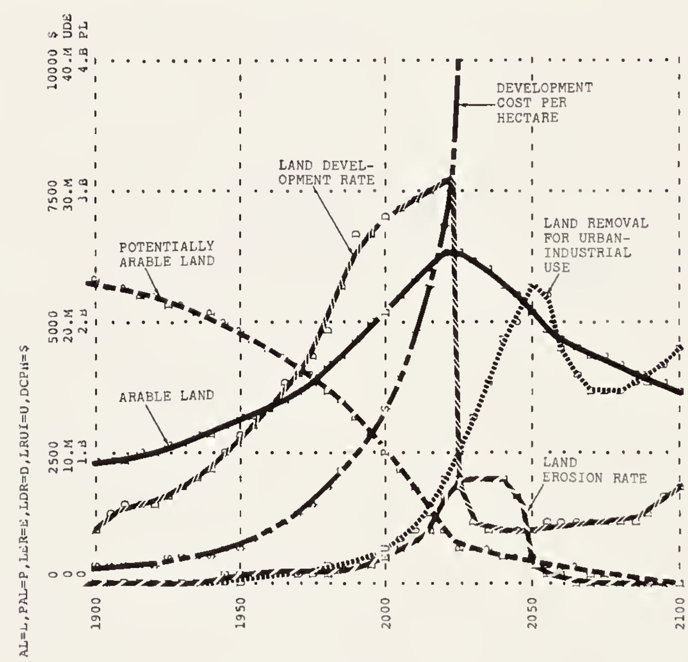
Run 4-5 (Figure 4-74) shows a simulation using a 35 percent increase in the estimate of the value of potentially arable land total PALT. Since more potentially arable land PAL exists, development costs remain low, and the rate of land development LDR is consistently higher than in the standard run. This increased rate of land development causes potentially arable land PAL to approach zero almost as quickly as it did in the standard run. Eventually, increasing development costs per hectare DCPH force an abandonment of land development around the year 2025—only five years later than in the standard run. Arable land AL peaks at a higher value than it reached in the standard run. Since the marginal return on land development is higher than in the standard run, a smaller fraction of investment is allocated to agricultural inputs throughout Run 4-5. Therefore, land yield LY does not reach the peak value obtained in the standard run, and there is less land erosion. Because of the lower cultivation intensity, the decline in arable land AL is less steep than in the standard run. Total food production reaches a higher value before it eventually declines.

Run 4-6 (Figure 4-75) shows a simulation using a decreased estimate of the value of potentially arable land total PALT. PALT is decreased from 3.2 to 2.4 billion hectares. In this simulation, arable land AL peaks about 10 years earlier than in the standard run. Since land development is marginally less productive than it was in the standard run, a larger fraction of investment is allocated to agricultural inputs. Land yield LY peaks at a higher value than in the standard run, bringing about more land erosion LER. The peak food production is about 20 percent less than the peak value of the standard run.

Notice that arable land AL no longer passes through its 1970 value of 1.4 billion hectares in the two sensitivity tests of PALT shown in Runs 4-5 and 4-6. A sensitivity test in PALT seeks to determine the possible consequences of incorrectly estimating PALT. But if the original estimate of PALT is poor, then some other compensat-



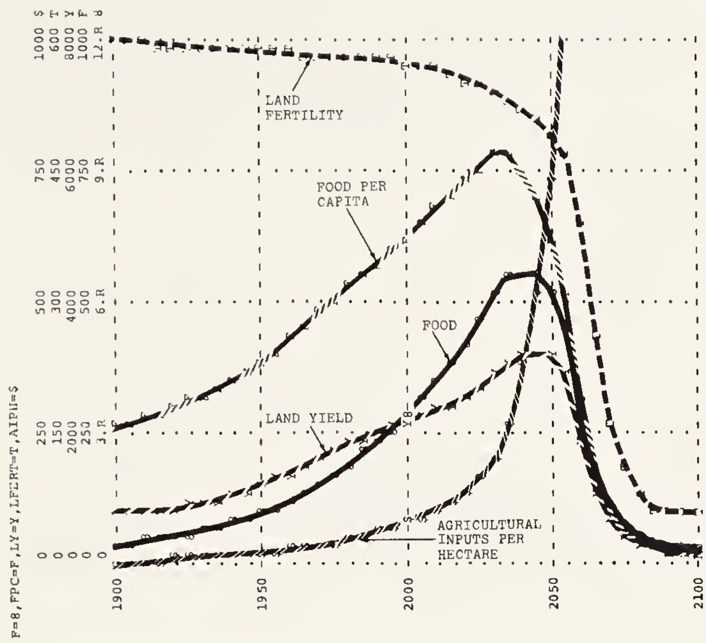
A. The behavior of land yields and food production



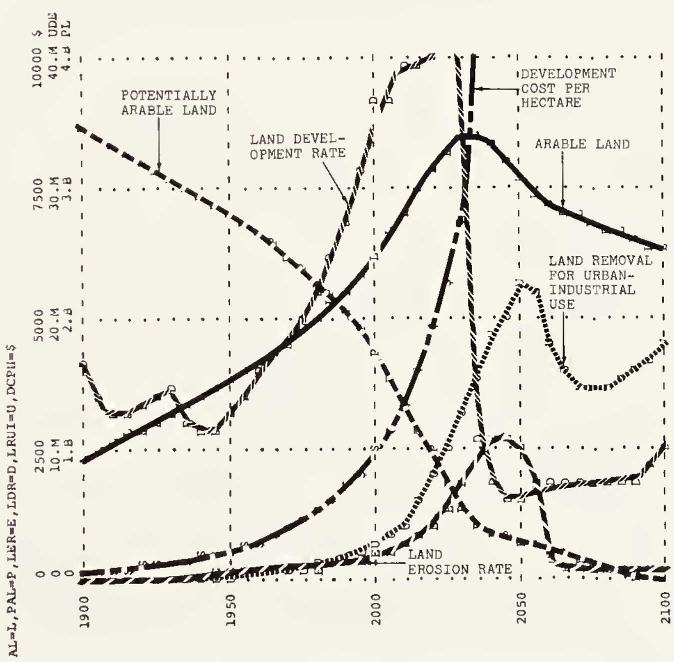
B. The behavior of arable land

Figure 4-73 Run 4-4: sensitivity test of the land yield multiplier from capital table, using the pessimistic LYMCT

ing relationship must also have been poorly estimated, since the model no longer tracks historical behavior. In this case the most obvious compensating relationship is development costs per hectare DCPH. If one assumes that a larger supply of potentially arable land actually exists, then the development costs per hectare DCPH associated with that larger supply of land must be adjusted. Otherwise, the larger supply of potentially arable land would have been developed at a faster rate than has



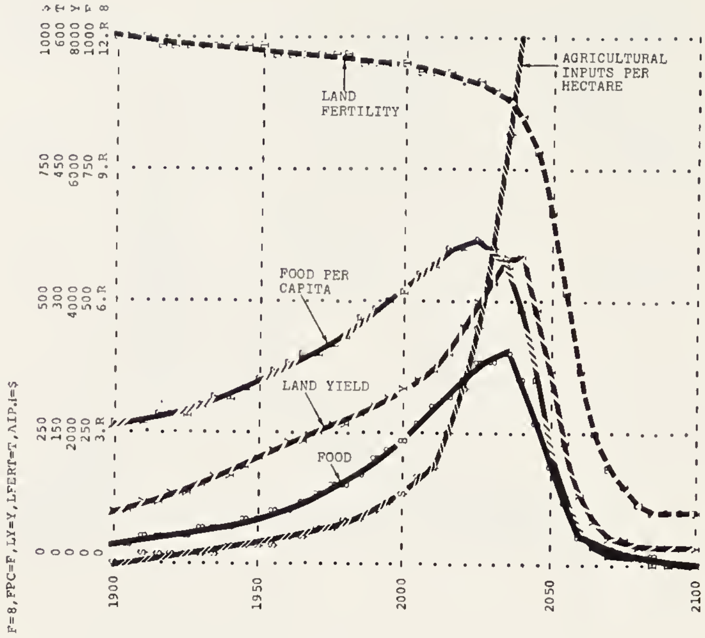
A. The behavior of land yields and food production



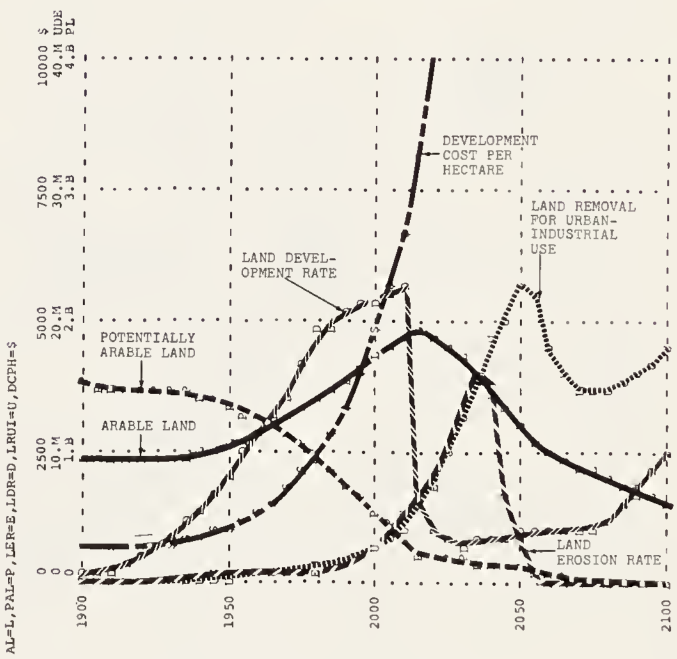
B. The behavior of arable land

Figure 4-74 Run 4-5: sensitivity test with a 35 percent increase in the estimate of the value of potentially arable land total

historically been the case. Run 4-7 (Figure 4-76) shows a more reasonable sensitivity test for PALT. In this run, PALT is increased 35 percent, and development costs per hectare DCPH are also increased, so that arable land AL tracks historical values during the 1900–1970 interval of the simulation. Eventually, arable land AL peaks at



A. The behavior of land yields and food production

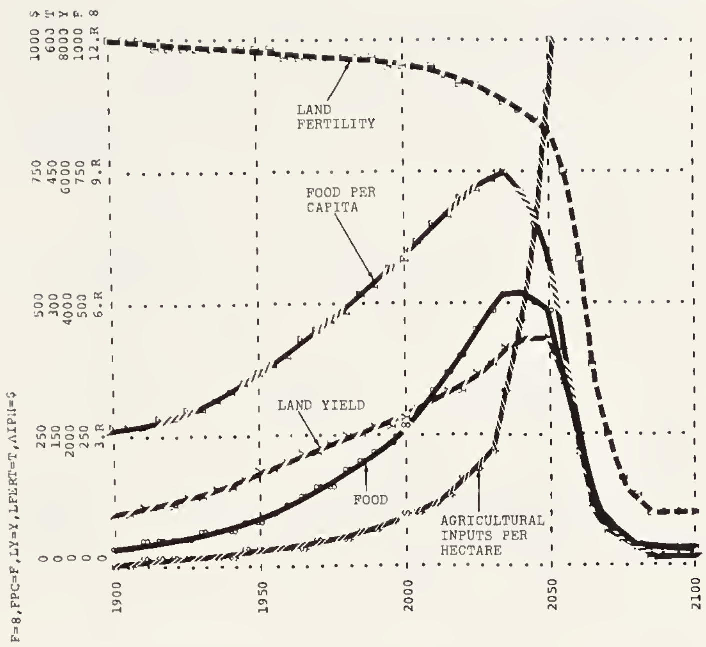


B. The behavior of arable land

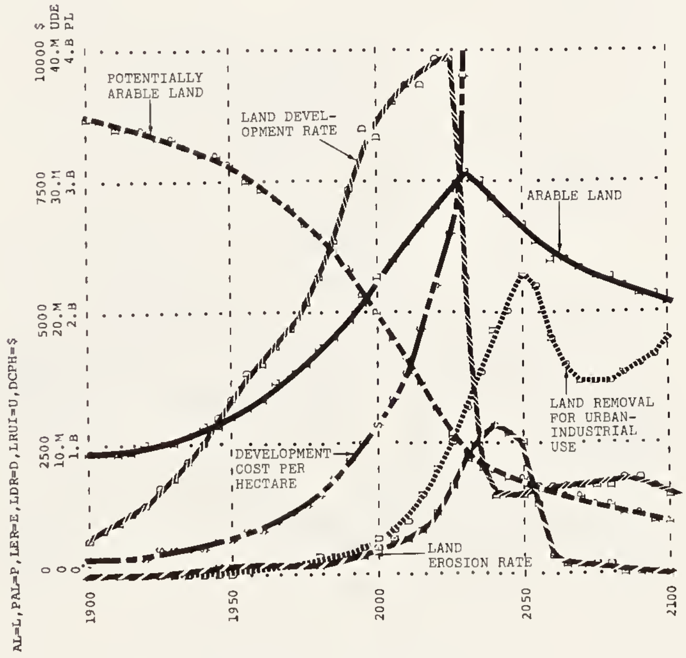
Figure 4-75 Run 4-6: sensitivity test with a 25 percent decrease in the estimate of the value of potentially arable land total

a slightly higher value than in the standard run but at a lower value than in the sensitivity run without the compensating increase in development costs. Total food production F also peaks at a higher value than in the standard run but at a lower value than in the sensitivity run without the compensating increase in development costs.

Note that when the sensitivity test of Run 4-5 is adjusted to track historical



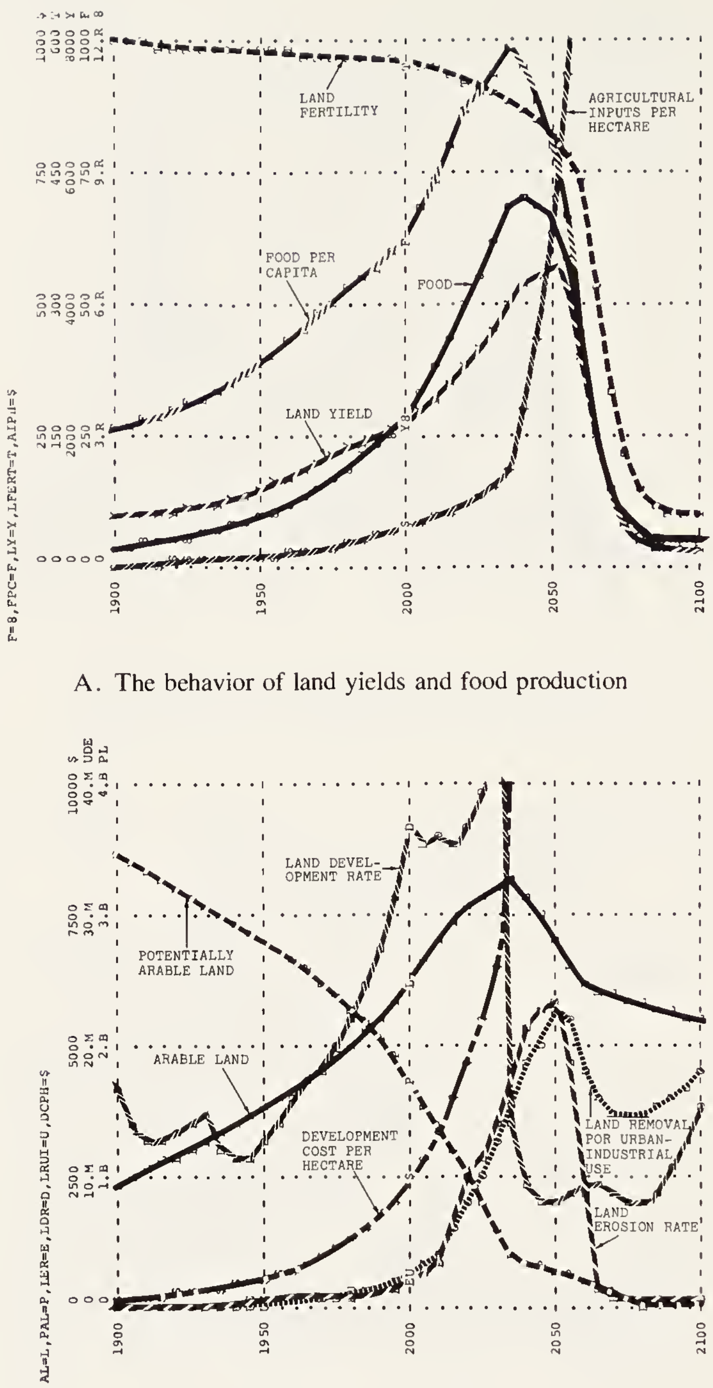
A. The behavior of land yields and food production



B. The behavior of arable land

Figure 4-76 Run 4-7: sensitivity test with a 35 percent increase in the estimate of the value of potentially arable land total and development costs adjusted to maintain historical behavior

behavior, the resulting behavior (Run 4-7) more closely resembles that shown in the standard run. Thus if no new mode of behavior appears in a simple sensitivity test such as Run 4-5, where the model is not even adjusted to track historical behavior, one might expect that no new mode of behavior will appear in a more rigorous sensitivity test such as that shown in Run 4-7, where the behavior of the model is



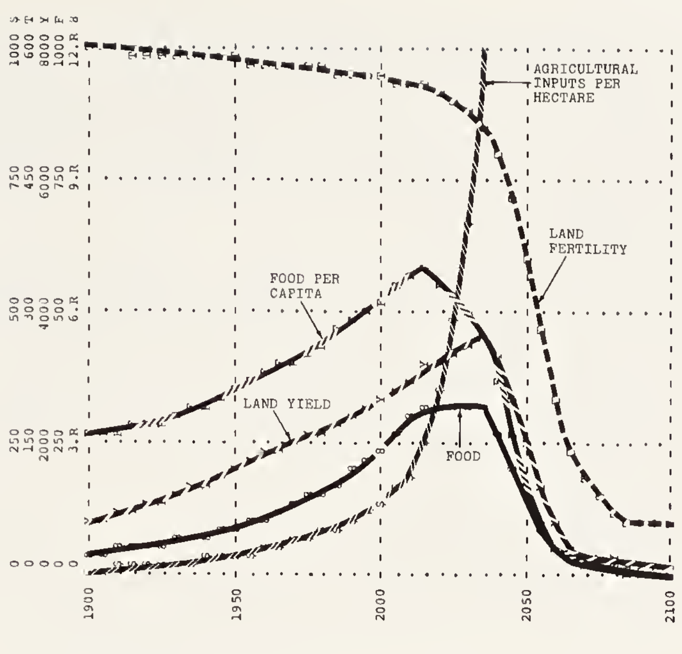
A. The behavior of land yields and food production

B. The behavior of arable land

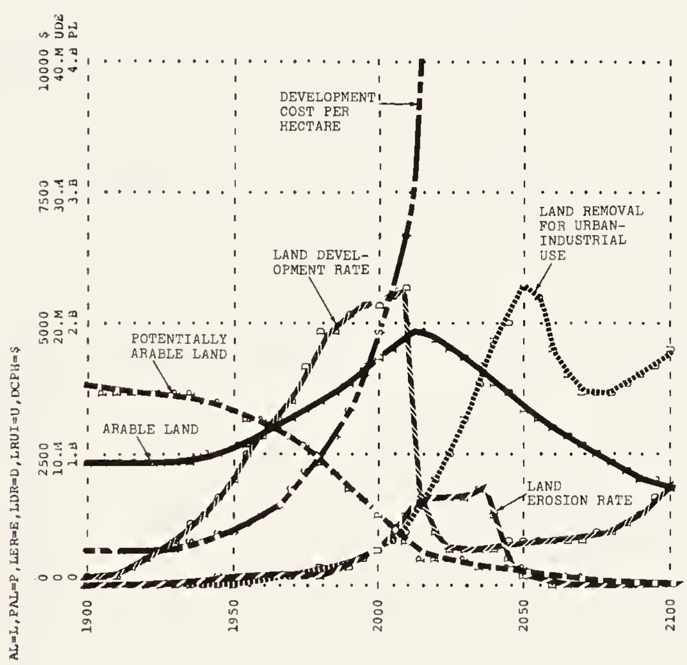
Figure 4-77 Run 4-8: sensitivity test with a 35 percent increase in the estimate of the value of potentially arable land total and a 50 percent increase in the upper limit of the land yield multiplier from capital

constrained to reproduce historical behavior. Further sensitivity tests in this sector were not adjusted to track historical behavior, for in each case the behavior mode was consistent with the standard run, Run 4-2.

Run 4-8 (Figure 4-77) shows a simulation in which both basic limits to food production, total land and land yield, are reestimated in an optimistic fashion. The



A. The behavior of land yields and food production



B. The behavior of arable land

Figure 4-78 Run 4-9: sensitivity test with a 25 percent decrease in the estimate of the value of potentially arable land total and a 25 percent decrease in the upper limit of the land yield multiplier from capital

total amount of potentially arable land available PALT is set to 4.35 billion hectares and the land yield multiplier from capital LYMC is set to the optimistic estimate shown in Figure 4-71. In this run, both land yield LY and arable land AL peak at higher values, allowing food production F to reach a higher value before its decline. Nevertheless, the decline is delayed by only about 10 years. The decline is more abrupt than it was in the standard run: higher land yield LY causes more land erosion LER, and the exponentially growing exogenous factors (population POP, persistent pollution index PPOLX, and industrial output IO) all grow to higher levels during the extra 10 years, causing lower land fertility, increased air pollution, and increased land removal for urban-industrial use.

Run 4-9 (Figure 4-78) shows a simulation in which both the amount of potentially arable land total available PALT and the land yield multiplier from capital LYMC are reestimated in a pessimistic fashion. PALT is set to 2.4 billion hectares and LYMC is set to the pessimistic estimate shown in Figure 4-71. A lower land yield LY and less potentially arable land PAL prevent food production F from reaching as high a value as that obtained in the standard run. However, the peak level of food production exhibited in Run 4-9 seems to be more sustainable than in the standard run. Note that food production F stays at its peak value for about 25 years before declining. The more stable behavior of food in this run is in part due to the fact that lower land yields LY lead to less land erosion LER than in the standard run.

Sensitivity Runs—Other Parameter Values

The previous sensitivity tests have shown the results of changing the estimates of the two basic constraints in the agriculture sector—total potentially arable land PALT and maximum land yield LY. The following runs show the model's sensitivity to estimates of three other relationships for which there is a lack of precise supporting data. Figures 4-79, 4-80, and 4-81 show three possible estimates (standard, pessimis-

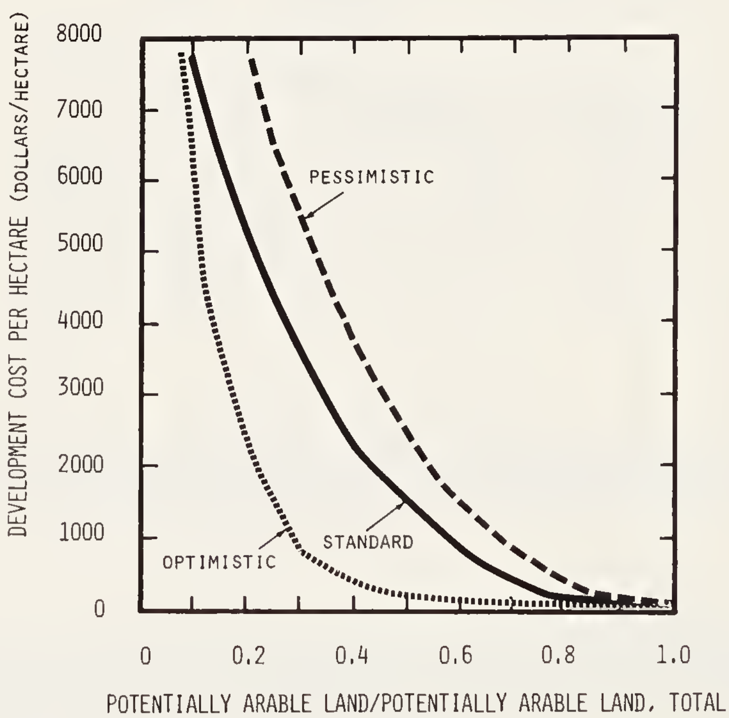


Figure 4-79 Standard, pessimistic, and optimistic estimates of the development costs per hectare table

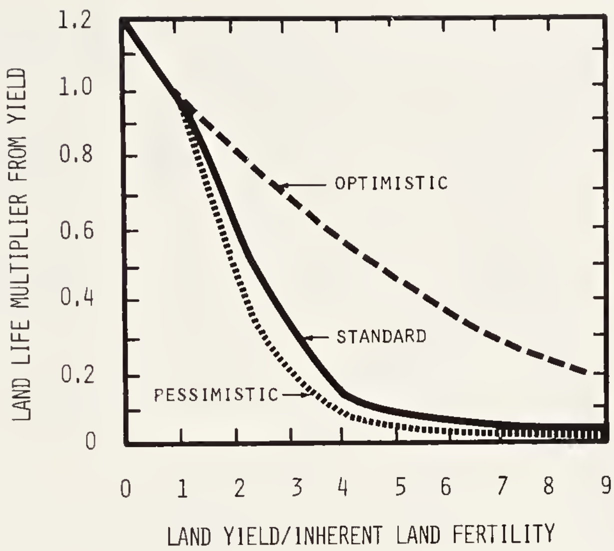


Figure 4-80 Standard, pessimistic, and optimistic estimates of the land life multiplier from yield table

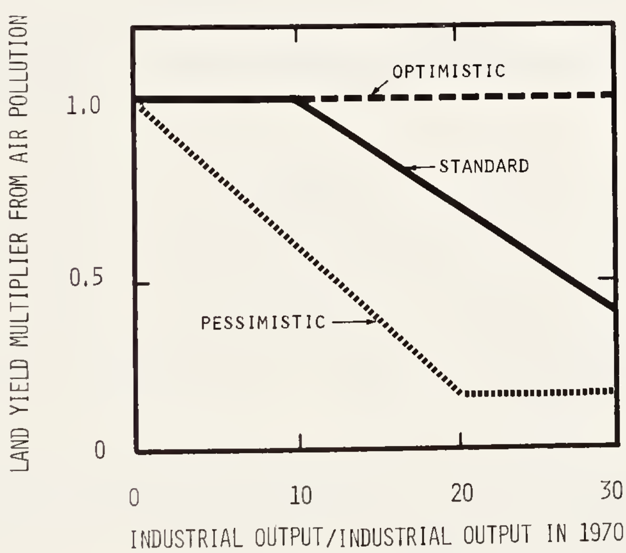


Figure 4-81 Standard, pessimistic, and optimistic estimates of the land yield multiplier from air pollution table

tic, and optimistic) for the hypothesized relationship between development costs per hectare and the amount of potentially arable land left to develop (DCPH), between land erosion and land yields (LLMY), and between air pollution and land yields (LYMAP). These three relationships control the rate at which food production can be either increased or eroded.

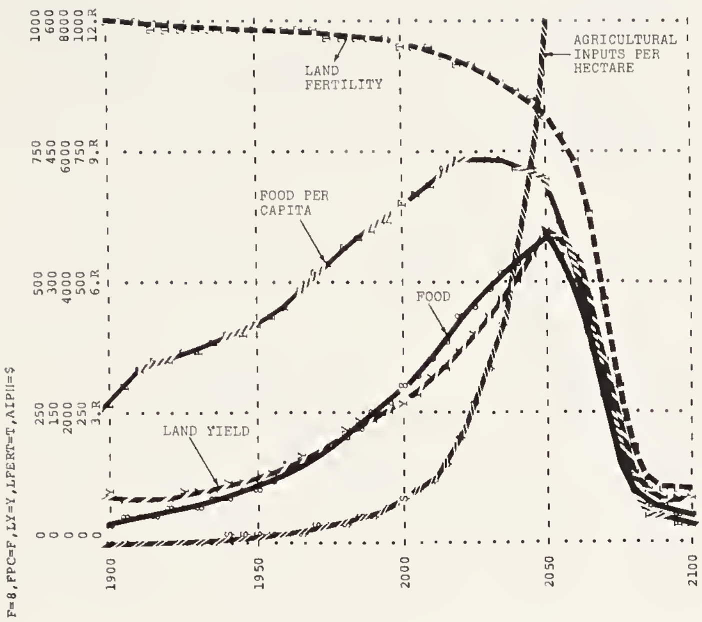
Run 4-10 (Figure 4-82) shows a simulation in which the estimates of these three relationships are changed in an optimistic fashion. The reestimates of the development cost relationship and the land erosion relationships cause arable land AL to peak at a higher value than its maximum in the standard run. Similarly, the optimistic reestimate of the adverse effect of air pollution on land yield LY causes LY to peak at a higher value. More arable land AL and higher land yield LY cause total food production F to peak at a higher value (about 20 percent higher) than in the standard run. The peak is not maintained, however, since land fertility and thus land yield are decreased by the exponentially rising level of pollution. The decline in food per capita in this run occurs only 20 years later than in the standard run.

Run 4-11 (Figure 4-83) shows a simulation in which all three relationships are reestimated in a pessimistic fashion. Despite the higher development costs the demand for food induces a rate of land development LDR sufficient to make arable land AL rise and peak at about the same value it reached in the standard run. Although arable land is more susceptible to erosion in this run, the adverse effects of air pollution prevent land yield LY from rising high enough to cause much land erosion LER. The decline in arable land AL is caused mainly by land removal for urban-industrial use LRUI. The peak value of food production F is about 40 percent lower than it was in the standard run.

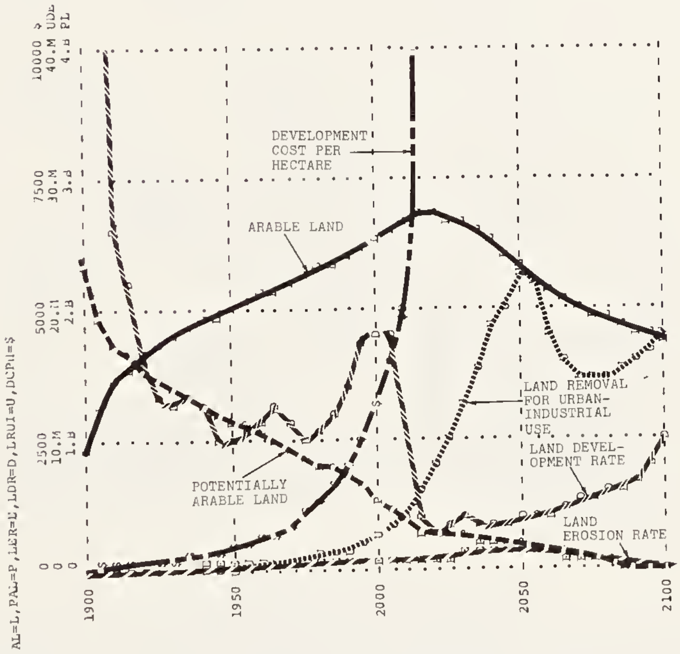
These sensitivity tests indicate that the dominant behavior mode of the agriculture sector with exponential driving functions is overshoot and decline, even given a wide variety of changes in parameter estimates. The overshoot should not be surprising, since with these driving functions all four of the necessary conditions for instability are present:

1. Rapid physical growth (assumed in the driving functions).
2. Physical limits to that growth (the upper limit on land yield LY and on the amount of potentially arable land total PALT available).
3. Delays in the feedback processes that adjust the growing quantities to physical limits (the driving conditions assume no such feedback, which corresponds to an infinitely long delay time).
4. Possible erosion of physical limits by overuse (overuse of agricultural inputs per hectare AIPH lead to higher land yield LY, which causes higher land erosion LER) or by misuse (abandoning land maintenance exacerbates the decline of land fertility LFERT).

The remaining simulation runs in this chapter further illustrate the behavior of the agriculture sector by examining its response to various policies that do more than change the numerical values within the model structure. These policies have the potential to alter the basic behavior mode of the sector, for they alter at least one of the four basic dynamic properties that lead to the unstable overshoot mode. First we discuss the results of a set of technological policies that attempt to deactivate the

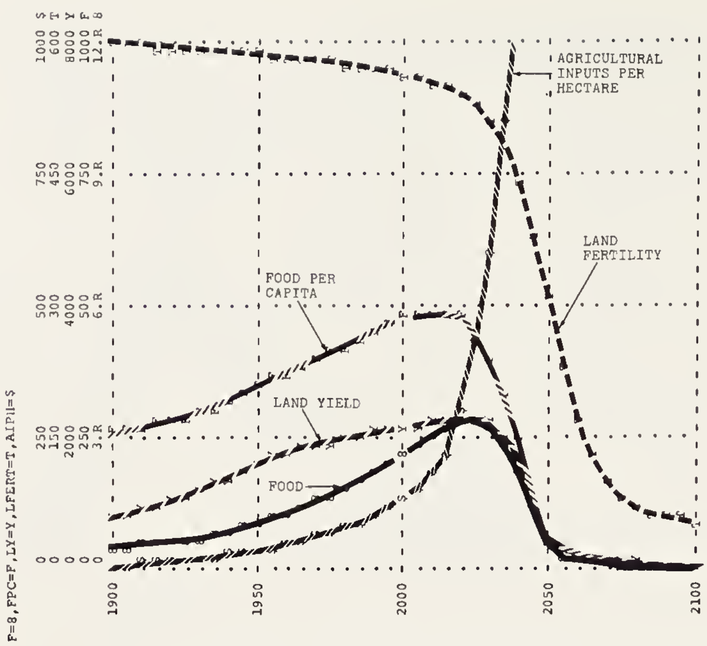


A. The behavior of land yields and food production

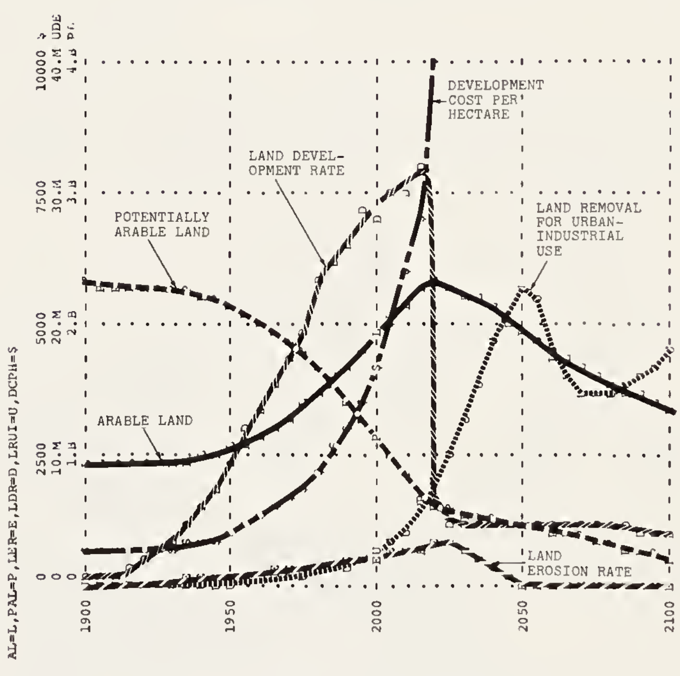


B. The behavior of arable land

Figure 4-82 Run 4-10: sensitivity test with optimistic estimates of the cost of land development, the adverse effects of air pollution on yield, and the extent to which high land yield causes land erosion



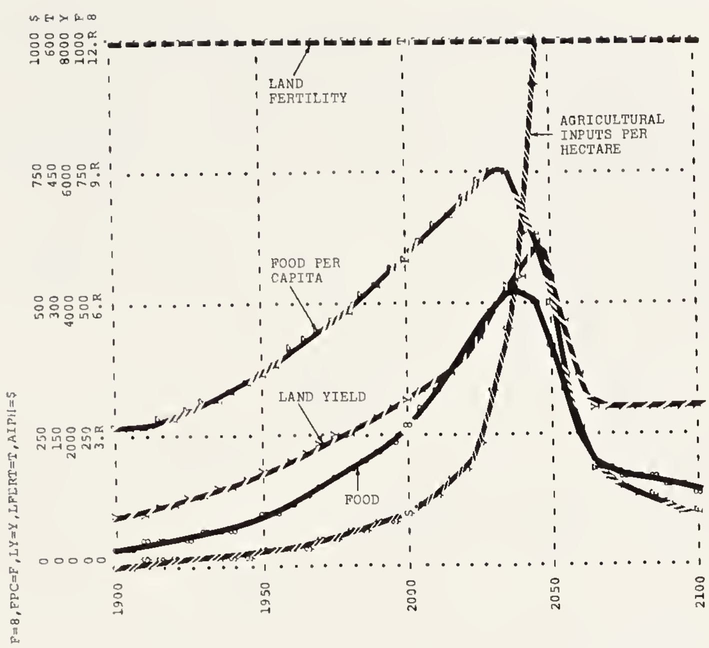
A. The behavior of land yields and food production



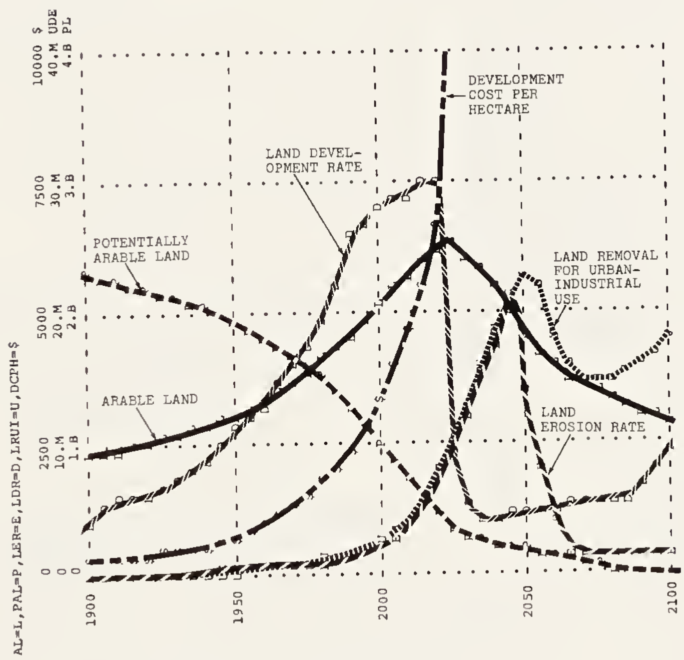
B. The behavior of arable land

Figure 4-83 Run 4-11: sensitivity test with pessimistic estimates of the cost of land development, the adverse effects of air pollution on yield, and the extent to which high land yield causes land erosion

various factors that erode the carrying capacity of the agriculture sector, and then we examine the behavior of the sector when the growth of the exogenous driving factors is stabilized.



A. The behavior of land yields and food production



B. The behavior of arable land

Figure 4-84 Run 4-12: policy run in which the impairment of land fertility from persistent pollutants is completely eliminated in 1975

Technological Policy Runs

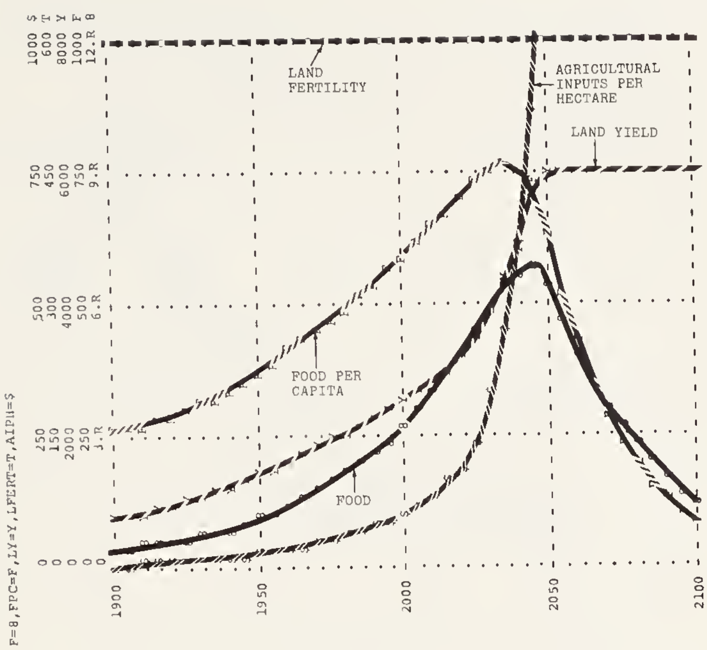
Run 4-12 (Figure 4-84) shows the behavior of the agriculture sector when loop 4 has been effectively removed by the initiation of technological policies in 1975 that are completely successful in eliminating the impairment of land fertility from persistent pollutants. Since land fertility has not been significantly impaired between 1900 and 1970, such a policy was modeled here by setting the land fertility degradation rate LFDR to zero throughout the simulation, without significantly altering the fit to historical behavior. This run shows that the overshoot and decline mode remains, even though land fertility maintains its maximum values throughout the run. The decline in total food production F occurs at about the same time (2040) as in the standard run. Also as in the standard run, arable land AL declines because of land erosion LER and land removal for urban and industrial use LRUI. Land yield LY declines due to the direct effects of air pollution.

To eliminate the decline in land yield LY exhibited in Run 4-12, the next simulation, Run 4-13 (Figure 4-85), assumes the initiation of policies in 1975 that completely eliminate both the adverse effects of air pollution on land yield LY and the impairment of land fertility LFERT by persistent pollution. Land yield LY is determined only by the amount of agricultural inputs per hectare AIPH, which are driven upward by the exponentially growing industrial· output. When agricultural inputs per hectare AIPH exceed 1,000 dollars per hectare after the year 2050, land yield LY stabilizes at the maximum possible value of 10 times the inherent land fertility, or 6,000 vegetable-equivalent kilograms per hectare-year. The higher land yield LY causes food production F to peak at a higher value (about 20 percent higher) than it reached in the standard run. Higher land yield LY also leads to more land erosion LER, however, and this increased land erosion causes arable land AL to decline more sharply than it did in the standard run. The decline in arable land AL causes a decline in food production F, which occurs around the year 2045—only five years later than in the standard run.

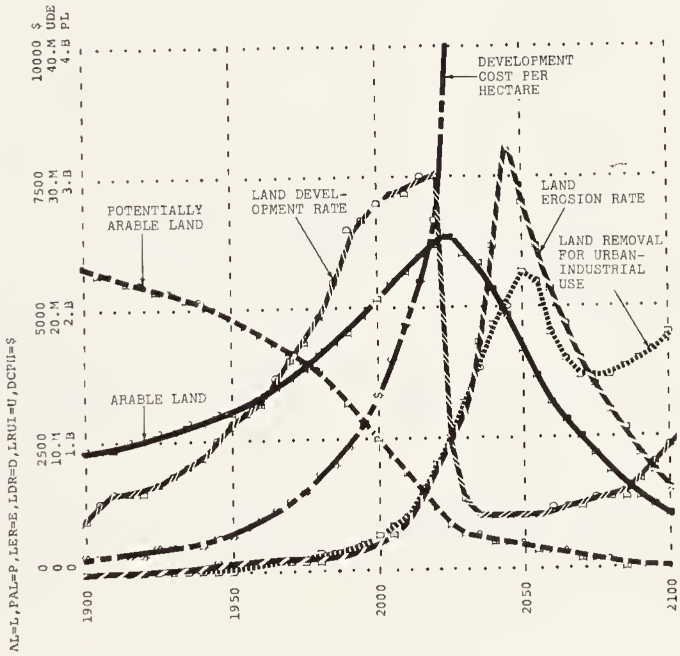
Run 4-14 (Figure 4-86) simulates the initiation of policies in 1975 to combat erosion, in addition to the previous policies that eliminated the effects of persistent pollutants and air pollution. In this simulation, land removal for urban and industrial use LRUI still causes arable land AL to decline around the year 2030. High land yield LY delays the decline of food production F till around 2055, 15 years later than in the standard run.

If the land required for urban and industrial use UILR is reduced to 25 percent of expected requirements, and if the other three factors contributing to the decline in food production capacity (land erosion and the effects of persistent pollutants and air pollution) are eliminated, the agriculture sector finally achieves a sustainable mode of high food production F as shown in Run 4-15. (Figure 4-87). Here total food production F levels off at its maximum value in the year 2060. Since population POP continues to grow, however, food per capita FPC gradually falls after the year 2060. Because of the continuing exponential growth in population POP, the decline in food per capita FPC is delayed only 30 years by this comprehensive set of technological policies that has removed all possibility of reducing the carrying capacity of the agriculture sector.

These policy runs have shown that the agriculture sector is capable of high sustained food production only if the four factors that erode the sector's carrying



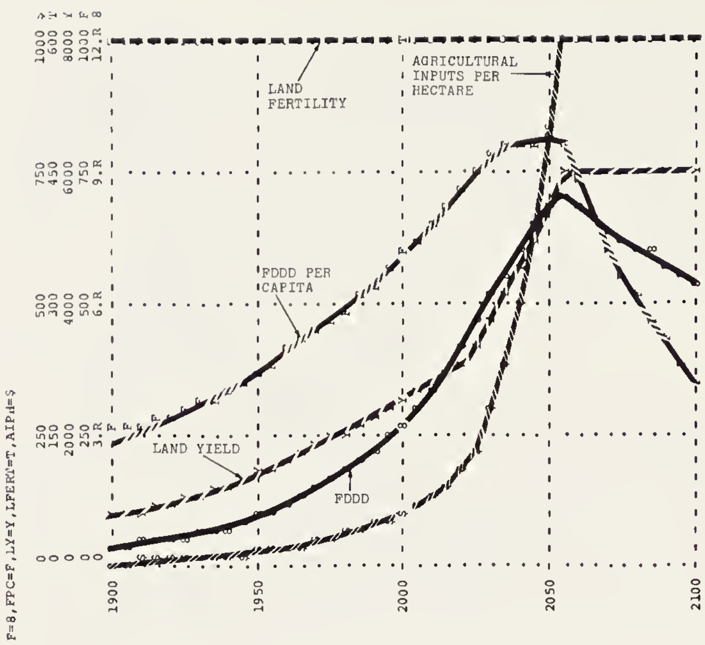
A. The behavior of land yields and food production



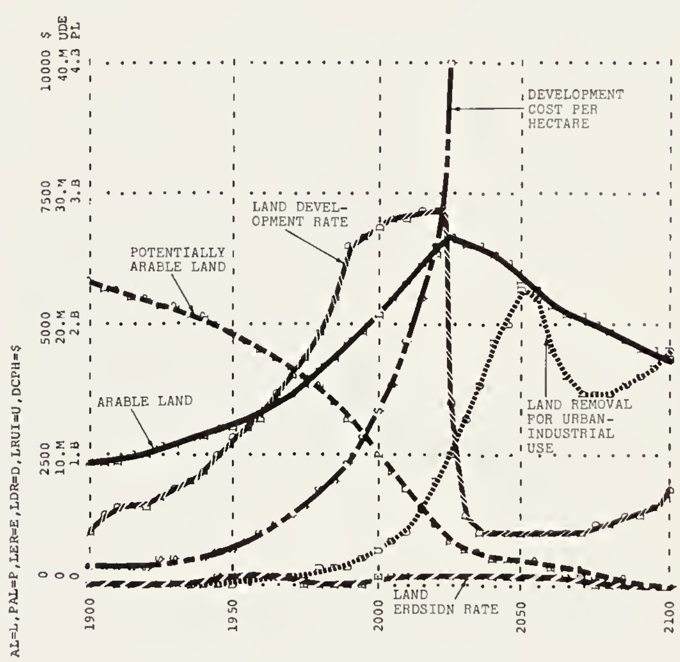
B. The behavior of arable land

Figure 4-85 Run 4-13: policy run in which the adverse effects of air pollution on land yield and the impairment of land fertility by persistent pollutants are completely eliminated in 1975

capacity are eliminated. Even then a decline in food per capita FPC is inevitable if the population POP is assumed to be growing exponentially. Because of the continuous exponential growth of the exogenous variables, the exact timing of the decline in food per capita is relatively insensitive either to parameter changes or to policy changes designed to maintain a constant carrying capacity.



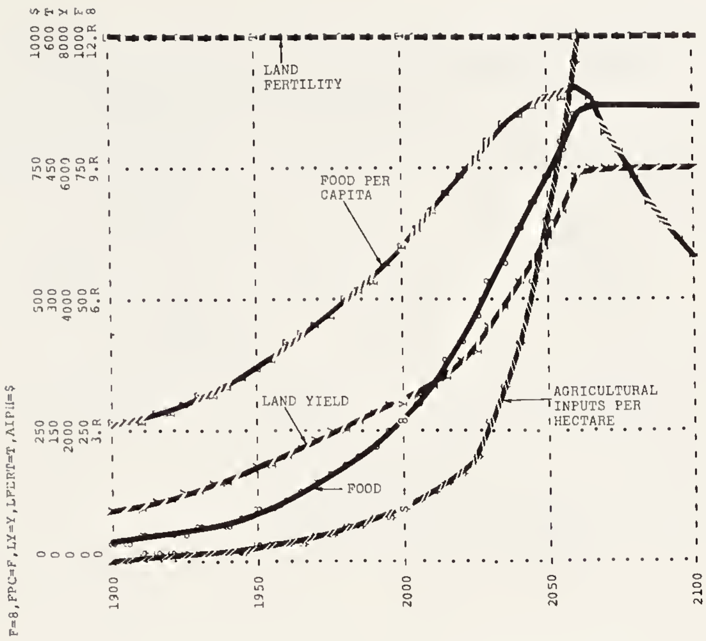
A. The behavior of land yields and food production



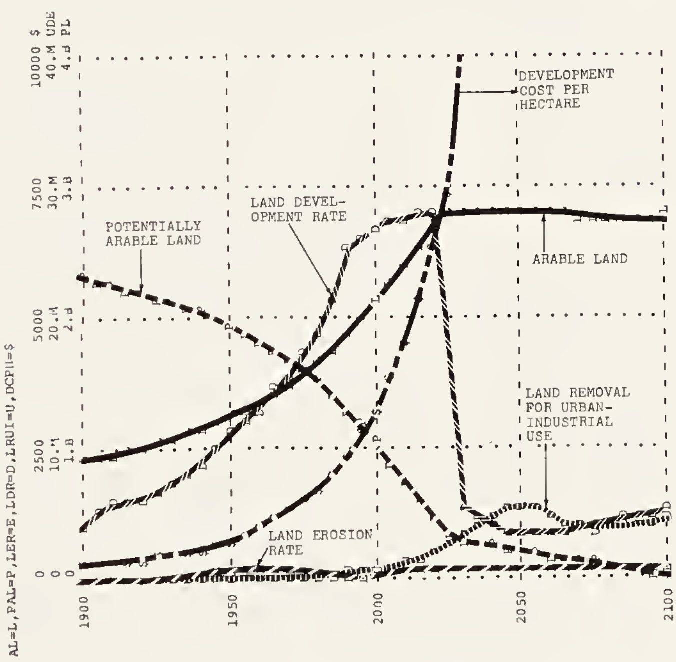
B. The behavior of arable land

Figure 4-86 Run 4-14: policy run in which efforts to combat land erosion are initiated in 1975, in addition to the previous policies that eliminate the adverse effects of air pollution and persistent pollution

The next sequence of runs investigates the agriculture sector's behavior when the exponential growth of the exogenous inputs is halted during the course of the run. Thus, from a given year on, the agriculture sector will be responding to constant levels of air pollution and persistent pollution, a constant amount of investment to be allocated, and a constant number of people whose food demands (IFPC) also remain constant.



A. The behavior of land yields and food production

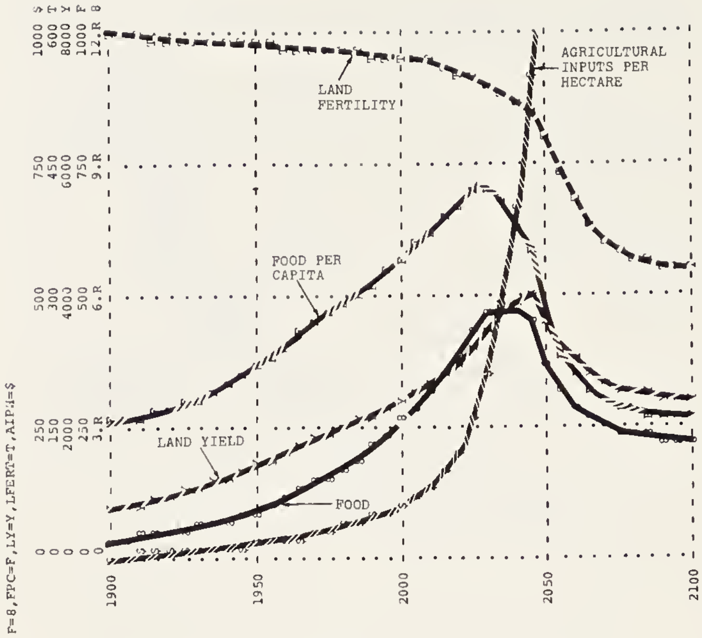


B. The behavior of arable land

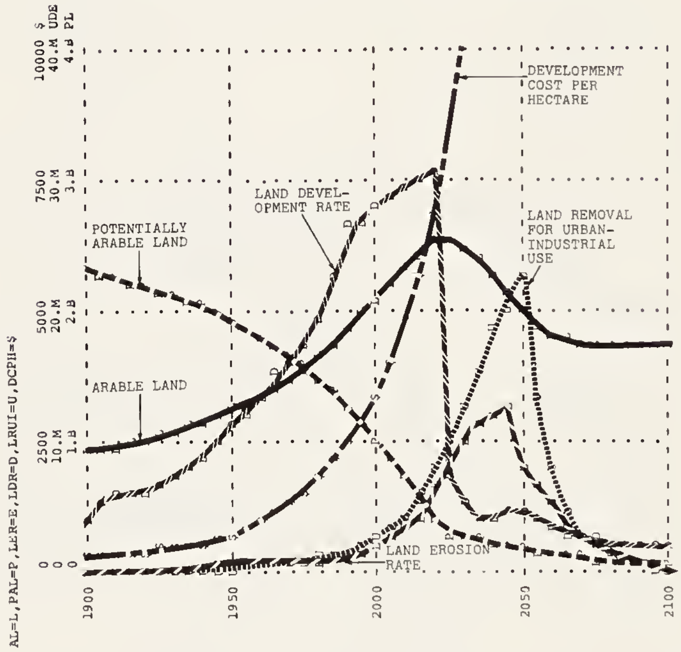
Figure 4-87 Run 4-15: policy run in which the land required for urban and industrial use is reduced to 25 percent of expected requirements, in addition to the previous policies that combat land erosion and eliminate the adverse effects of air pollution and persistent pollution

Equilibrium Runs

In the first of the equilibrium runs (equilibrium refers to the condition of other sectors of the model, which, having reached equilibrium, provide the agriculture sector with constant inputs), the exogenous inputs are assumed to level off in the year 2050—10 years after the decline in food production F has begun in the standard run. All relationships endogenous to the agriculture sector are the same as they were in the



A. The behavior of land yields and food production



B. The behavior of arable land

Figure 4-88 Run 4-16: equilibrium run in which the exogenous inputs level off in the year 2050

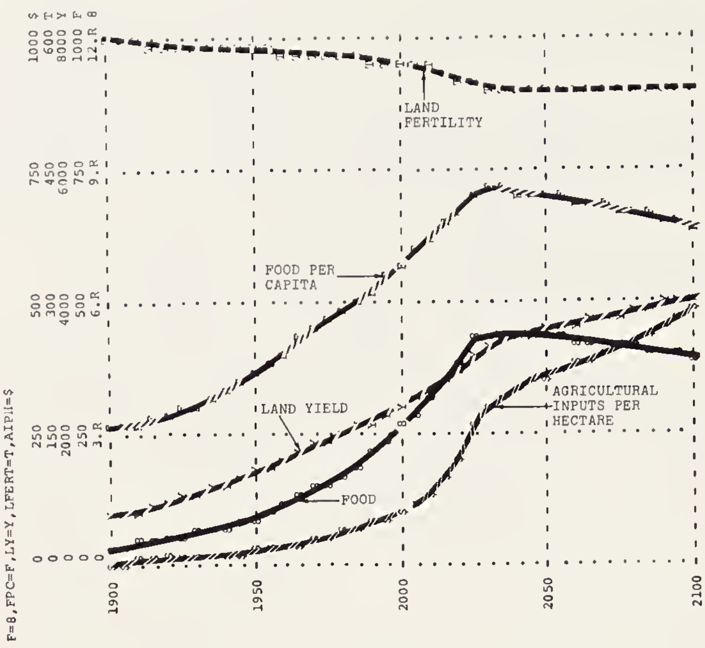
standard run. The resulting dynamic behavior is shown in Run 4-16 (Figure 4-88), where both total food production F and food per capita FPC still overshoot and decline. This decline is caused by a continued decrease in both arable land AL and land fertility LFERT after 2050. Arable land AL continues to decrease due to the high levels of land erosion LER and land removal for urban and industrial use LRUI. Continued high rates of land erosion LER are caused by high land yield LY. Land removal for urban-industrial use LRUI continues to decrease the arable land AL till about the year 2070. Land fertility LFERT declines gradually after 2050, and eventually levels off at its equilibrium value of 320 vegetable-equivalent kilograms per hectare-year. This equilibrium value of land fertility is lower than the maximum land fertility because of the significant amount of persistent pollution present at equilibrium.

Run 4-17 (Figure 4-89) shows a simulation in which the exponentially growing exogenous inputs level off in the year 2025. The slight decline in food production F and food per capita FPC is again caused by a gradual reduction in arable land AL due to erosion. The rate of land erosion LER continues to increase in this run since land yields LY continue to increase slightly. The agricultural system as a whole very nearly reaches equilibrium in this run, and the amount of food per capita is maintained at about 700 vegetable-equivalent kilograms per person-year, which is about 150 percent of the 1970 value.

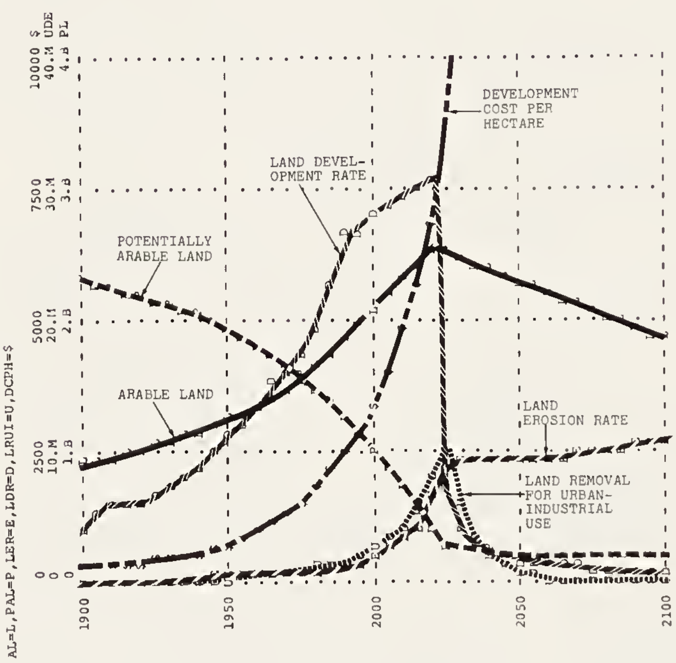
The final simulation, Run 4-18 (Figure 4-90), assumes that the growth in population POP, industrial output IO, and the index of persistent pollution PPOLX is halted in the year 2000. Here food production F and food per capita FPC achieve high sustainable levels. Food per capita FPC reaches an equilibrium level that is only slightly lower than its peak value in the standard run. This equilibrium level of food per capita FPC is about 50 percent higher than the 1970 level. Since both land development and land erosion are maintained at low rates in this run, the total stock of arable land is maintained at a constant level.

The stable behavior shown in Run 4-18 is made possible by the fact that none of the factors that tend to erode the carrying capacity of the agriculture sector are allowed to reach a high value. Land removal for urban-industrial use LRUI approaches zero around the year 2020 because the amount of urban-industrial land UIL is finally brought into equilibrium with the amount of urban-industrial land required UILR. A small amount of land erosion LER continues, but it is balanced by an equally low rate of land development LDR. This balance can continue only if a reserve amount of potentially arable land PAL still exists. A comparison of Runs 4-17 land and 4-18 indicates that the extra 25 years of high rates of land development LDR in Run 4-17 use up the reserve of potentially arable land PAL necessary to maintain the equilibrium of Run 4-18. Another way of maintaining this equilibrium would be to implement new policies for sufficient investment in land erosion control.

The last three runs show that it is possible for the agriculture sector to exhibit equilibrium behavior rather than overshoot and decline if the exogenous driving functions of population POP, industrial output IO, and the index of persistent pollution PPOLX are not allowed to grow exponentially and indefinitely. Runs 4-16, 4-17, and 4-18 illustrate the trade-off between short-term and long-term behavior in the sector. Physical growth ensures high food production in the short term but causes



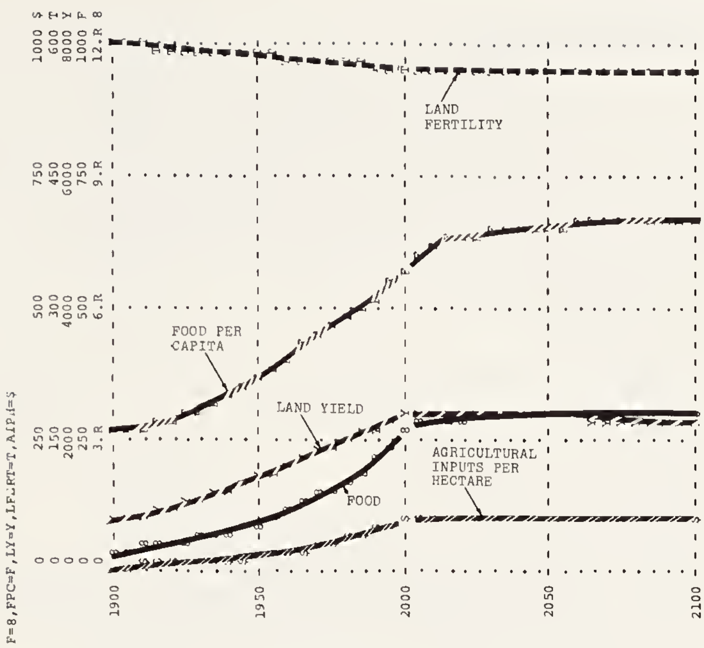
A. The behavior of land yields and food production



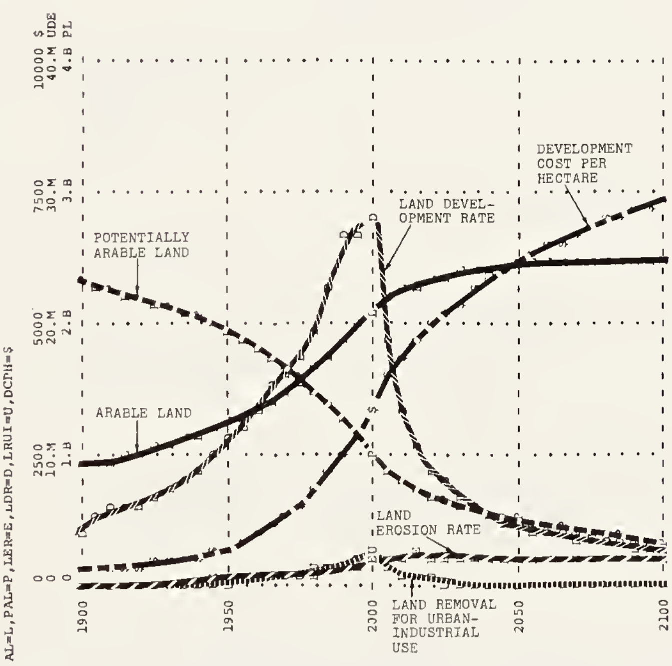
B. The behavior of arable land

Figure 4-89 Run 4-17: equilibrium run in which the exogenous inputs level off in the year 2025

food availability to be lower in the long term, due to the negative side effects of growth. The stabilization of growth results in lower food production in the short term but avoids the negative side effects that decrease the capacity for food production, thus ensuring higher and more stable levels of food in the long term.



A. The behavior of land yields and food production



B. The behavior of arable land

Figure 4-90 Run 4-18: equilibrium run in which the exogenous inputs level off in the year 2000

Additional runs in Chapter 7 show the interaction of the agriculture sector with the other sectors of the model. In these runs, population POP, industrial output IO, and the index of persistent pollution PPOLX are no longer considered to be exogenous functions but are instead determined endogenously in the model.

APPENDIX: PROGRAM LISTING

```
        *       AGRICULTURE SECTOR WITH EXOGENOUS INPUTS
        NOTE
        NOTE    LOOP 1: FOOD FROM INVESTMENT IN LAND DEVELOPMENT
        NOTE
84      A       LFC.K=AL.K/PALT
        C       PALT=3.2E9
85      L       AL.K=AL.J+(DT)(LDR.JK-LER.JK-LRUI.JK)
        N       AL=ALI
        C       ALI=.9E9
86      L       PAL.K=PAL.J+(DT)(-LDR.JK)
        N       PAL=PALI
        C       PALI=2.3E9
87      A       F.K=LY.K*AL.K*LFH*(1-PL)
        C       LFH=.7
        C       PL=.1
88      A       FPC.K=F.K/POP.K
89      A       IFPC.K=CLIP(IFPC2.K,IFPC1.K,TIME.K,PYEAR)
90      A       IFPC1.K=TABHL(IFPC1T,IOPC.K,0,1600,200)
        T       IFPC1T=230/480/690/850/970/1070/1150/1210/1250
91      A       IFPC2.K=TABHL(IFPC2T,IOPC.K,0,1600,200)
        T       IFPC2T=230/480/690/850/970/1070/1150/1210/1250
92      A       TAI.K=IO.K*FIOAA.K
93      A       FIOAA.K=CLIP(FIOAA2.K,FIOAA1.K,TIME.K,PYEAR)
94      A       FIOAA1.K=TABHL(FIOAA1T,FPC.K/IFPC.K,0,2.5,.5)
        T       FIOAA1T=.4/.2/.1/.025/0/0
95      A       FIOAA2.K=TABHL(FIOAA2T,FPC.K/IFPC.K,0,2.5,.5)
        T       FIOAA2T=.4/.2/.1/.025/0/0
96      R       LDR.KL=TAI.K*FIALD.K/DCPH.K
97      A       DCPH.K=TABHL(DCPHT,PAL.K/PALT,0,1,.1)
        T       DCPHT=1E5/7400/5200/3500/2400/1500/750/300/150/75/50
        NOTE
        NOTE    LOOP 2: FOOD FROM INVESTMENT IN AGRICULTURAL INPUTS
        NOTE
98      A       CAI.K=TAI.K*(1-FIALD.K)
99      A       AI.K=SMOOTH(CAI.K,ALAI.K)
        N       AI=5E9
100     A       ALAI.K=CLIP(ALAI2,ALAI1,TIME.K,PYEAR)
        C       ALAI1=2
        C       ALAI2=2
101     A       AIPH.K=AI.K*(1-FALM.K)/AL.K
102     A       LYMC.K=TABHL(LYMCT,AIPH.K,0,1000,40)
        T       LYMCT=1/3/3.8/4.4/4.9/5.4/5.7/6/6.3/6.6/6.9/7.2/7.4
        X       /7.6/7.8/8/8.2/8.4/8.6/8.8/9/9.2/9.4/9.6/9.8/10
103     A       LY.K=LYF.K*LFERT.K*LYMC.K*LYMAP.K
104     A       LYF.K=CLIP(LYF2,LYF1,TIME.K,PYEAR)
        C       LYF1=1
        C       LYF2=1
105     A       LYMAP.K=CLIP(LYMAP2.K,LYMAP1.K,TIME.K,PYEAR)
106     A       LYMAP1.K=TABHL(LYMAP1T,IO.K/IO70,0,30,10)
        T       LYMAP1T=1/1/.7/.4
107     A       LYMAP2.K=TABHL(LYMAP2T,IO.K/IO70,0,30,10)
        T       LYMAP2T=1/1/.7/.4
        C       IO70=7.9E11
        NOTE
        NOTE    LOOPS 1 & 2: THE INVESTMENT ALLOCATION DECISION
        NOTE
108     A       FIALD.K=TABHL(FIALDT,(MPLD.K/MPAI.K),0,2,.25)
        T       FIALDT=0/.05/.15/.30/.50/.70/.85/.95/1
109     A       MPLD.K=LY.K/(DCPH.K*SD)
        C       SD=.07
110     A       MPAI.K=ALAI.K*LY.K*MLYMC.K/LYMC.K
        A       MLYMC.K=TABHL(MLYMCT,AIPH.K,0,600,40)
111     T       MLYMCT=.075/.03/.015/.011/.009/.008/.007/.006/
        X       .005/.005/.005/.005/.005/.005/.005/.005
        NOTE
        NOTE    LOOP 3: LAND EROSION AND URBAN-INDUSTRIAL USE
        NOTE
112     A       ALL.K=ALLN*LLMY.K
```

```
          C     ALLN=6000
113       A     LLMY.K=CLIP(LLMY2.K,LLMY1.K,TIME.K,PYEAR)
114       A     LLMY1.K=TABHL(LLMY1T,LY.K/ILF,0,9,1)
          T     LLMY1T=1.2/1/.63/.36/.16/.055/.04/.025/.015/.01
115       A     LLMY2.K=TABHL(LLMY2T,LY.K/ILF,0,9,1)
          T     LLMY2T=1.2/1/.63/.36/.16/.055/.04/.025/.015/.01
116       R     LER.KL=AL.K/ALL.K
117       A     UILPC.K=TABHL(UILPCT,IOPC.K,0,1600,200)
          T     UILPCT=.005/.008/.015/.025/.04/.055/.07/.08/.09
118       A     UILR.K=UILPC.K*POP.K
119       R     LRUI.KL=MAX(0,(UILR.K-UIL.K)/UILDT)
          C     UILDT=10
120       L     UIL.K=UIL.J+(DT)(LRUI.JK)
          N     UIL=UILI
          C     UILI=8.2E6
          NOTE
          NOTE  LOOP 4: LAND FERTILITY DEGRADATION
          NOTE
121       L     LFERT.K=LFERT.J+(DT)(LFR.JK-LFD.JK)
          N     LFERT=LFERTI
          C     LFERTI=600
122       A     LFDR.K=TABHL(LFDRT,PPOLX.K,0,30,10)
          T     LFDRT=0/.1/.3/.5
123       R     LFD.KL=LFERT.K*LFDR.K
          NOTE
          NOTE  LOOP 5: LAND FERTILITY REGENERATION
          NOTE
124       R     LFR.KL=(ILF-LFERT.K)/LFRT.K
          C     ILF=600
125       A     LFRT.K=TABHL(LFRTT,FALM.K,0,.10,.02)
          T     LFRTT=20/13/8/4/2/2
          NOTE
          NOTE  LOOP 6: DISCONTINUING LAND MAINTENANCE
          NOTE
126       A     FALM.K=TABHL(FALMT,PFR.K,0,4,1)
          T     FALMT=0/.04/.07/.09/.1
127       A     FR.K=FPC.K/SFPC
          C     SFPC=230
128       A     PFR.K=SMOOTH(FR.K,FSPD)
          N     PFR=1
          C     FSPD=2
          NOTE
          NOTE  EXOGENOUS INPUTS TO THE AGRICULTURE SECTOR
          NOTE
          NOTE  POPULATION GROWS EXPONENTIALLY AT 1.2% PER YEAR
          NOTE
          A     POP.K=CLIP(POP2.K,POP1.K,TIME.K,EYEAR)
          C     EYEAR=2500
          A     POP1.K=POPI*EXP(.012*(TIME.K-1900))
          A     POP2.K=POPI*EXP(.012*(EYEAR-1900))
          C     POPI=1.65E9
          NOTE
          NOTE  INDUSTRIAL OUTPUT GROWS EXPONENTIALLY AT 3.6% PER YEAR
          NOTE
          A     IO.K=CLIP(IO2.K,IO1.K,TIME.K,EYEAR)
          A     IO1.K=IOI*EXP(.036*(TIME.K-1900))
          A     IO2.K=IOI*EXP(.036*(EYEAR-1900))
          C     IOI=.67E11
          A     IOPC.K=IO.K/POP.K
          NOTE
          NOTE  PERSISTENT POLLUTION GROWS EXPONENTIALLY AT 3% PER YEAR
          NOTE
          A     PPOLX.K=CLIP(PPOLX2.K,PPOLX1.K,TIME.K,EYEAR)
          A     PPOLX1.K=PPOLXI*EXP(.03*(TIME.K-1900))
          A     PPOLX2.K=PPOLXI*EXP(.03*(EYEAR-1900))
          C     PPOLXI=.12
          NOTE
          NOTE  CONTROL CARDS
          NOTE
          C     PYEAR=1975
          N     TIME=TIMEN
          C     TIMEN=1900
          SPEC  DT=.25/LENGTH=2100/PLTPER=5/PRTPER=0
          PLOT  F=8(0,12E12)/FPC=F(0,1000)/LY=Y(0,8E3)/
          X     LFERT=T(0,600)/AIPH=$(0,1000)
          PLOT  AL=L,PAL=P(0,4E9)/LER=E,LDR=D,
          X     LRUI=U(0,4E7)/DCPH=$(0,1E4)
          RUN   STANDARD
```

```
NOTE
NOTE    PARAMETER CHANGES FOR THE AGRICULTURE SECTOR RUNS
NOTE
NOTE    HISTORICAL RUN
NOTE
C       PLTPER=2
C       LENGTH=1970
PLOT    F=8(0,12E12)/FPC=F(0,1000)/LY=Y(0,8E3)/
X       LFERT=T(0,600)/AIPH=$(0,1000)
PLOT    AL=L,PAL=P(0,4E9)/LER=E,LDR=D,
X       LRUI=U(0,4E7)/DCPH=$(0,1E4)
PLOT    TAI=T(0,2E13)/FIALD=*(0,.4)/MPAI=I,MPLD=D(0,100)
PLOT    FR=R(0,4)/FALM=M(0,.1)/LFERT=T(0,600)/
X       LFD=1,LFR=2(0,80)/LFRT=D(0,20)
RUN     FIGURE 4-69: HISTORICAL RUN
NOTE
NOTE    STANDARD RUN
NOTE
RUN     FIGURE 4-70: STANDARD RUN
NOTE
NOTE    SENSITIVITY TESTS
NOTE
T       LYMCT=1/3/3.8/6/7/8/8.4/8.8/9.2/9.6/10/10.4/10.8/
X       11.2/11.6/12/12.4/12.8/13.2/13.6/14/14.2/14.4/
X       14.6/14.8/15
PLOT    F=8(0,12E12)/FPC=F(0,1000)/LY=Y(0,8E3)/
X       LFERT=T(0,600)/AIPH=$(0,1000)
PLOT    AL=L,PAL=P(0,4E9)/LER=E,LDR=D,
X       LRUI=U(0,4E7)/DCPH=$(0,1E4)
RUN     FIGURE 4-72: SENSITIVITY-OPTIMISTIC LYMCT
T       LYMCT=1/3/3.8/4.4/4.9/5.4/5.6/5.7/5.8/5.9/6/
X       6.1/6.2/6.3/6.4/6.5/6.6/6.7/6.8/6.9/7/7.1/
X       7.2/7.3/7.4/7.5
RUN     FIGURE 4-73: SENSITIVITY-PESSIMISTIC LYMCT
C       PALI=3.45E9
C       PALT=4.35E9
RUN     FIGURE 4-74: SENSITIVITY-OPTIMISTIC PALT
C       PALI=1.5E9
C       PALT=2.4E9
RUN     FIGURE 4-75: SENSITIVITY-PESSIMISTIC PALT
C       PALI=3.45E9
C       PALT=4.35E9
T       DCPHT=3E5/1E5/7400/5200/3500/2400/1500/750/
X       300/150/75
RUN     FIGURE 4-76: SENSITIVITY-RIGOROUS OPTIMISTIC TEST IN PALT
T       LYMCT=1/3/3.8/6/7/8/8.4/8.8/9.2/9.6/10/10.4/10.8/
X       11.2/11.6/12/12.4/12.8/13.2/13.6/14/14.2/14.4/
X       14.6/14.8/15
C       PALI=3.45E9
C       PALT=4.35E9
RUN     FIGURE 4-77: SENSITIVITY-OPTIMISTIC PALT AND LYMCT
T       LYMCT=1/3/3.8/4.4/4.9/5.4/5.6/5.7/5.8/5.9/6/
X       6.1/6.2/6.3/6.4/6.5/6.6/6.7/6.8/6.9/7/7.1/
X       7.2/7.3/7.4/7.5
C       PALI=1.5E9
C       PALT=2.4E9
RUN     FIGURE 4-78: SENSITIVITY-PESSIMISTIC PALT AND LYMCT
T       DCPHT=1E5/5200/2400/750/300/150/100/60/40/30/25
T       LLMY1T=1.2/1/.9/.8/.7/.5/.4/.3/.25/.2
T       LLMY2T=1.2/1/.9/.8/.7/.5/.4/.3/.25/.2
T       LYMAP1T=1/1/1/1
T       LYMAP2T=1/1/1/1
RUN     FIGURE 4-82: SENSITIVITY-OPTIMISTIC DCPHT, LLMYT AND LYMAPT
T       DCPHT=3E5/1E5/7400/5200/3500/2400/1500/750/300/150/75
T       LLMY1T=1.2/1/.5/.2/.1/.05/.025/.01/.005/.001
T       LLMY2T=1.2/1/.5/.2/.1/.05/.025/.01/.005/.001
T       LYMAP1T=1/.5/.1/.1
T       LYMAP2T=1/.5/.1/.1
RUN     FIGURE 4-83: SENSITIVITY-PESSIMISTIC DCPHT, LLMYT AND LYMAP
NOTE
NOTE    TECHNOLOGICAL POLICY RUNS
NOTE
T       LFDRT=0/0/0/0
RUN     FIGURE 4-84: FERTILITY DEGRADATION PROBLEM ELIMINATED
T       LFDRT=0/0/0/0
T       LYMAP2T=1/1/1/1
RUN     FIGURE 4-85: ALL POLLUTION EFFECTS ELIMINATED
```

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T       LFDRT=0/0/0/0
T       LYMAP2T=1/1/1/1
T       LLMY2T=1.2/1/1/1/1/1/1/1/1/1
RUN     FIGURE 4-86: POLLUTION PROBLEMS AND EROSION ELIMINATED
T       LFDRT=0/0/0/0
T       LYMAP2T=1/1/1/1
T       LLMY2T=1.2/1/1/1/1/1/1/1/1/1
NOTE    ** THE FOLLOWING CHANGE MUST BE MADE IN EDIT MODE:
NOTE    ** A UILR.K=UILPC.K*POP.K*.25
RUN     FIGURE 4-87: POLLUTION, EROSION, AND URBAN LAND NEEDS CONTROLLED
NOTE
NOTE    EQUILIBRIUM RUNS
NOTE
C       EYEAR=2050
RUN     FIGURE 4-88: EQUILIBRIUM IN 2050
C       EYEAR=2025
RUN     FIGURE 4-89: EQUILIBRIUM IN 2025
C       EYEAR=2000
RUN     FIGURE 4-90: EQUILIBRIUM IN 2000
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REFERENCES

Allan 1965	Allan, William. *The African Husbandman.* New York: Barnes & Noble, 1965.
Arkley 1969	Arkley, R. J. "The Vanishing Land, or Population and Land Use in California." Mimeographed. As quoted in University of California, Institute of Ecology, Environmental Systems Group, "A Model of Society," April 1969.
Atkins 1963	Atkins, S. W. *Economic Appraisal of Conservation Farming in the Grenada-Loving-Memphis Soil Area of West Tennessee.* University of Tennessee, Agriculture Experimental Station, Knoxville, Bulletin 369 (October 1963).
Bear 1965	Bear, Firman E. *Soils in Relation to Crop Growth.* New York: Reinhold, 1965.
Best and Coppock 1962	Best, R. H., and J. T. Coppock. *The Changing Use of Land in Britain.* London: Faber and Faber, 1962.
Borgstrom 1970*a*	Borgstrom, Georg A. "The Dual Challenge of Health and Hunger: A Global Crisis." Science and Public Affairs, *Bulletin of the Atomic Scientist,* October 1970, pp. 42–46.
Borgstrom 1970*b*	Borgstrom, Georg A. *Too Many: A Story of Earth's Biological Limitations.* Rev. ed. New York: Macmillan, 1970.
Brown 1970*a*	Brown, Lester R. *Seeds of Change: The Green Revolution and Development in the 1970's.* New York: Praeger Publishers, 1970.
Brown 1970*b*	Brown, Lester R. "Human Food Production as a Process in the Biosphere." *Scientific American,* September 1970.
Buckman and Brady 1960	Buckman, Henry O., and Nyle C. Brady. *The Nature and Properties of Soils.* New York: Macmillan, 1960.
Cépède, Houtart, and Grond 1964	Cépède, M., F. Houtart, and L. Grond. *Population and Food.* New York: Sheed and Ward, 1964.
CEQ 1970	Council on Environmental Quality. *Environmental Quality.* Washington, D.C.: Government Printing Office, 1970.
CEQ 1972	Council on Environmental Quality. *Environmental Quality.* Washington, D.C.: Government Printing Office, 1972.
Clawson, Held, and Stoddard 1965	Clawson, M., B. Held, and C. H. Stoddard. *Land for the Future.* Baltimore: Johns Hopkins University Press for Resources for the Future, 1965.

CRAM 1969	*Resources and Man: A Study and Recommendations* by the Committee on Resources and Man of the Division of Earth Sciences, National Academy of Sciences–National Research Council, with the cooperation of the Division of Biology and Agriculture. San Francisco: W. H. Freeman, 1969.
Cramer 1967	Cramer, H. H. *Plant Protection and World Crop Production.* Leverkusen: Farbenfabriken Bayer A.G., 1967.
Doane 1957	Doane, Robert R. *World Balance Sheet.* New York: Harper & Row, 1957.
Economic Report of the President 1969	*Economic Report of the President.* Washington, D.C., January 1969.
FAO 1970*a*	Food and Agriculture Organization of the United Nations. *Provisional Indicative World Plan for Agricultural Development.* Rome, 1970.
FAO 1970*b*	Food and Agriculture Organization of the United Nations. *The State of Food and Agriculture, 1970.* Rome, 1970.
Fei and Ranis 1964	Fei, J. C., and G. Ranis. *Development of the Labor Surplus Economy.* Homewood, Ill.: Richard D. Irwin, 1964.
Fei and Ranis 1969	Fei, J. C., and G. Ranis. "Economic Development in Historical Perspective." *American Economic Review* 59, no. 2, pp. 386–401.
Gomez-Pompa 1972	Gomez-Pompa, A., et al. "The Tropical Rain Forest: A Nonrenewable Resource." *Science* 177:762.
Harris, Tolley, and Contu 1963	Harris, R., G. S. Tolley, and A. J. Contu. *Cropland Reservations in the South.* North Carolina State College, Information Series 100, May 1962.
Harte and Socolow 1971	Harte, J., and R. Socolow, eds. *The Patient Earth.* New York: Holt, Rinehart and Winston, 1971.
Heady and Tweeten 1963	Heady, E., and L. Tweeten. *Resource Demand and the Structure of the Agricultural Industry.* Ames: Iowa State University Press, 1963.
Held and Clawson 1965	Held, R. Burnell, and Marion Clawson. *Soil Conservation in Perspective.* Baltimore: Johns Hopkins University Press, 1965.
Hoover 1970	Hoover, Dale M. "An Economic Analysis of Farmland Development." *Agricultural Economics Research* 22 (1970), no.2.
IBRD 1970	International Bank for Reconstruction and Development. *World Bank Atlas.* Washington, D.C., 1970.
Jorgenson 1970	Jorgenson, D. W. "The Development of the Dual Economy." *Economic Journal* 71 (June 1961): 309.
Kunstadter 1972	"Spirits of Change Capture the Karens." *National Geographic* 141:267.
Lewis 1954	Lewis, W. A. "Economic Development with Unlimited Supplies of Labor." *Manchester School of Economics and Social Studies* 22 (May 1954): 139.
Meadows et al. 1972	Meadows, D. H. et al., *The Limits to Growth.* New York: Universe Books, 1972.
Middleton, Kendrick, and Schwalm 1950	Middleton, J. T., J. B. Kendrick, and H. W. Schwalm. "Injury to Herbaceous Plants by Smog or Air Pollution." *Plant Disease Reporter* 34: 245–252.

Miller and Krusekopf 1932	Miller, M. F., and H. H. Krusekopf. *The Influence of Systems of Cropping and the Methods of Culture on Surface Runoff and Soil Erosion.* Missouri Agricultural Experimental Station, Bulletin 117. Columbia, 1932
Ministry of Agriculture, Fisheries and Food	Great Britain. Ministry of Agriculture, Fisheries, and Food, Department of agriculture and Fisheries for Scotland. *A Century of Agricultural Statistics.* Great Britain, 1866–1966. London, 1968.
Nye and Greenland 1960	Nye, P. H., and D. J. Greenland. *The Soil under Shifting Cultivation.* Farnham, England: Royal Commonwealth Agricultural Bureaux, 1960.
Pilpel 1971	Pilpel, N. "Structure of the Soil under Stress." *Ecologist,* December 1971.
Prestbo 1971	Prestbo, John A. "Shrinking Farmland." *Wall Street Journal,* July 20, 1971.
PSAC 1967	United States. President's Science Advisory Committee. *The World Food Problem.* Report of the Panel on the World's Food Supply. Vols. 1–3. Washington, D.C.: Government Printing Office, 1967.
Revelle 1963	Revelle, Roger. "Water." *Scientific American,* September 1963.
Revelle et al. 1971	Revelle, Roger, et al., eds. *Rapid Population Growth: Consequences and Policy Implications.* Vol. 2. Baltimore: Johns Hopkins University Press for the National Academy of Sciences, 1971.
Ryther 1969	Ryther, John H. "Photosynthesis and Fish Production in the Sea." *Science* 166 (1969): 72.
Salter, Lewis, and Slipher 1941	Salter, R. M., R. D. Lewis, and J. A. Slipher. *Our Heritage the Soil.* Ohio Agricultural Experimental Station, Extension Bulletin 175 (1941).
Shantzis and Behrens 1973	Shantzis, S., and W. Behrens, III. "Population Control Mechanisms in a Primitive Agricultural Society." In *Toward Global Equilibrium,* edited by D. L. Meadows and D. H. Meadows, Wright-Allen Press, Cambridge, Mass.: 1973.
Shaw 1970	Shaw, Robert d'A. *Jobs and Agricultural Development.* Overseas Development Council Monograph no. 3, 1970.
SMFA-SMA 1971	Sweden. Royal Ministry for Foreign Affairs, Royal Ministry of Agriculture. *Air Pollution across National Boundaries: The Impact on the Environment of Sulfur in Air and Precipitation.* Stockholm: Norstedg and Sons, 1971.
Snider 1950	Snider, H. J. *Soil Building with Legumes.* Illinois Agricultural Experiment Station, Bulletin 539. Urbana, June 1950.
Streeten 1971	Streeten, Paul. "How Poor Are the Poor Countries?" In *Development in a Divided World,* edited by Dudley Seers and Leonard Joy, pp. 67–83. Harmondsworth, Eng.: Penguin Books, 1971.
Trundeanu and Zwerman 1958	Trundeanu, Julian, and Paul J. Zwerman. "An Evaluation of Some Economic Factors and Farming Attitudes That May Influence Acceptance of Soil Conservation Practices." *Journal of Farm Economics,* November 1958, p. 910.
Tsui 1959	Tsui, Y. C. *Summary Report on Farm Income of Taiwan in 1957 in Comparison with 1952.* Chinese-American Joint Com-

	mission on Rural Reconstruction, Economic Digest Series no. 13 (1959).
Tyler 1972	Tyler, G. "Heavy Metals Pollute Nature, May Reduce Productivity." *Ambio* 1:52.
U.N. 1970*a*	United Nations. Department of Economic and Social Affairs. *Statistical Yearbook, 1969.* New York, 1970 (and earlier editions).
U.N. 1970*b*	United Nations. *Yearbook of National Accounts Statistics.* Vol. 1. New York, 1970.
U.S.D.A. 1962	United States. Department of Agriculture. "Major Uses of Land and Water in the United States with Special References to Agriculture." *Agricultural Economic Report,* no. 13 (1962), pp. 9–11.
U.S.D.A. 1965	United States. Department of Agriculture. *Changes in Agriculture in 26 Developing Nations, 1948 to 1963.* Foreign Agricultural Economic Report, no. 27. Washington, D.C., 1965.
U.S.D.A. 1970	United States. Department of Agriculture. *Economic Progress of Agriculture in Developing Nations, 1950–1968.* Washington, D.C., 1970.
Wharton 1969	Wharton, Clifton R., Jr. "The Green Revolution: Cornucopia or Pandora's Box?" *Foreign Affairs,* April 1969, pp. 465–466.
Williams and Couston 1962	Williams, Moyle, and John Couston. *Crop Production Levels and Fertilizer Use.* Rome: Food and Agriculture Organization of the United Nations, 1962.

5
Nonrenewable Resource Sector

Roger F. Naill and William W. Behrens III

5.1 INTRODUCTION

This chapter describes the effects of an assumed finite supply of nonrenewable resources on the World3 economy. A nonrenewable resource is defined here as a mineral or fossil-fuel commodity that (1) is essential to industrial production processes and (2) is regenerated on a time scale that is long compared with the 200-year time horizon of the model. For example, coal and oil are included as nonrenewable resources, while wood pulp and wool are renewable resources that are not considered in this sector. Nineteen examples of nonrenewable resources are listed in Figure 5-1. Our aim in this sector is to specify a set of model relationships that (1) represent the basic factors controlling the use of nonrenewable resources, and (2) relate the cost of extracting and processing them to the productive efficiency of the industrial sector of World3.

The second section of this chapter (5.2) describes the real-world historical behavior exhibited by the important variables in the nonrenewable resource sector. Next, the underlying theory and assumptions used to formulate the model structure are described in the section on basic concepts (5.3). The specific relationships assumed in the sector are then brought together into a causal structure (5.4). The model equations are given in section 5.5, which also explains the individual parameter values chosen for the equations. The final section (5.6) presents a series of simulation runs of the nonrenewable resource sector that illustrate the dynamic behavior resulting from the assumptions in the sector, test the sensitivity of behavior to changes in parameter values, and explore the effects of various policies on this behavior.

5.2 HISTORICAL BEHAVIOR MODES

Exponential growth in the production and usage of nonrenewable resources has been the most prominent long-term historical behavior mode of importance to the sector. Figure 5-2 shows the historical growth in the rate of production of six critical nonrenewable resources. Although the historical rate of growth varies for each resource, it is clear from this figure that exponential growth in resource production has been a general historical characteristic of the world economy. In fact, aggregate world production and usage of nonrenewable resources increased by 4.1 percent per year between 1950 and 1970 (NCMP 1972). The U.S. Bureau of Mines forecasts that the total world demand for resources will grow at an annual rate of 3.6–5.5 percent per year to the year 2000 (Bureau of Mines 1970, p. 3).

Over the long term, the grade, or concentration in ore, of a mined resource tends to decrease as more reserves are mined. For the fossil fuels, the parallel to the decline in the grade of ore mined is the decline in discoveries per foot of exploration. Figure 5-3 shows the time trends for copper ore mined and for crude oil discoveries. From these trends, one would expect the unit costs of obtaining resources to increase over time. Yet for most nonrenewable resources, the dollar cost per resource unit has remained relatively constant or has even declined (Potter and Christy 1962, Barnett

1 Resource	2 Identified Resources[a]	3 Hypothetical[b] plus Speculative[c] Resources	4 1970 Production[d]	5 Static Resource Index[e] (Years)		6 Projected Growth Rate[f] (%/Year)			7 Exponential Resource[g] Index (Years)	
				LOW	HIGH	LOW	AVE.	HIGH	LOW	HIGH
Aluminum	1.2×10^9 tons[h]	2.4×10^9 tons[i]	1.1×10^7 tons	110	340	5.1	6.4	7.7	33	49
Chromium	4.9×10^9 tons[j]	4×10^9 tons[j]	6.7×10^6 tons[j]	730	1,300	2.0	2.6	3.3	115	137
Coal	9.5×10^{12} tons	7.3×10^{12} tons (hyp.)	3.1×10^9 tons	3,100	5,100	3.0	4.1	5.3[k]	118	132
Cobalt	9.9×10^9 lbs	12×10^9 lbs[l]	5.2×10^7 lbs	190	420	1.0	1.5	2.0	90	132
Copper	3.4×10^8 tons	4×10^8 tons (hyp.) 3.2×10^8 tons (spec.)	6.6×10^6 tons	52	160	3.4	4.6	5.8	27	46
Gold	3.5×10^8 troy oz[m]	8.4×10^8 troy oz	4.8×10^7 troy oz	7	25	3.4	4.1	4.8[o]	6	17
Iron	7.1×10^{11} tons[p]	no estimate available	8.5×10^8 tons[p]	840	n.a.	1.3	1.8	2.3	154	n.a.
Lead	1.4×10^8 tons[q]	1.7×10^9 tons	3.7×10^6 tons	38	490	1.7	2.0	2.4	28	119
Manganese	1.4×10^{10} tons[r]	1×10^{10} tons (hyp.)	2.0×10^7 tons	710	1,200	2.4	2.9	3.5	106	123
Mercury	7.2×10^6 flasks[s]	1.7×10^7 flasks[t]	2.9×10^5 flasks	25	84	2.2	2.6	3.1	19	44
Molybdenum	6.3×10^{10} lbs	2.2×10^{12} lbs (hyp.)	1.7×10^8 lbs	390	1,400	4.0	4.5	5.0	65	92
Natural gas	1.1×10^{15} ft^3 [m]	1×10^{16} ft^3	3.8×10^{13} ft^3	30	300	3.9	4.7	5.5	19	58
Nickel	9.0×10^7 tons	15×10^7 tons (spec.)	6.9×10^5 tons	130	350	2.8	3.4	4.0	50	75
Petroleum	6.3×10^{11} bbls[q]	1.2×10^{12} bbls	1.7×10^{10} bbls	38	110	2.9	3.9	4.9	23	43
Platinum[u]	4.2×10^8 troy oz	1.9×10^8 troy oz (hyp.)	4.2×10^6 troy oz	100	140	3.1	3.8	4.5	41	49
Silver	5.4×10^9 troy oz[q]	4.2×10^9 troy oz [v]	3.0×10^8 troy oz	18	32	1.5	2.7	4.0	15	23
Tin	2.3×10^7 tons	1×10^7 tons (hyp.) 8.4×10^6 tons (spec.)	2.6×10^5 tons	88	160	0	1.1	2.3	62	92
Tungsten	2.9×10^9 lbs[m]	no estimate available	7.6×10^7 lbs	39	n.a.	2.1	2.5	2.9	27	n.a.
Zinc	1.7×10^9 tons	3.9×10^9 tons	6.0×10^6 tons	280	930	2.5	2.9	3.3	76	115

[a]Identified resources are defined as specific, identified mineral deposits that may or may not be profitably recoverable with existing technology and economic conditions. Unless otherwise noted, data are from U.S. Geological Survey, *United States Mineral Resources* (Washington, D.C.: U.S. Government Printing Office, 1973). This source provides a comprehensive assessment of the geological availability of United States and world nonrenewable resources, drawing from the most up-to-date research in the case of each commodity.

[b]Hypothetical resources are defined as undiscovered mineral deposits, whether of recoverable or subeconomic grade, that are geologically predictable as existing in known districts. Unless otherwise noted, data are from ibid.

[c]Speculative resources are defined as undiscovered mineral deposits, whether of recoverable or subeconomic grade, that may exist in unknown districts or in unconventional form. Unless otherwise noted, data are from ibid.

[d]Production data are from U.S. Department of the Interior, *Minerals Yearbook 1971*, (Washington, D.C.: U.S. Government Printing Office, 1973). The production rate is equal to the consumption rate unless, in the short term, world resource stockpiles are being built up or depleted. Over the long time horizon of concern in this table, however, it suffices to assume that production equals consumption.

[e]The static resource index is defined as the number of years global resources will last at current global production rates. The low index is calculated by dividing the identified resources of column 2 by the current annual production, column 4. The high index is calculated by dividing the sum of identified, hypothetical, and speculative resources (column 2 plus column 3) by the current annual production, column 4.

[f]Projected growth rates from U.S. Bureau of Mines, *Mineral Facts and Problems, 1970* (Washington, D.C.: Government Printing Office, 1970).

[g]The number of years global resources will last if production grows exponentially at the average annual rate of growth. Calculated by the formula

$$\text{exponential index} = \frac{\ln\left((R \times S) + 1\right)}{R}$$

where R = average rate of growth from column 6
S = high or low static indices from column 5.

[h]Known reserves of bauxite, expressed in aluminum equivalent, from U.S. Bureau of Mines, *Mineral Facts and Problems, 1970*.

[i]Potential (conditional, hypothetical, and speculative) resources of bauxite, expressed in aluminum equivalent (bauxite assumed to yield 25 percent aluminum by weight).

[j]Chromite ore.

[k]Bureau of Mines contingency forecasts, based on assumptions that coal will be used to synthesize gas and liquid fuels.

[l]United States only.

[m]Known reserves from U.S. Bureau of Mines, *Mineral Facts and Problems, 1970*.

[n]Potential (conditional, hypothetical, and speculative) resources.

[o]Includes Bureau of Mines estimates of gold demand for hoarding.

[p]Iron ore.

[q]Known reserves from U.S. Geological Survey, *United States Mineral Resources*.

[r]Manganese ore.

[s]Estimate of mercury recoverable at 400 dollars per flask.

[t]Estimate of mercury recoverable at 1,000 dollars per flask.

[u]The platinum group metals, consisting of platinum, palladium, irridium, osmium, rhodium, and ruthenium.

[v]Conditional and hypothetical silver resources in the United States only.

Figure 5-1 The geologic availability of world nonrenewable resources

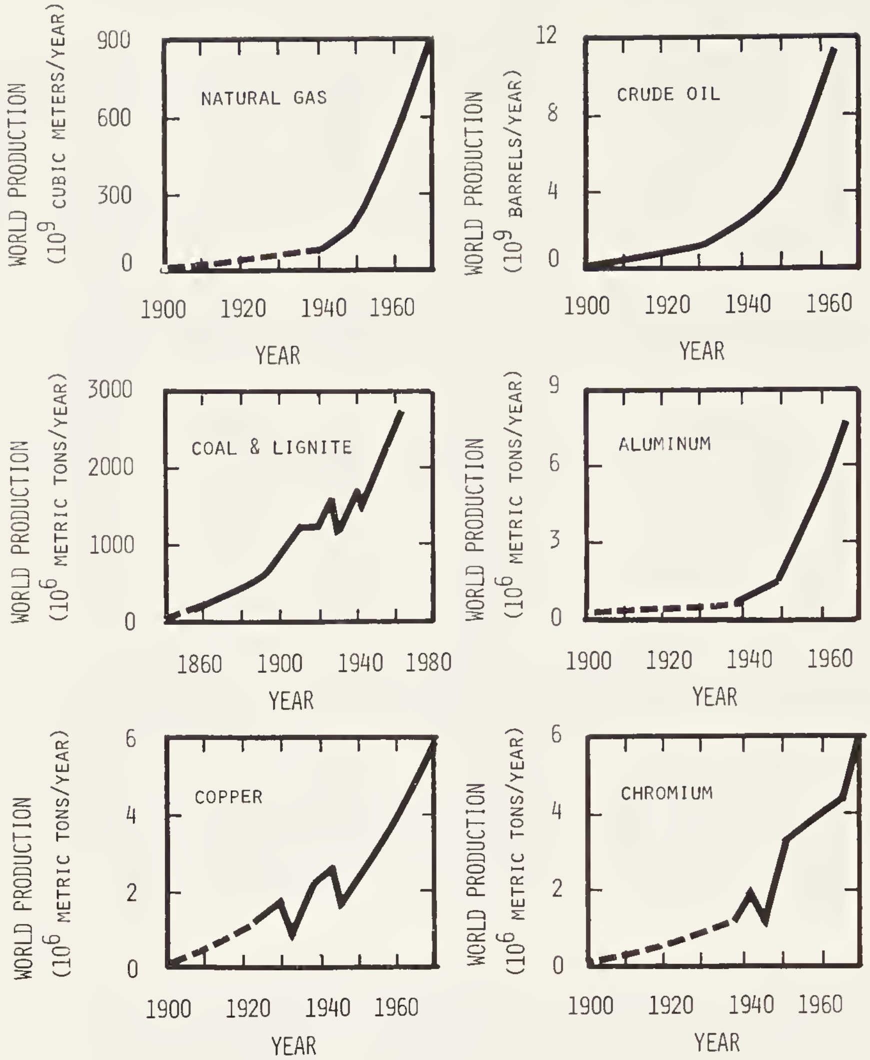
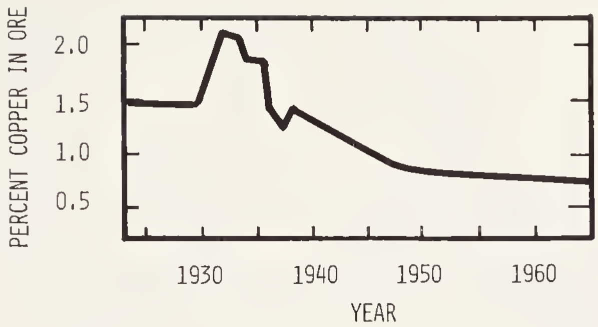


Figure 5-2 Exponential growth in world production of nonrenewable resources
Sources: Data from CRAM 1969, *Minerals Yearbook* 1970, U.N. 1970.

and Morse 1963). Figure 5-4 shows the cost per unit of product for the aggregate U.S. minerals industry from 1870 to 1957. There are a few potentially significant exceptions; for example, Figure 5-5 shows that the long-term trend of natural gas exploration is toward rising costs.

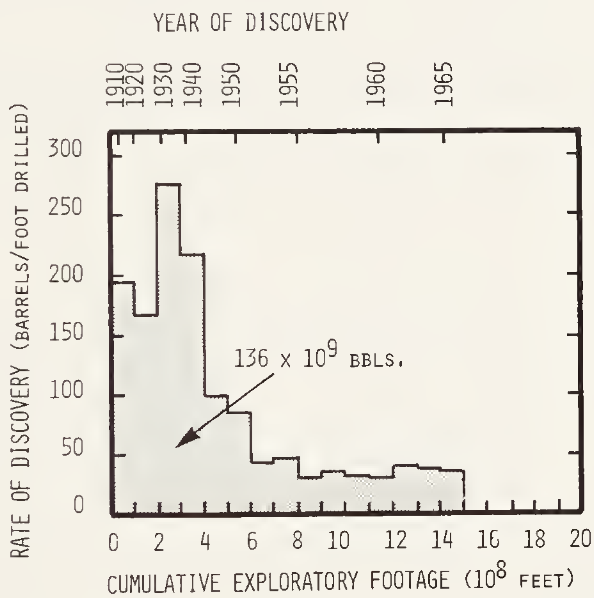
In addition to long-term cost trends, resource prices often reflect short-term cost fluctuations caused by delays in the acquisition of new production capacity. However, because the primary purpose of the model is to explain long-term trends, short-term fluctuations are not represented. An explanation of the dynamic determinants of resource commodity price cycles can be found in Meadows (1970).

Another long-term trend in the supply of global nonrenewable resources is the increasing dependence of the more industrialized countries on the resources of the developing countries. A prime example is oil in the United States. Until 1948 the United States was a net exporter of oil, but by 1970 it was importing 22 percent of its



A. Grade of copper ore mined, 1925–1965

Source: From *Resources and Man: A Study and Recommendations* by the Committee on Resources and Man of the Division of Earth Sciences, National Academy of Science–National Research Council, with the cooperation of the Division of Biology and Agriculture, p. 124. W. H. Freeman and Company. Copyright © 1969.



B. Crude oil discoveries per foot of exploratory footage in the United States, exclusive of Alaska, 1860–1967

Source: Hubbert 1967, p. 2223.

Figure 5-3 Declining grade of copper ore mined and declining returns to exploratory drilling for crude oil

oil (NPC 1971, p. 13), and this percentage has been steadily increasing. Although this trend may have a profound influence on the world economy in the future, in World3 its effects were considered to be mainly political in nature and were not modeled.*

*The international political implications of resource scarcity are to be studied under National Science Foundation Grant no. GI-34808X, a research project titled "The Dynamics of Long-Term Resource Availability" to be conducted at the Thayer School of Engineering, Dartmouth College, from 1972 to 1975.

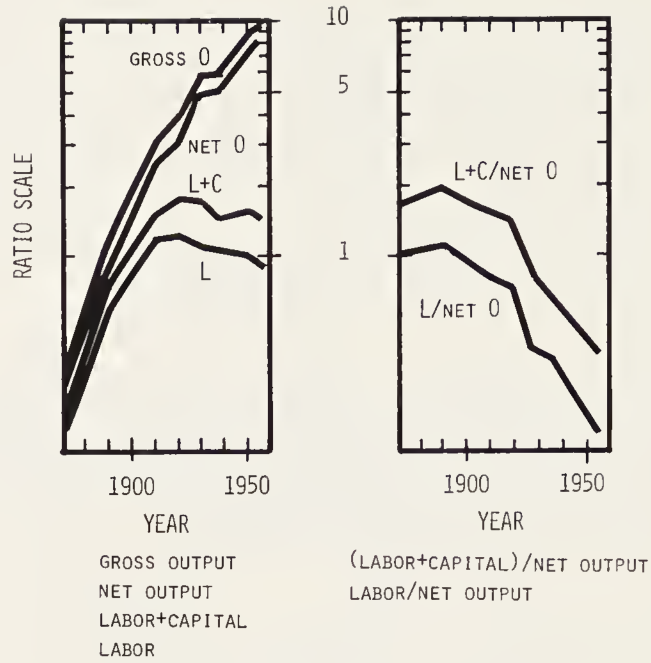


Figure 5-4 U.S. minerals: output, labor and capital inputs, and cost per unit of product, 1870–1957

Source: Adapted from Barnett and Morse 1963, p. 160.

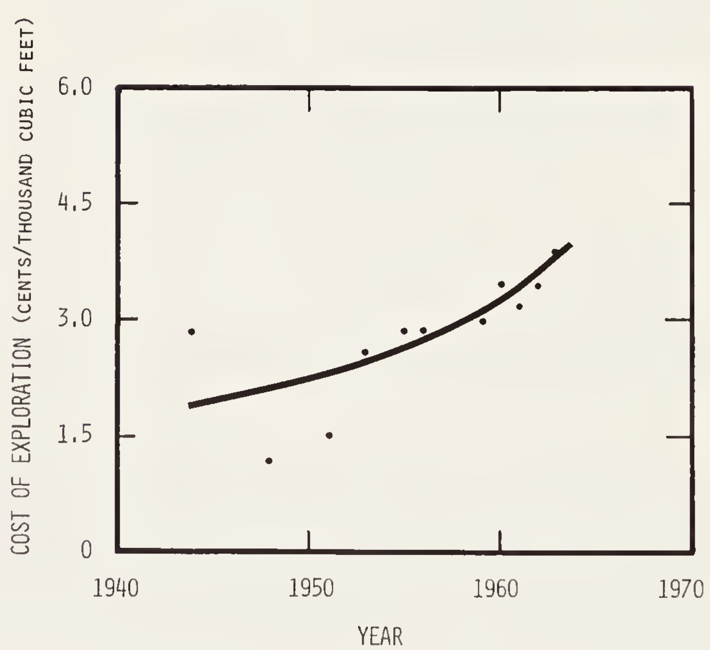


Figure 5-5 Cost of exploration in the natural gas industry, 1944–1963

Source: Data from Naill 1973.

5.3 BASIC CONCEPTS

The Fundamental Postulate

The fundamental postulate of the nonrenewable resource sector was that re sources are present on the earth in finite supply and are distributed widely in grade and in location. Furthermore, it was assumed that this finite stock of resources is not destroyed when used but instead is dispersed geographically or changed chemically (for example, the rusting of iron or the combustion of fossil fuels). Figure 5-6 summarizes these concepts in DYNAMO flow notation, representing the flow of nonrenewable resources through the world economy from unknown virgin resources to useful products and finally to pollution.

The finite stock of virgin resources is discovered at a rate that depends on existing exploration technologies and the amount of capital invested in exploration. After discovery, these resources are classified as proven reserves. The reserves are then extracted from their original location and refined into processed raw material, which is then made into products that are eventually discarded to become solid waste. Solid waste can be either recycled and converted back to processed raw material or disregarded, in which case it eventually disintegrates or disperses to such an extent that profitable recycling is impossible. The dispersed or degraded resource is termed a pollutant.

The finiteness, or nonrenewability, of resources is represented in Figure 5-6 by the lack of any exogenous material sources feeding into the system. Furthermore, no material is actually destroyed (except in fission and fusion processes); no material leaves the system shown in Figure 5-6. Resources may exist at any time in any of the six forms shown in the figure, but the total amount of resources in the world system is a conserved quantity.

The flow of resources through the world economy can also be viewed by considering the different entropy states associated with each of the material levels. Figure 5-7 gives a hypothetical quantitative example of the changes in entropy states associated with this flow. The resource is usable as processed raw material when it is in its highest concentration or lowest entropy state ($S=1$). The resource's entropy tends to increase through dispersion or chemical conversion as the resource is processed into materials in use ($S=3$). When a material is discarded, its entropy state is increased as solid waste ($S=10$) and increased even more as a pollutant ($S=1{,}000$).

To convert a material into its most usable form (processed raw material), its entropy must be decreased. According to the second law of thermodynamics, that cannot be accomplished without adding energy to the resource system. The conversion of proven reserves to processed raw material "costs" something—in this simplified case ΔE_1 energy units. Similarly, the conversion of solid waste to processed raw material costs ΔE_2 energy units. If only energy costs were associated with resource processing, recycling would occur when ΔE_2 is less than ΔE_1; if ΔE_2 is greater than ΔE_1, virgin resources would be utilized. Finally, the difference between a pollutant

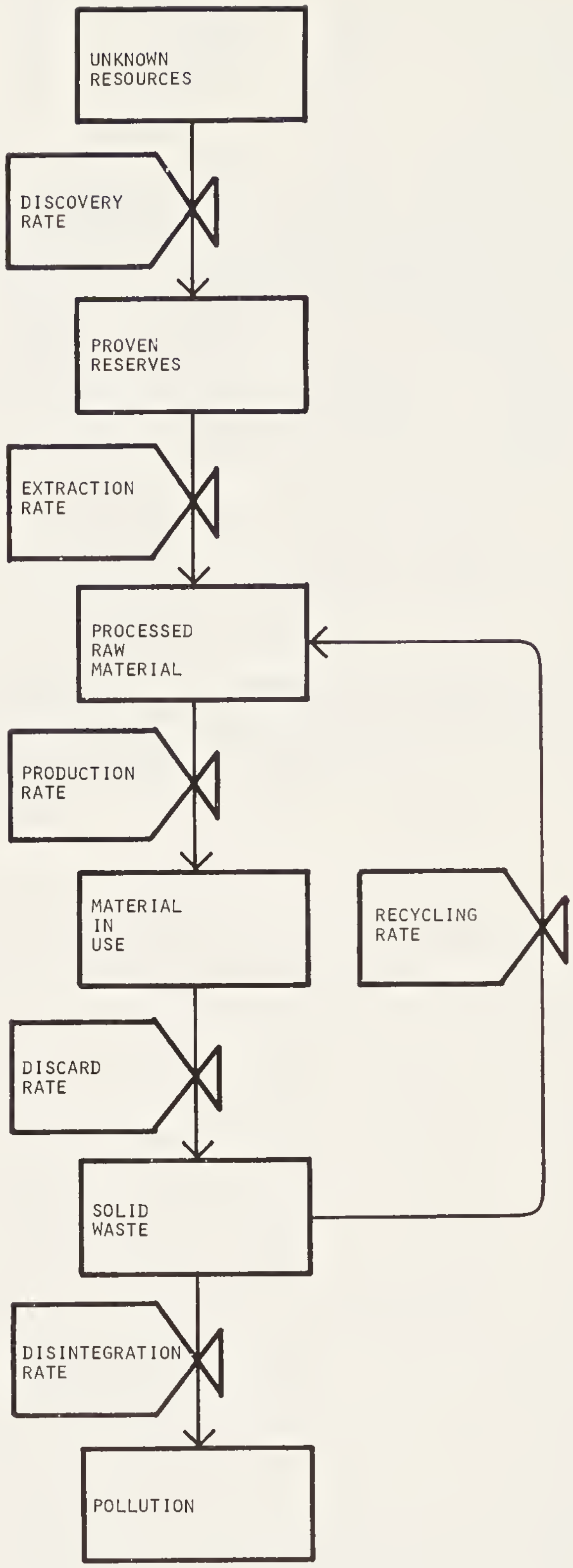


Figure 5-6 The flow of nonrenewable resources through the world economy

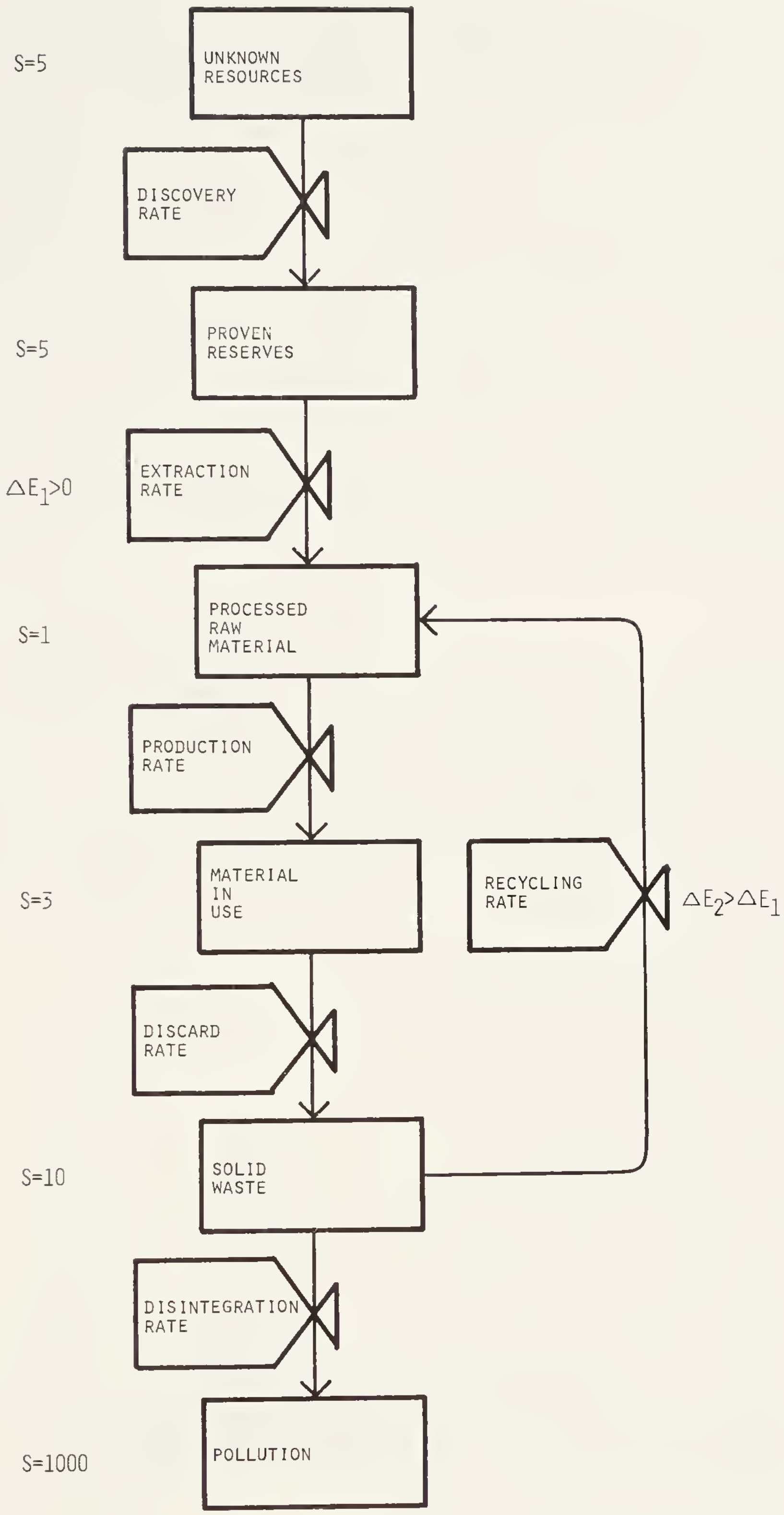


Figure 5-7 The change in entropy associated with the flow of nonrenewable resources

and a resource can be viewed as a matter of entropy: a pollutant is a discarded resource that is so dispersed geographically or so contaminated chemically that its recovery may not be technologically or economically feasible.

Although the amount of available energy appears to be a theoretical constraint on the usable resource base, energy costs at the present time contribute very little to the total cost of processing most resources. Figure 5-8 shows the percentage cost, based on 1966 data, of purchased electric power in the primary metal industries (AMM 1970). Only in the production of primary aluminum and electrometallurgical products is the energy cost of processing the raw material greater than 5 percent of the total processing cost. Most of the cost in current resource processing is actually material capital (for example, drilling rigs, processing plants, and distribution systems). Therefore, in the world model, the cost involved in converting resources to processed raw materials suitable for use was measured in terms of the fraction of industrial capital that must be allocated to obtain the resources required for the

Primary Metal Industries	**Cost of Purchased Power to Value of Shipment (percent)**
Blast furnaces and steel mills	2.0
Electrometallurgical products	11.3
Steel wire drawing	1.0
Cold finishing of steel shapes	0.7
Steel pipe and tubes	0.8
Gray iron foundries	1.2
Malleable iron foundries	2.3
Steel foundries	2.7
Primary copper	0.8
Primary lead	0.3
Primary zinc	4.3
Primary aluminum	12.1
Primary nonferrous metals, other	3.7
Secondary nonferrous metals	0.3
Copper rolling and drawing	1.0
Aluminum rolling and drawing	1.0
Rolling and drawing, other	0.8
Nonferrous wire drawings, etc.	0.8
Aluminum castings	1.0
Brass, bronze, and copper castings	1.0
Nonferrous castings, other	1.3
Iron and steel forgings	0.9
Nonferrous forgings	1.3
Primary metal industries, other	2.1

Figure 5-8 Electric power cost in U.S. metal industries
Source: AMM 1970, p. 113. Reprinted with the permission of Metal Statistics, American Metal Market/Metalworking News (1970). Copyright © 1970, Fairchild Publications, Inc.

present level of industrial output. Energy costs might be added in an extension of this model, but the entire energy question would probably be best modeled separately, making a distinction between energy resources and material resources.

Level of Aggregation

In the resource sector of World3, a number of simplifying assumptions cause its structure to differ from that shown in Figure 5-6: unknown resources and proven reserves are aggregated into one level that decreases over time as resources are utilized by the industrial sector, and the three levels of processed raw material, material in use, and solid waste are omitted. Therefore, the direct connection between resource use and pollution is not modeled. Instead, pollution generation is modeled as a function of resource use.

If Q_T is the total world supply of nonrenewable resources, representing the sum of unknown and proven reserves, then the possible usage rate of virgin materials over time U(t) is limited by

$$\int_0^t U(t)\,dt \leq Q_T, \tag{5.1}$$

where U(t) may be measured in resource units per year.* The integral may be very much less than Q_T, since some part of Q_T may ultimately be uneconomic to use. This usage rate must both start and end at zero, taking some series of nonnegative values so that its integral is less than or equal to Q_T. The only physical constraint put on the usage rate is that expressed by equation (5.1). One can imagine two extreme possibilities for this curve of the usage rate as a function of time (Figure 5-9). The users

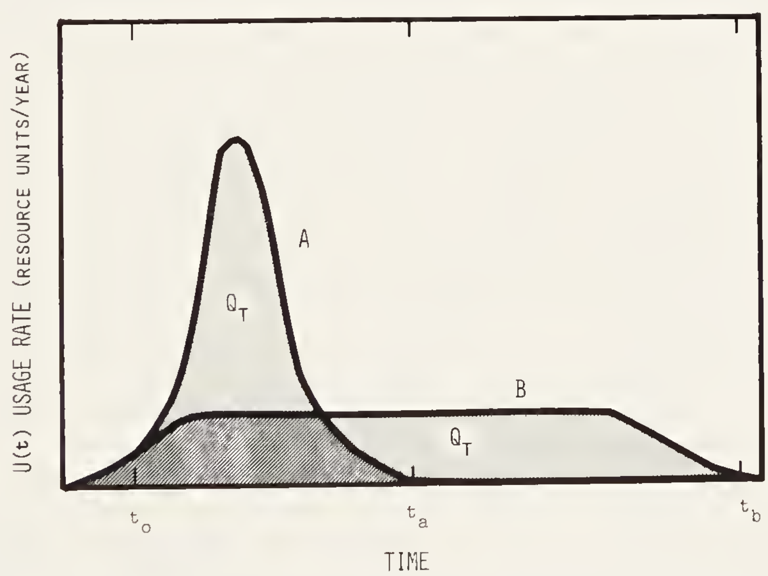


Figure 5-9 Possible usage rates of nonrenewable resources over time

*The following discussion is based on material in M. King Hubbert's "Energy Resources" in CRAM 1969. Hubbert develops his theory for fossil fuel resources, but the basic concepts are applicable to any nonrenewable resource.

of resources are able to choose whether the rate of resource consumption will follow a pattern similar to curve A or curve B of Figure 5-9. If they choose a usage rate similar to curve A, the total length of time for which they have the use of the resource is t_a. If they choose curve B, the corresponding time is t_b. In both cases the total area under the usage curve is equal to Q_T.

This simplified formulation of unidirectional resource flow assumes no recycling. Since institutional, technological, and economic factors today are such that most processed raw material comes from virgin sources, the use of recycled resources is not explicitly a part of the model structure. However, recycling can be enacted as a policy variable at any time in a model run; its effects on the sector behavior are described in section 5.6.

The representation of nonrenewable resources by a single level ignores the distinction between an unknown resource underground that has not been discovered and a proven reserve that has been located but has not been extracted and processed. The level of resources in the world model must then represent the sum of unknown resources and proven reserves that can be tapped for use at some finite cost, including discovery, extraction, processing, and distribution costs.

Increasing Costs of Obtaining Resources

The world model assumes that the cost of obtaining the next unit of resources must eventually rise as more resources are extracted from the earth. As stated earlier, the fundamental postulate of the nonrenewable resource sector is that resources are present in finite supply and are distributed widely in grade and location. If it is assumed that the best grades and the nearest locations are utilized first, then they will normally be used in an order of ascending cost, creating an identifiable "resource conversion path" (Figure 5-10). The horizontal portions of the path indicate periods

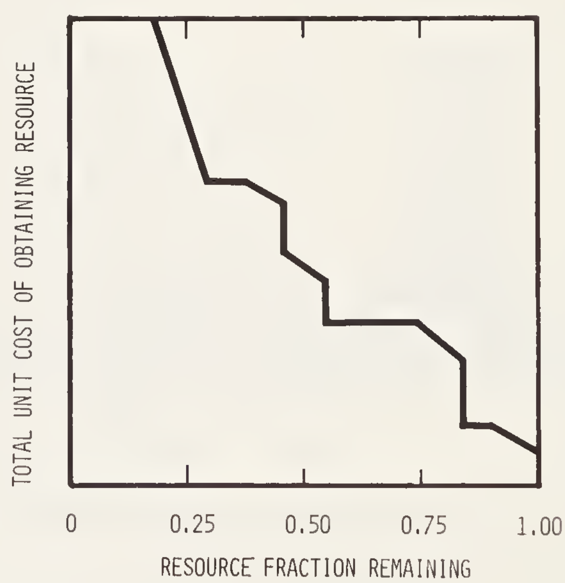


Figure 5-10 Resource conversion path
Source: Adapted from Barnett and Morse 1963.

in which output grows with no increase in unit costs; the vertical portions represent periods in which costs must increase before output can continue to grow.

For the purposes of this model, it is assumed only that resource costs tend to rise in the long run as the fraction of resources remaining decreases. One might expect periods of decreasing costs due to new low-cost reserve discoveries or technological breakthroughs. Short-term commodity price cycles may also decrease price briefly, but the overall long-run tendency is toward increasing costs with a decreasing nonrenewable resource fraction remaining. The long-run relationship is based on the physical characteristics of mineral distribution, whereas short-term variations are due to local or transient changes in distribution or extraction economics. The world model is based only on the long-term physical relationship.

In terms of the entropy analysis described earlier, the assumption of increasing costs stems from the fact that resources exist in widely varied entropy states, and man tends to process the low-entropy resources first. This implies that the amount of energy necessary to convert a resource to processed raw material increases as higher-entropy resources are mined.

As shown earlier, however, energy at present is a minor fraction of resource extraction costs, the major cost or input being industrial capital—the amount of capital goods necessary to process a given grade of raw material. The industrial capital stock consists of all the buildings and machines that are used in the construction of new buildings and machines and in the production of anything else that is a manufactured physical good. The capital stock also includes the mining equipment, pipelines, railroad cars, and smelters used to locate, extract, process, and distribute nonrenewable resources.

Thus the capital stock can be visualized as consisting of two fractions—the fraction required to obtain the raw materials (mineral and fossil fuel resources), and the fraction required to convert the raw materials into usable industrial output. As nonrenewable resource stocks are depleted, the efficiency of resource extraction goes down, forcing producers to allocate more capital to obtaining resources. As lower-quality ores are mined and new deposits must be sought in increasingly inaccessible places, a larger fraction of total industrial capital must be diverted from production to the exploration, extraction, and processing of nonrenewable resources. As stated by the Paley Commission on Materials Policy in 1952, "exhaustion is not waking up to find the cupboard is bare, but the need to devote constantly increasing efforts to acquiring each pound of materials from natural resources which are dwindling both in quality and quantity . . . " (Materials Policy Commission 1952). The reallocation of capital to resource extraction raises the fraction of total capital allocated to obtaining resources as illustrated in Figure 5-11. If it is not offset by technological improvements in the efficiency of capital, the reallocation of capital manifests itself as rising monetary costs of nonrenewable resources.

The Function of Technology in the Resource Sector

As shown in the section on time trends (5.2), the cost per resource unit has not in fact increased but has stayed relatively constant, or has even declined. As stated by

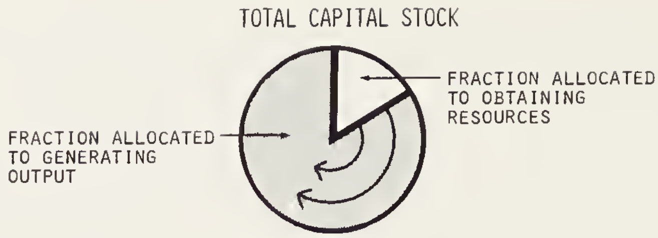


Figure 5-11 Shift over time in the fraction of capital that must be allocated to obtaining resources

Adelman: ''This is the basic paradox of mineral economics. At any given moment, man is running down his limited stock of minerals, and running up the cost of their extraction. Yet as time passes, real costs and prices fall more often than they rise'' (Adelman 1970, p. 132). The resolution of the paradox derives from continuing advances in technology. Adelman (1970) states that ''improved technology usually more than offsets the tendency to rising cost (Adelman 1970, p. 131).''

It is clear that in the past, advancing technology has enabled man to tap sources of lower and lower quality at the same or lower relative unit cost, and we may assume that the unit cost reflects the fraction of capital allocated to obtaining resources. Advancing technology thus tends to reduce the fraction of capital allocated to obtaining resources by increasing the productive efficiency of each unit of capital. This effect of technology was included in the model and is described in detail in the section defining the equation for the fraction of capital allocated to obtaining resources FCAOR.

Will technology continue to offset the tendency toward rising costs forever? Ayres and Kneese give five convincing arguments for expecting resource costs to rise in the future as more resources are depleted:

> 1. Lower quality ores in some important materials do not necessarily exist in exploitable quantities. This appears to be the case for lead and zinc [Brooks 1967]. The same is probably true for practical purposes with regard to hydrocarbons *as such* (i.e., for nonfuel purposes) since hydrocarbons are not simply dispersed by consumption but are actually used up—that is, chemically transformed into CO_2 and H_2O. Thus we face the likelihood that hydrocarbons will ultimately become rather scarce resources, being replaceable only from natural photosynthesis or by chemical synthesis involving large expenditures of energy.
>
> 2. The increased output of the extractive industries in the last century can be attributed in part to the opening up of previously unexplored areas (e.g., Canada, Siberia, Africa, Brazil, Australia). Except for the ocean bottom—which is not easily accessible or easy to exploit—''new'' sources will become rarer and rarer in the future.
>
> 3. The prices of mineral commodities historically have not reflected social costs arising from pollution and waste disposal. But these costs evidently increase nonlinearly as the amount of processing increases (requiring more energy and more technological inputs) and human settlement becomes more dense. We anticipate

that in the long term social costs of obtaining new materials will mount greatly. Low prices have also been subsidized to some extent by devices such as "depletion allowances."

4. The increased productivity of the extractive industries in the last century is also partly due to economies of scale and the application of mechanical technology. Both are probably subject to the law of diminishing returns. That is, the effort and investment required to achieve further productivity gains in the future will probably be much greater than has been true in the past.

5. The developed countries (except for the Soviet Union) are rapidly using up their domestic high-grade sources of minerals and fossil fuels and becoming dependent on the less-developed nations. The latter, in turn, rely on raw material exports for foreign exchange to purchase needed technological goods and services. It is not unlikely that raw material exporters will increasingly band together to multiply their bargaining power and increase their revenues from this source (this—apart from successful war by the rich nations on the poor—is, in fact, one of the more plausible scenarios for achieving a fairly radical redistribution of wealth and technology in the world). [Ayres and Kneese 1971, pp. 12–13]

Technology was not included explicitly as a single variable in World3, for we regard present trends in technology as integral parts of many different system relationships and new technologies as important policy tools still available but not yet utilized by society. The effects of technology were included implicitly in some model variables in the resource sector (such as the fraction of capital allocated to obtaining resources FCAOR) to the extent warranted by past and probable future trends. We believe an advance in technology beyond these probable trends is properly viewed as an exogenous policy variable.

New technologies can affect two relationships in the nonrenewable resource sector when applied as exogenous policy variables. First, the implementation of new advances in technologies of exploration, extraction, and production can further decrease the fraction of capital that must be allocated to obtaining the resources necessary to sustain industrial output at any given level of remaining resources. Second, the implementation of new technological advances that improve the quality of products (and thus product lifetimes), increase recycling, or reduce the quantity of resources needed in each product tend to decrease the per capita resource usage rate. These effects are discussed in detail in the section on model equations (5.5) and tested in the section on simulation runs (5.6).

5.4 CAUSAL STRUCTURE

The observed long-term behavior of the world's nonrenewable resource system can be summarized as exponential growth in resource usage and a tendency toward rising costs of obtaining resources, which has historically been offset by technology. To explain these trends, the underlying assumptions in the model are:

1. The finite stock of nonrenewable resources constantly decreases over time.
2. The capital costs of obtaining resources increase as the accessibility (grade, depth of deposit, location) of those resources deteriorates.

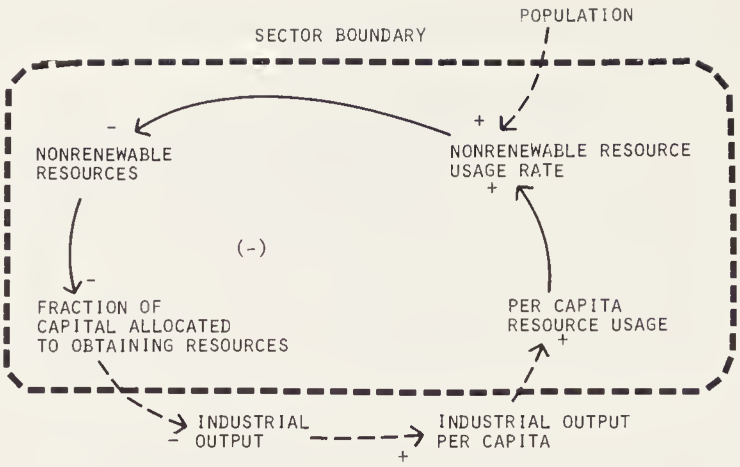


Figure 5-12 Causal-loop diagram of the nonrenewable resource sector

3. The tendency toward rising costs may be temporarily offset by advances in technology but, with the assumption of a finite resource supply, costs must ultimately rise as the stock of resources nears depletion.
4. The nonrenewable resource usage rate in any given year is the product of the total population and the per capita resource usage.
5. As the level of industrial output per capita increases, the per capita resource demand to support that industrialization also increases.

The causal-loop diagram describing the interrelationships among variables in the nonrenewable resource sector (Figure 5-12) shows that the sector is simply a single negative feedback loop. As nonrenewable resources near depletion, the fraction of capital that must be allocated to obtaining them eventually increases. For a given level of the capital stock, an increase in the fraction of capital allocated to obtaining resources implies a decrease in industrial output. Given a constant population, a reduction in industrial output reduces industrial output per capita directly. The reduced industrial output per capita leads to a lower per capita resource usage, which reduces the nonrenewable resource usage rate and leads to a slower depletion of nonrenewable resources, completing the negative feedback.

In the normal mode of operation of the model, both population and industrial capital grow exponentially. Under these growth conditions, even as capital is diverted to obtaining resources, industrial output may continue to rise—as long as the rate of growth of capital exceeds the rate of shift of capital from production to obtaining resources. Thus in a growing economy the economic consequences of resource depletion (shifting capital, leading to rising costs) may continue practically unnoticed for a long time.

However, if resources are depleted at an exponentially increasing rate, the cost of obtaining more resources will increase more rapidly. Therefore, the rate at which capital must be shifted (away from industrial production and toward obtaining the resources necessary to support that production) tends to increase and must eventually slow the rate of growth in industrial output as resources near depletion. The effect is at first imperceptible, for the reasons already noted, but becomes more significant as

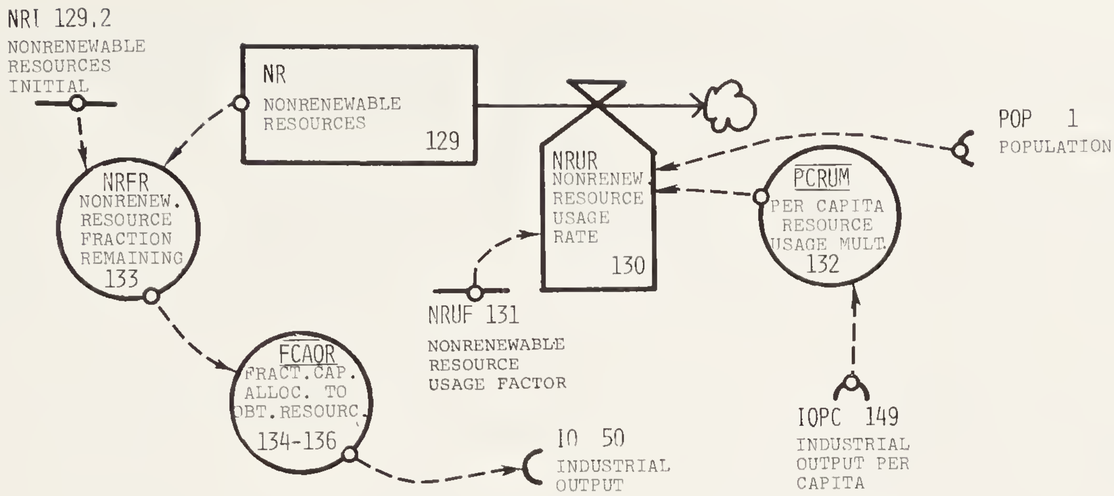


Figure 5-13 DYNAMO flow diagram of the nonrenewable resource sector

resource costs rise more quickly due to exponential depletion.

A DYNAMO flow diagram depicting the structure of the nonrenewable resource sector and its interaction with the rest of World3 is shown in Figure 5-13.

5.5 DESCRIPTION OF EQUATIONS

Nonrenewable Resources NR

```
NR.K=NR.J+(DT)(-NRUR.JK)                                129, L
NR=NRI                                                  129.1, N
NRI=1E12                                                129.2, C
    NR      - NONRENEWABLE RESOURCES (RESOURCE UNITS)
    DT      - TIME INTERVAL BETWEEN CONSECUTIVE
                CALCULATIONS (YEARS)
    NRUR    - NONRENEWABLE RESOURCE USAGE RATE (RESOURCE
                UNITS/YEAR)
    NRI     - NONRENEWABLE RESOURCES INITIAL (RESOURCE
                UNITS)
```

Nonrenewable resources NR, the total stock of resources available for use at any given time, are defined as follows:

$$NR(t) = NRI - \int_0^t NRUR(t)\,dt \qquad (5.2)$$

where NRI equals the initial amount of nonrenewable resources in the World3 system and NRUR equals the nonrenewable resource usage rate.

NR(t) at any given time is a positive quantity, for resources are never completely depleted; rather, their usage is curtailed by economic forces. The aggregation of all nonrenewable resources into a single level requires a clear definition of the role of nonrenewable resources. In the world model, nonrenewable resources NR were defined as the nonrenewable materials used in industrial production, for example, iron, lead, mercury, and copper, as well as the fossil fuels. Nonrenewable resources that are directly used in farming activities, such as phosphorous and potassium, were excluded from this analysis; but iron and other materials used to produce farm equipment and buildings were included. The availability of nonrenewable resources affects the world economy in two extremes: when they are in plentiful supply, they contribute with little cost to the process of creating industrial output; however, if there is a shortage of these materials, industrial production can be curtailed.

Although all mineral and fossil fuel resources share similar dynamic characteristics, they do not share a common initial value. One discrepancy among materials occurs in the variety of measuring schemes used: mercury is expressed in terms of 76-pound flasks, silver in terms of troy ounces, coal in terms of tons. To eliminate this source of confusion, resources are expressed as a multiple of the usage in some base year, as suggested by Forrester (1971). If 1970 is the base year, then by this measure the level of mercury resources in 1970, for example, would be the number of years the 1970 supply of mercury could sustain the 1970 level of mercury usage.

When this method is used to compute the remaining total stock of a resource at a given time, we have termed the resulting number the *static resource index*. In the world model, because both undiscovered resources and proven reserves are aggregated into one level, current estimates of the static index for world nonrenewable resources must reflect this aggregated level. This index thus represents the number of years the world's total stock of unused resources could support the 1970 level of industrialization, given the total 1970 population. Column 5 of Figure 5-1 gives the current resource indices for nineteen of the most important nonrenewable resources.

The static resource indices represent U.S. Geological Survey estimates of total world resources. Because of the high level of uncertainty involved in these estimates, both high and low estimates are given for each resource. The low index is calculated from *identified* resources (column 2), defined as specific, identified mineral deposits that may or may not have been evaluated for extent and grade and whose contained minerals may or may not be profitably recoverable with existing technology and economic conditions. The high index is calculated from the sum of *identified, hypothetical,* and *speculative* resources (column 2 plus column 3). Hypothetical resources are defined as undiscovered mineral deposits, whether of recoverable or subeconomic grade, that are geologically predictable as existing in known districts. Speculative resources are defined as undiscovered mineral deposits, whether of recoverable or subeconomic grade, that may exist in unknown districts or in unconventional form (USGS 1973).

These estimates represent the ultimate *geologic availability* of each resource, irrespective of economic or technological conditions. As stated by Brobst and Pratt of the U.S. Geological Survey, "geologic availability . . . is the ultimate determinant of mineral potential" (USGS 1973, p. 6). It is this concept of ultimate geologic availability that is encompassed by the level of nonrenewable resources NR in the world model. Economic and technological factors are included in the determination of the fraction of capital that must be allocated to obtaining these resources FCAOR, which is explained later in this section.

An evaluation of column 5 of Figure 5-1 indicates that a realistic range for the aggregate static resource index is probably between 100 and 500 years. The current model uses 250 years as an order-of-magnitude estimate of the 1970 static index of global nonrenewable resources. Other estimates for the parameter will be tested in section 5.6 of this chapter.

The 250-year estimate of the static resource index assumes a substantial degree of substitutability between the available stocks of currently utilized nonrenewable resources: as materials with reserve life indices lower than 250 years are depleted, those with higher indices can be used in their place at slightly higher costs. If little substitutability were assumed, the aggregate resource index would reflect the resource index of the scarcest resources, for as those resources are depleted, the world economy would be severely restricted.

The world model estimate of 250 years reflects the order of magnitude of the resource indices of only the nonrenewable resources listed in Figure 5-1. Thus the 250-year estimate assumes that no new materials more abundant than those listed in Figure 5-1 will become substantial inputs to the industrial production process without an enormous increase in real costs. Other assumptions might be tested by varying both the initial value of nonrenewable resources NRI and the cost associated with those resources, represented by the fraction of capital allocated to obtaining resources FCAOR.

The calculation of nonrenewable resources initial NRI proceeds as follows: for a 250-year static resource index in 1970, the value of nonrenewable resources NR in 1970 must equal the amount of resources consumed each year by one person in 1970 (defined as one resource unit), multiplied by the population POP in 1970, and multiplied by 250 years. The nonrenewable resource utilization factor NRUF is a policy test variable that enables the analyst to change the rate of usage of resources. When NRUF equals one, the usage rate of resources in 1970 equals one resource unit per year:

$$\begin{aligned} \text{NR}(1970) &= \text{NRUF} \times \text{POP} \times 250 \\ &= 1 \times 3.6 \times 10^9 \times 250 \\ &= 9 \times 10^{11} \text{resource units} \end{aligned} \tag{5.3}$$

To obtain the initial value of nonrenewable resources NRI, the amount of resources consumed from 1900 to 1970 must be added to the 1970 level of resources. The growth in population and resource usage indicates that this quantity is on the order of 1×10^{11} resource units. Simulations of the model indicate that a value of NRI equal to 1×10^{12} yields a static resource index of 250 years in 1970. It is interesting to note that the level of resources available in 1900 is equivalent to a static resource index of approximately 3,500 years. The sensitivity of the model to changes in the initial value of nonrenewable resources NRI is tested in the final section of this chapter.

Nonrenewable Resource Usage Rate NRUR

```
NRUR.KL=(POP.K)(PCRUM.K)(NRUF.K)                       130, R
    NRUR    - NONRENEWABLE RESOURCE USAGE RATE (RESOURCE
                UNITS/YEAR)
    POP     - POPULATION (PERSONS)
    PCRUM   - PER CAPITA RESOURCE USAGE MULTIPLIER
                (RESOURCE UNITS/PERSON-YEAR)
```

```
    NRUF   - NONRENEWABLE RESOURCE USAGE FACTOR
                (DIMENSIONLESS)

NRUF.K=CLIP(NRUF2,NRUF1,TIME.K,PYEAR)                     131, A
NRUF1=1                                                   131.1, C
NRUF2=1                                                   131.2, C
    NRUF   - NONRENEWABLE RESOURCE USAGE FACTOR
                (DIMENSIONLESS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    NRUF2  - NRUF, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    NRUF1  - NRUF, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
```

The level of nonrenewable resources NR is depleted by the nonrenewable resource usage rate NRUR, which is defined as the product of current population and current per capita consumption. In the model it was assumed that the level of industrial output per capita IOPC determines the level of per capita resource use through the per capita resource usage multiplier PCRUM. This multiplier is normalized so that when NRUF is set equal to 1.0 the per capita usage is equal to the 1970 world average per capita resource usage. In several runs, NRUF was decreased to simulate the impact of technological advances that are resource conserving, such as increases in product lifetimes or reductions in the quantity of resources used per product.

Per Capita Resource Utilization Multiplier PCRUM

```
PCRUM.K=TABHL(PCRUMT,IOPC.K,0,1600,200)                  132, A
PCRUMT=0/.85/2.6/4.4/5.4/6.2/6.8/7/7                     132.1, T
    PCRUM  - PER CAPITA RESOURCE USAGE MULTIPLIER
                (RESOURCE UNITS/PERSON-YEAR)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    PCRUMT - PCRUM TABLE
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                PERSON-YEAR)
```

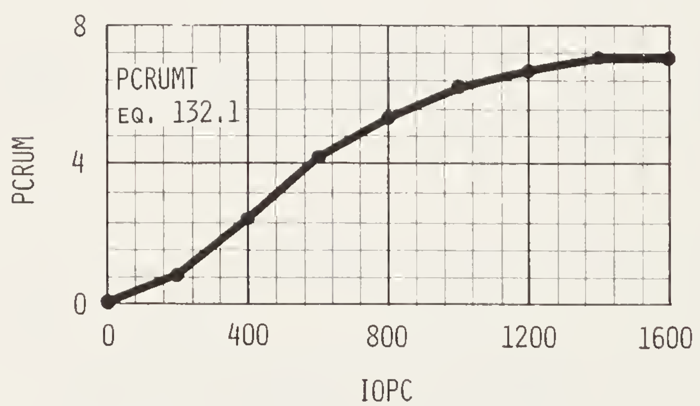


Figure 5-14 Per capita resource usage multiplier table

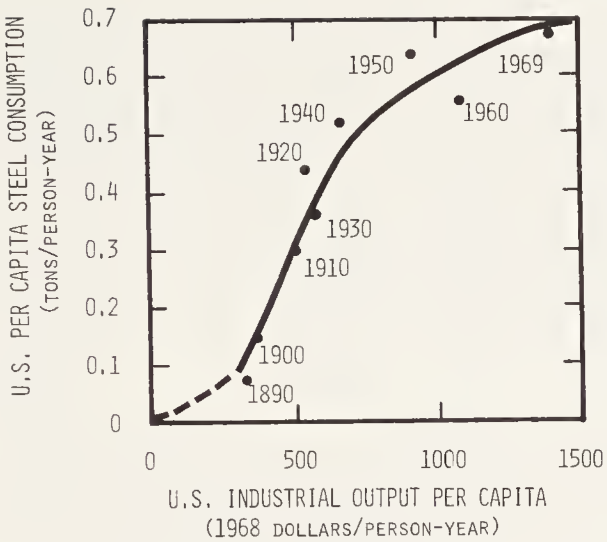


Figure 5-15 Per capita steel consumption in the United States as a function of industrial output per capita, 1890–1969

Sources: Steel production from AMM 1970; IOPC derived from GNP data in U.S.D.C. 1969.

Per capita resource usage is assumed to be a nonlinear function of industrial output per capita IOPC, the measure of industrial development used in the model. At low levels of IOPC, much of the industrial output is devoted to agricultural activities, which consume fewer nonrenewable resources than do industrial activities. At very high levels of IOPC, a large fraction is devoted to services, which also consume fewer resources. The combination of these two characteristics of industrial development produces the S-shaped relationship illustrated in Figure 5-14. The units of per capita resource usage were normalized to 1.0 at 1970 per capita usage levels.

This relationship can be supported empirically by examining the per capita consumption of materials in different countries at one point in time and in a single country over time. The original data cited in this section relate per capita usage to GNP per capita; we have converted GNP per capita to industrial output per capita IOPC according to the development patterns recorded in Chapter 3. Figure 5-15 plots time-series data of per capita steel consumption in the United States versus IOPC. The curve shows not only the rising per capita consumption at low levels of IOPC but also that steel consumption per capita begins to level off as IOPC reaches very high values. Figure 5-16, a similar curve drawn for per capita copper consumption in the United States (time-series data), shows a similar trend.

It is possible that the leveling off of the per capita consumption of steel at the higher values of industrial output per capita may be caused by a time trend toward the substitution of other materials for steel in industrial production. This is probably not the case, however, for the cross-sectional data reveal a similar relationship (Figure 5-17). If, in fact, the substitution of other materials and not a shift to service-oriented output causes the steel consumption curve to level off, then the hypothesized per capita resource usage multiplier PCRUM relationship should reflect a continuing increase of per capita consumption as a function of IOPC. If we should assume that the per capita resource demand does not level off as industrialization proceeds, the

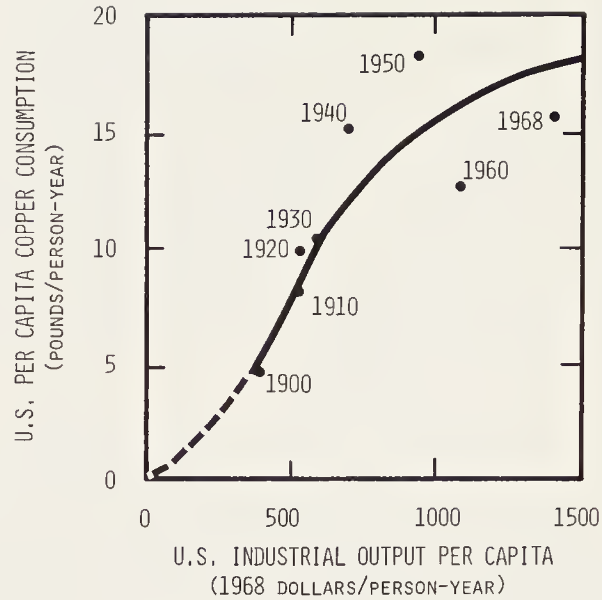


Figure 5-16 Per capita copper consumption in the United States as a function of industrial output per capita, 1900–1968

Source: Copper consumption from AMM 1970; IOPC derived from GNP data in U.S.D.C. 1969.

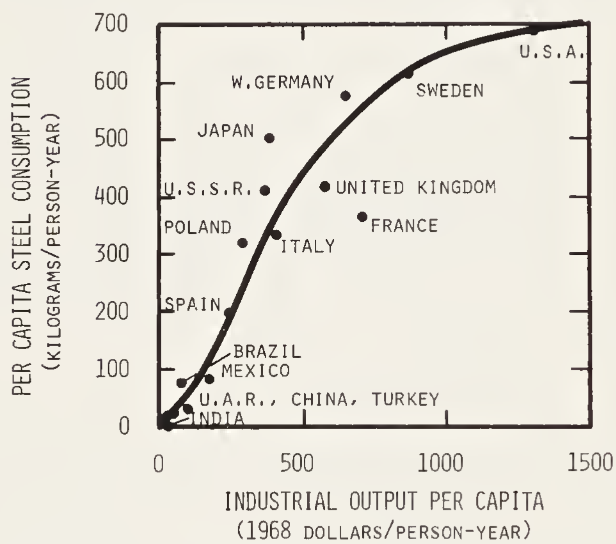


Figure 5-17 Per capita steel consumption as a function of industrial output per capita, selected countries, 1970

Source: Steel consumption from U.N. 1970; IOPC derived from GNP data in *WBA* 1970.

demand for resources would increase beyond that assumed in the present model as industrialization proceeds, which would be a less conservative assumption than that made in World3.

The numerical values used in the per capita resource usage multiplier relationship PCRUMT in the world model were obtained from Figures 5-15, 5-16, and 5-17 in the following manner: if we take 220 dollars per person-year as the world average industrial output per capita IOPC in 1970 (see Chapter 3), then the point on the curve at which PCRUM represents usage normalized at its 1970 level would be at approximately 100 kilograms per person-year for steel (Figure 5-17). As IOPC increases, per capita steel consumption tends to level off at a value of 700 kilograms per person-year, seven times its value at the 1970 level of IOPC. A similar trend is exhibited for copper: per capita copper consumption levels off at about seven times its value at the 1970 level of IOPC—220 dollars per person-year. The relationship for PCRUM has been drawn to reflect these trends with per capita consumption reaching a constant level at seven times its reference level when IOPC is approximately six times its 1970 world average level of 220 dollars per person-year. These numbers express only order-of-magnitude estimates of the expected demand for resources as industrialization proceeds.

The S-shaped curve of per capita resource usage PCRUM shown in Figure 5-14 is included in the world model simply as an indication of apparent real-world trends. The curve represents hypotheses about human values and about technology, both of which could change in the future. The relationship can be altered at any time in the model simulation to test the effects of significant system changes (such as the increased recycling of resources) that would increase or decrease the amount of nonrenewable resources NR each person consumes. A change in per capita resource usage can be accomplished in the present model in two ways: first, by changing the nonrenewable resource utilization factor NRUF from its normal value of 1.0, it is assumed that resource conservation reduces per capita consumption equally at all levels of industrial output per capita IOPC and thus does not change the general S-shaped characteristics of the PCRUM relationship; second, other hypotheses of the behavior of per capita resource usage as a function of IOPC (such as a continually increasing relationship, discussed earlier) can be tested by changing the PCRUM relationship directly.

Nonrenewable Resource Fraction Remaining NRFR

```
NRFR.K=NR.K/NRI                                         133, A
    NRFR   - NONRENEWABLE RESOURCE FRACTION REMAINING
               (DIMENSIONLESS)
    NR     - NONRENEWABLE RESOURCES (RESOURCE UNITS)
    NRI    - NONRENEWABLE RESOURCES INITIAL (RESOURCE
               UNITS)
```

The nonrenewable resource fraction remaining NRFR is simply the fractional amount of resources that has not been exploited. It was calculated by dividing the current level of nonrenewable resources NR by the initial level of resources NRI. This fraction is used to determine resource costs, measured by the fraction of capital allocated to obtaining resources FCAOR. The value of NRFR in 1970 is 0.9.

Fraction of Capital Allocated to Obtaining Resources FCAOR

```
FCAOR.K=CLIP(FCAOR2.K,FCAOR1.K,TIME.K,PYEAR)        134, A
    FCAOR  - FRACTION OF CAPITAL ALLOCATED TO OBTAINING
               RESOURCES (DIMENSIONLESS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    FCAOR2 - FCAOR, VALUE AFTER TIME=PYEAR
               (DIMENSIONLESS)
```

```
        FCAOR1 - FCAOR, VALUE BEFORE TIME=PYEAR
                    (DIMENSIONLESS)
        TIME   - CURRENT TIME IN THE SIMULATION RUN
        PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

    FCAOR1.K=TABHL(FCAOR1T,NRFR.K,0,1,.1)                  135, A
    FCAOR1T=1/.9/.7/.5/.2/.1/.05/.05/.05/.05/.05           135.1, T
        FCAOR1 - FCAOR, VALUE BEFORE TIME=PYEAR
                    (DIMENSIONLESS)
        TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
        FCAOR1T- FCAOR1 TABLE
        NRFR   - NONRENEWABLE RESOURCE FRACTION REMAINING
                    (DIMENSIONLESS)

    FCAOR2.K=TABHL(FCAOR2T,NRFR.K,0,1,.1)                  136, A
    FCAOR2T=1/.9/.7/.5/.2/.1/.05/.05/.05/.05/.05           136.1, T
        FCAOR2 - FCAOR, VALUE AFTER TIME=PYEAR
                    (DIMENSIONLESS)
        TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
        FCAOR2T- FCAOR2 TABLE
        NRFR   - NONRENEWABLE RESOURCE FRACTION REMAINING
                    (DIMENSIONLESS)
```

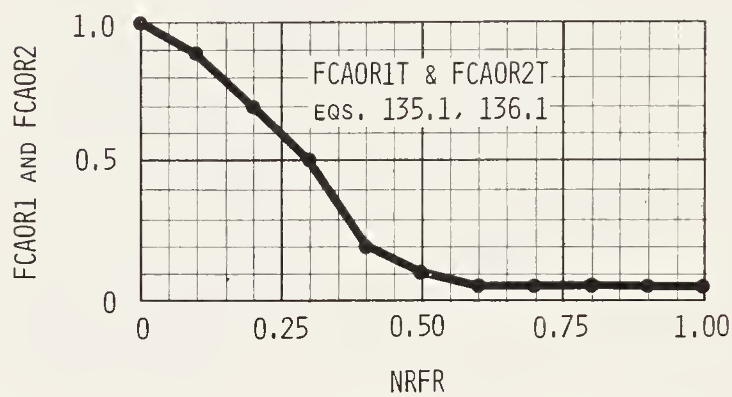


Figure 5-18 Fraction of capital allocated to obtaining resources table

The capital available to produce finished industrial output IO is defined as the total industrial capital IC multiplied by 1−FCAOR, where FCAOR is the fraction of capital that must be allocated to obtaining resources. The assumption of finite resources demands that FCAOR must approach one as resources near depletion so that industrial output IO (defined as manufactured material goods manufactured from resources) will gradually fall to zero. When the level of obtainable resources nears zero, industrial output IO must be curtailed because any level of IO demands resources. Thus the value of FCAOR at any time defines the necessary fraction of the capital stock that must be allocated to obtain the resources required for the present level of IO. The assumption that FCAOR must approach one as resources approach zero provides an adjustment mechanism that curtails the use of resources before the finite stock is exhausted. It corresponds to a rise in capital costs (and thus resource prices) as resources are depleted. Since the rising costs reduce the resource usage rate, the fraction of nonrenewable resources remaining NRFR never actually reaches zero in any model run; therefore, FCAOR never reaches one, and resources are never completely depleted. The form of the assumed relationship for FCAOR is shown in Figure 5-18.

Barnett and Morse (1963) have also examined the hypothesis that the fraction of capital allocated to obtaining resources FCAOR must rise as resources are depleted. Figure 5-19 shows time-series data for total capital, capital in mining, and capital in agriculture for the U.S. economy. Barnett and Morse conclude from this figure that the fraction of capital allocated to all extractive industries (agriculture and mining) is decreasing rather than increasing. Figure 5-20 illustrates the time-dependent behavior of the fraction of capital allocated to obtaining nonrenewable resources only, derived from Figure 5-19 by dividing mining capital by total capital. It appears that FCAOR has increased slightly over the long term, although it remains a very small fraction of total capital (2 percent). It is clear that technological advances in both extraction and substitution tend to counteract the hypothesized economic effects of resource scarcity and are undoubtedly responsible for the drop in the fraction of capital allocated to mining after 1920.

Although the data presented in Figure 5-20 are for the U.S. economy, they give some insights into the determination of a small portion of the FCAOR relationship hypothesized in Figure 5-18. Over the model's historical period (1900–1970), we assumed that the world economy consumed only one-tenth of its total initial stock of nonrenewable resources NR, so the nonrenewable resource fraction remaining NRFR decreases from 1.0 to 0.9 between 1900 and 1970. From Figure 5-20 it is clear that this small fraction of total resources, representing the highest grades and the most accessible locations, were available at a very low cost in terms of the fraction of total capital that had to be allocated to obtaining them. During this period, the economic effects of depletion were not great and were rather easily counteracted by technological advances. Figure 5-20 shows that for the U.S. economy the fraction of capital

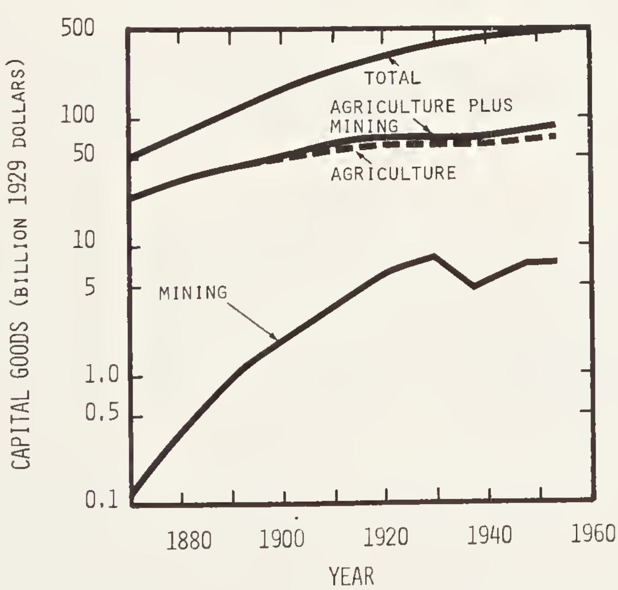


Figure 5-19 Capital goods in the U.S. private domestic economy and in agriculture and mining, 1869–1953
Source: Barnett and Morse 1963, p. 220.

allocated to mining remained minimal, at levels that were never a significant hindrance to the industrial process. For these reasons, we assumed that FCAOR remains at a minimal value of 5 percent of total capital in the world model as NRFR decreases from 1.0 to 0.9 from 1900 to 1970.

To estimate the behavior of FCAOR as the total stock of resources is depleted beyond this historical period, one can examine the pattern of costs of individual resources in geographic areas where those resources are nearing depletion. Crude oil and natural gas reserves in the continental United States are significant examples: the total reserves of both resources have been depleted to less than half their estimated initial reserves by 1970 (CRAM 1969).

In the case of U.S. oil, Figure 5-3 illustrates the number of barrels of oil obtained per foot of well drilled as a function of the cumulative number of feet drilled. Because the capital costs per foot drilled have been either constant or rising (Energy Study Group 1965), the capital cost per barrel discovered has been rising. Using an estimate of 10 dollars per foot drilled for the drilling cost (Energy Study Group 1965, p. 149) and an estimate of 165 $\times 10^9$ barrels as the total initial supply of oil resources in the continental United States (CRAM 1969, p. 183), it is possible to plot the relationship between the cost per barrel and the fraction of U.S. oil remaining as shown in Figure 5-21, where rising unit discovery costs are clearly in evidence. A similar relationship has been derived for the discovery cost per cubic foot of U.S. natural gas versus the fraction of natural gas resources remaining (see Figure 5-22).

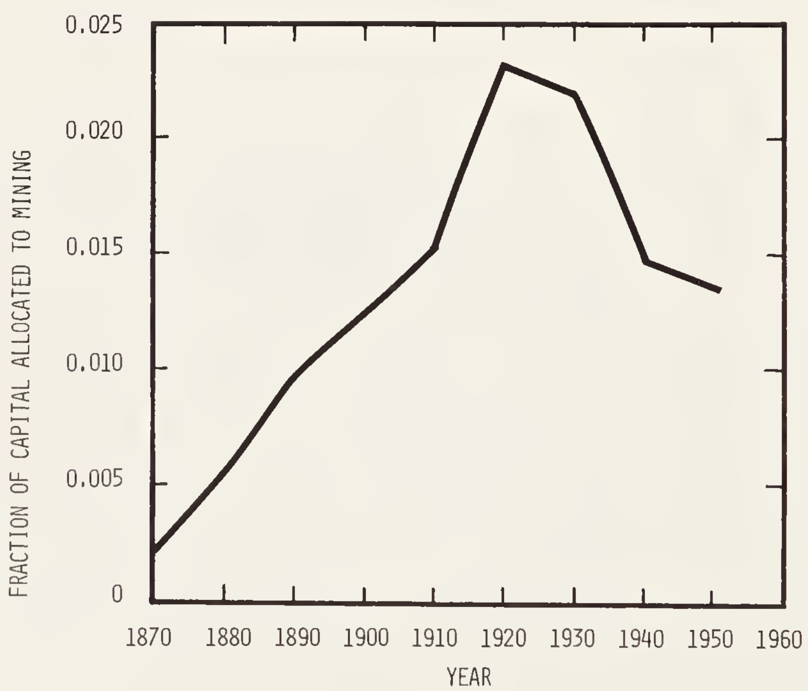


Figure 5-20 Fraction of capital allocated to obtaining mineral resources in the United States, 1870–1950

Source: Data derived from Barnett and Morse 1963, p. 220.

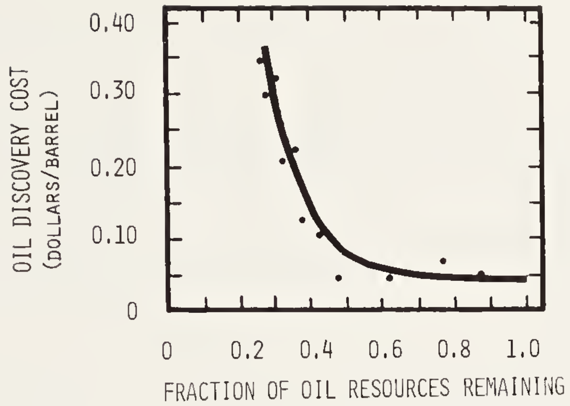


Figure 5-21 The cost of U.S. oil exploration as a function of the fraction of oil resources remaining, 1910–1965
Source: Data derived from CRAM 1969, p. 186.

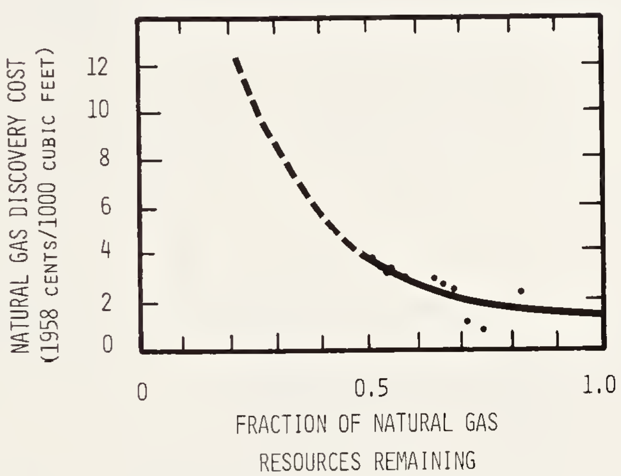


Figure 5-22 The cost of exploration for U.S. natural gas as a function of the fraction of natural gas resources remaining, 1944–1963
Sources: Data derived in Naill 1973 (from cost and discovery data in API 1967 and AGA 1970).

Figures 5-21 and 5-22 show significant cost rises as the fraction of resources remaining NRFR drops below half the estimate of initial resources. Thus we assumed in World3 that the progress of technology will continue to offset the effects of resource depletion until half the initial resources are depleted. At that point, resource costs, represented by the fraction of capital allocated to obtaining resources FCAOR, begin to rise (Figure 5-18).

It is important to note how tenuous this assumption may be. The depletion of oil and natural gas resources in the United States may be no more than significant exceptions to the general behavior of most nonrenewable resources as they undergo depletion. Certainly, much research concerning the long-term effects of resource depletion is needed to obtain a better estimate of this relationship. However, for the purposes of the model, the only significant characteristic of the relationship in determining the long-term behavior modes of World3 is the fact that FCAOR *must* rise toward 1.0 as resources near depletion.

The exact shape of the FCAOR curve, the assumed initial value of nonrenewable resources NRI, and the rate of growth of resource consumption are the three major determinants of the time remaining before rising resource costs interfere with the growth of industrial capital. Of these three determinants, the rate of growth of consumption (resulting from the rate of growth of population POP and of industrial output per capita IOPC) is by far the most important, as will be demonstrated in section 5.6 and in Chapter 7. If resource usage continues to increase at rates approximating the long-term trend of 4 percent per year, a relatively large error in the estimation of NRI or FCAOR will cause only a small error in the timing of the eventual increase in resource costs.

In the formulation of the FCAOR relationship, the assumption that FCAOR will remain constant at a low value as resources are depleted to half their initial value implies significant future advances in exploration and extraction technologies. To test the effects of technological advances beyond those included in the model, one can imagine the two forms of FCAOR shown in Figure 5-23. The solid line represents the standard FCAOR curve, which assumes improvements in exploration and extraction technologies as a part of current trends; the broken line assumes advances in exploration and extraction technologies beyond those included in the standard FCAOR relationship.

As can be seen in Figure 5-23, substantial improvements in technology enable FCAOR to remain at a low value for a larger fraction of the lifetime of resources. However, as the fraction of resources remaining NRFR approaches zero, the fraction of capital that must be allocated to obtaining resources must increase to 1.0.

The next section tests the sensitivity of the behavior of the nonrenewable resource sector to changes in the FCAOR relationship, the initial value of nonrenewable resources NRI, and the growth of the nonrenewable resource usage rate NRUR.

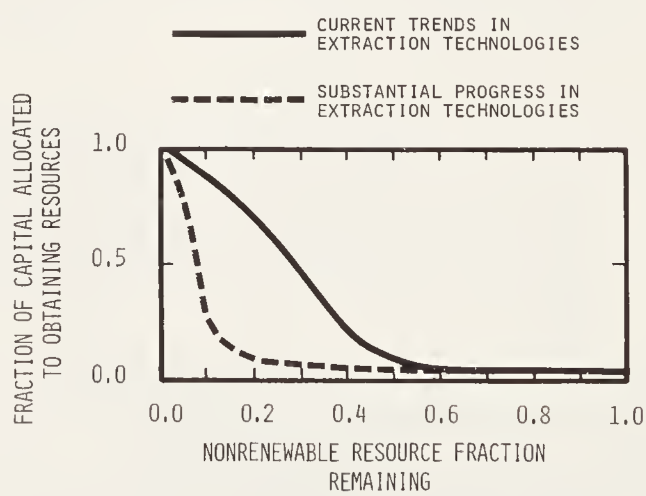


Figure 5-23 The effects of additional advances in extraction technologies on the fraction of capital that must be allocated to obtaining resources

5.6 SIMULATION RUNS

To illustrate the behavior of the nonrenewable resource sector, it was simulated alone, using simplified assumptions about inputs from the rest of the model. The equations governing the investment and depreciation rates of industrial capital (described in Chapter 3) were added to the resource sector to complete the sector's single negative feedback loop. The structure used for the simulations in this section is shown in Figure 5-24.

Since, in these simulations, we wished to focus on the single negative feedback loop relating resource depletion and industrial activity, it was assumed for these runs that the world population grows at a constant 1.2 percent per year and that its growth will not be affected by developments in the nonrenewable resource sector. The feedback interaction of the nonrenewable resource sector with the population sector is discussed in the simulations of World3 in its entirety (Chapter 7). The reinvestment fraction of industrial output was assumed to be constant at 33 percent; the average life of industrial capital ALIC was assumed to be 14 years (see Chapter 3).

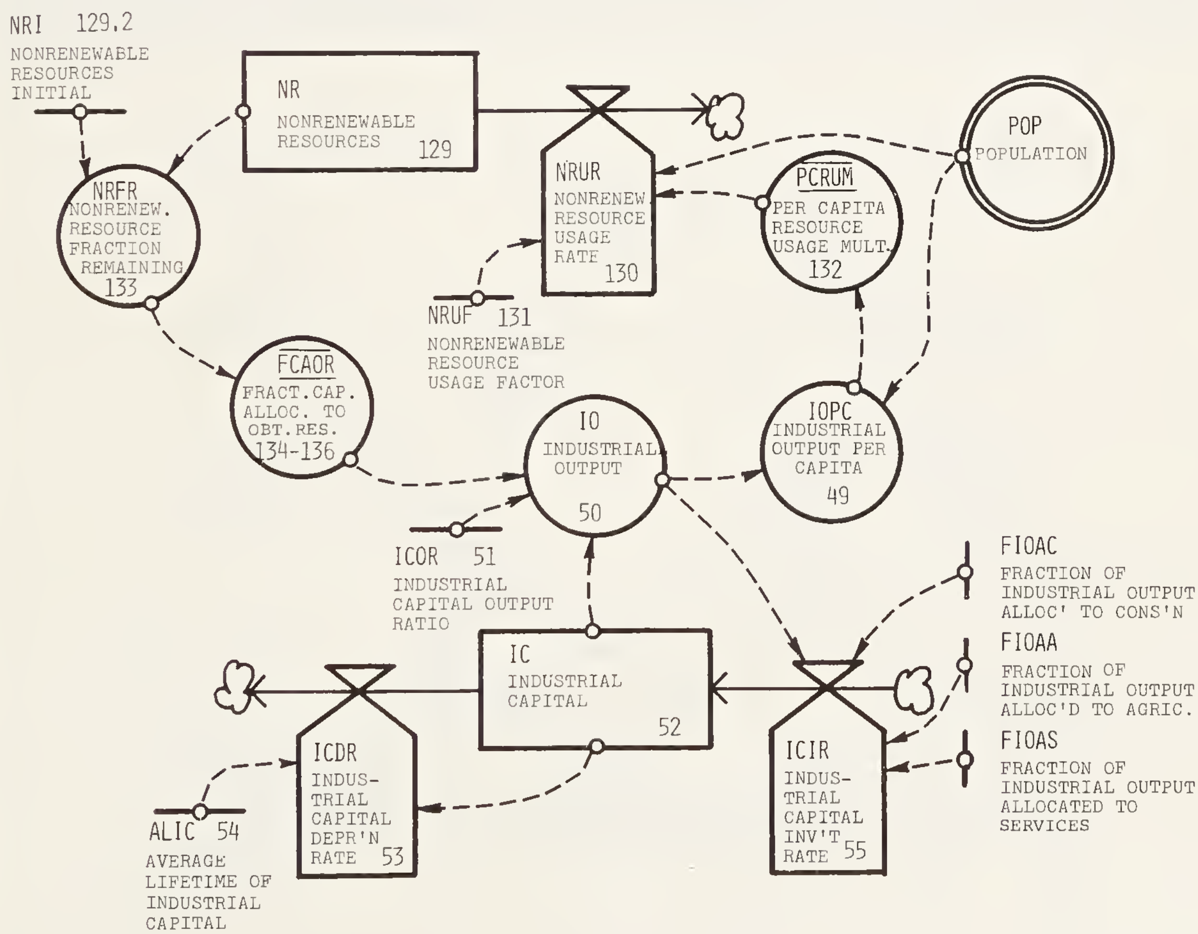


Figure 5-24 DYNAMO flow diagram for the nonrenewable resource sector simulation runs

Run 5-1 (Figure 5-25) illustrates the standard run from a 200-year simulation of the nonrenewable resource sector shown in Figure 5-24. Industrial capital IC and industrial output IO grow from 1900 until 2025, when the depletion of nonrenewable resources reverses this growth trend. The declining grade of nonrenewable resources requires that a larger and larger fraction of the capital base be allocated to resource processing activities. The capital costs of obtaining resources do not have to increase very much to cause a reduced growth rate of industrial capital. For example, if the fraction of capital allocated to obtaining resources FCAOR were to increase by 10 percent per year, and the annual net reinvestment (investment rate less depreciation rate) were less than 10 percent per year, then usable (processed goods) output would fall and total investment in industrial capital would begin to fall. The initial static resource index in the year 1900 of this run exceeds 3,500 years. In 1970 the static index has declined to 250 years because of a great increase in the rate of resource consumption. By the year 2025, only 55 years after 1970, the exponentially growing consumption rate has depleted the initial resources by about 50 percent. The costs of obtaining resources are rising and reversing the process of economic growth because of the necessary shift of capital to obtaining resources.

During a short period before the year 2020, both industrial output IO and the fraction of capital allocated to obtaining resources FCAOR are rising. The rise in the latter may occur unnoticed during this time, for the rate of increase in FCAOR is less

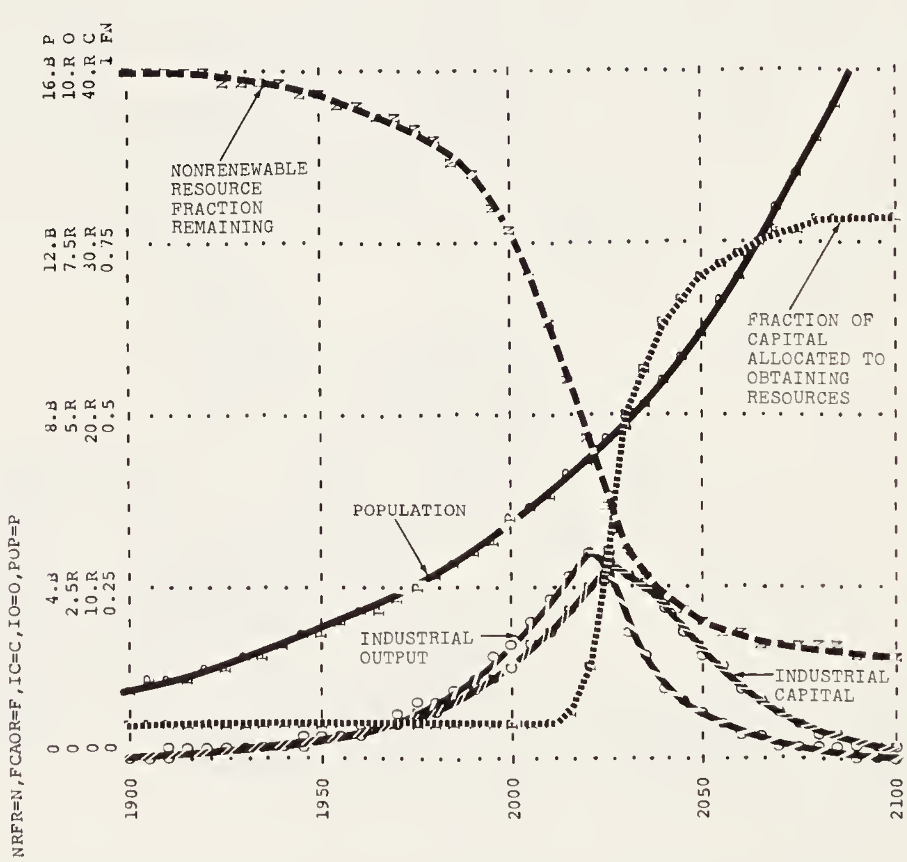


Figure 5-25 Run 5-1: standard run for the nonrenewable resource sector

than the rate of growth in capital; thus total output is increasing. Because of the continued exponential growth in the consumption of resources, however, this rate of increase in FCAOR eventually exceeds the rate of economic growth, thereby slowing the rate of reinvestment of industrial capital. By the year 2020 the rate of shift of capital to obtaining resources is large enough to cause industrial output IO to decline.

The method of estimating the initial value of nonrenewable resources was described earlier in this chapter. It was pointed out that the value used in the model is a reasonable estimate but one subject to much uncertainty. To test the sensitivity of the sector's behavior to this estimate, the initial value of nonrenewable resources was doubled in Run 5-2 (Figure 5-26). In this run, industrial capital IC increases for a longer period of time and reaches a higher value before turning downward. The maximum value reached by IC is almost twice as high as in the standard run, Run 5-1 (Figure 5-25). The peak, however, occurs only about 20 years later than in the standard run. Doubling the initial supply of nonrenewable resources in 1900 lengthens the period of capital growth by only 20 years.

This apparent insensitivity to the initial value of resources is understandable when one considers the factors governing the usage rate during the first hundred years of the run. Of primary importance is the relationship between the exponentially growing capital stock and the exponentially growing population. Exponential growth in industrial capital IC causes industrial output IO to grow exponentially, given a constant capital-output ratio and a stable fraction of capital allocated to obtaining

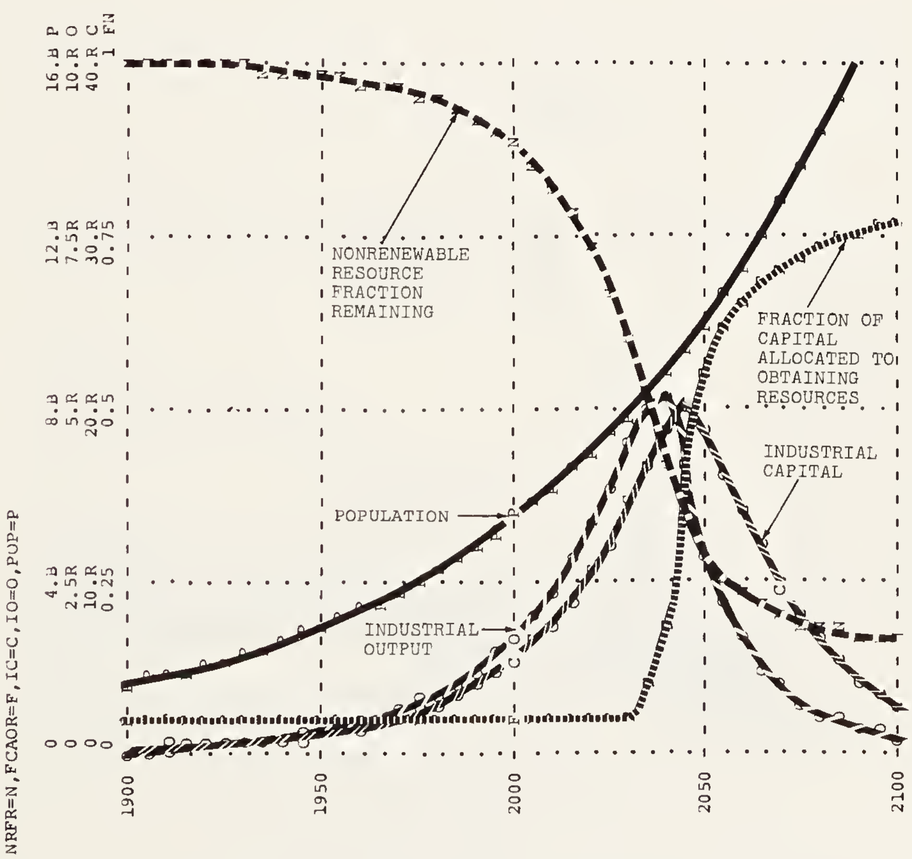


Figure 5-26 Run 5-2: Behavior of the sector with double the initial value of nonrenewable resources

resources FCAOR. Because industrial output IO is growing at a faster rate than population POP, industrial output per capita IOPC increases steadily during this period. As a result, per capita resource usage also increases. When combined with a growing population, the net growth in the resource usage rate amounts to about 4 percent per year.

Column 6 of Figure 5-1 gives the projected rates of growth in several mineral and fossil-fuel resources. The exponential resource index, or the length of time that resources would remain available under conditions of exponentially growing usage rates, is given in column 7. This index illustrates the dominant role of exponentially growing usage rates in the resource system. Continued exponential growth in usage makes the static resource index wholly inaccurate; Figure 5-27 illustrates the relationship between the static resource index and the exponential resource index for various rates of growth. The graph indicates that as long as usage is growing exponentially, even at low rates of growth, there is a drastic reduction in the potential lifetime of the resource. The amount of this reduction depends more on the fact that the growth is exponential than on the precise rate of increase. Reducing the rate of increase from 4 percent to 3 percent has very little effect on the potential lifetime of a given resource. The dominance of exponential growth is the cause of the insensitivity of the sector's behavior to errors in estimates of the initial value of nonrenewable resources NRI, as illustrated by Run 5-2 (Figure 5-26).

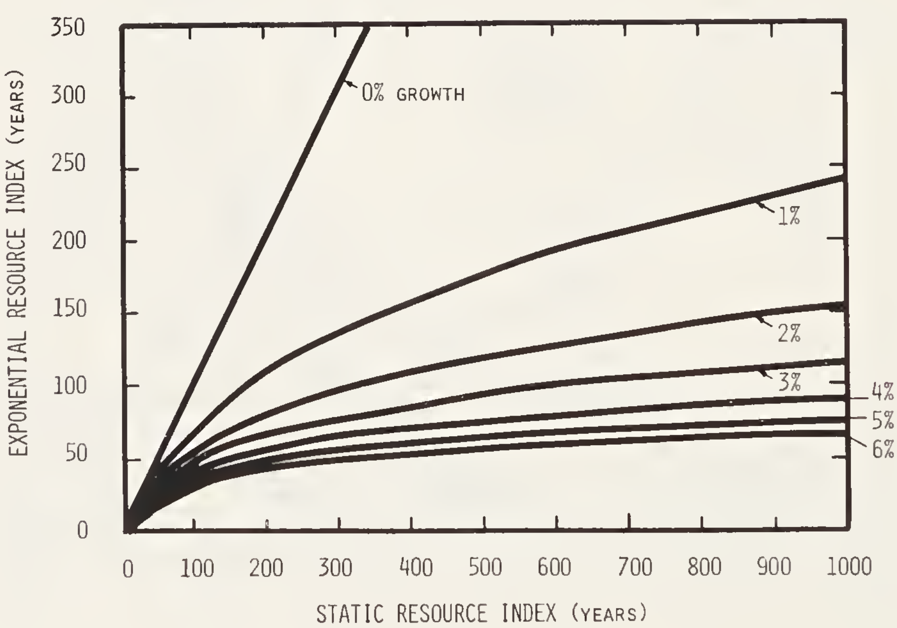


Figure 5-27 Exponential versus static resource indices as a function of annual growth rates

The effect of cost-reducing extraction technologies on the fraction of capital allocated to obtain resources FCAOR has also been discussed. The standard run, Run 5-1, was simulated with a form of the FCAOR relationship equivalent to the solid line in Figure 5-23. The broken line in Figure 5-23 illustrates a form of FCAOR that would reflect significant new technological advances that lower the costs of resource processing. A simulation of the resource sector with the latter form of FCAOR yields the behavior shown in Run 5-3 (Figure 5-28). The major effect of this change is to postpone the decline in industrial output IO for a few years and then to precipitate a rapid decline in IO, as opposed to the more gradual decline shown in Run 5-1. This result is due to the ability of advancing technologies to offset the inherent effects of resource depletion (such as declining grades and deposits) temporarily, thus encouraging resource utilization in the short run. In the long run, when the effects of depletion finally are manifested in higher resource costs, the FCAOR curve climbs so steeply that the system has little time to adjust.

To the extent that the model assumptions reflect the real-world resource system, technologies that maintain low costs in the resource industries without simultaneously discouraging an exponential usage of resources appear to be counterproductive in the long run. Technologies that lower the cost of mining virgin minerals tend to eliminate the economic incentive to look for more abundant substitutes or to increase recycling.

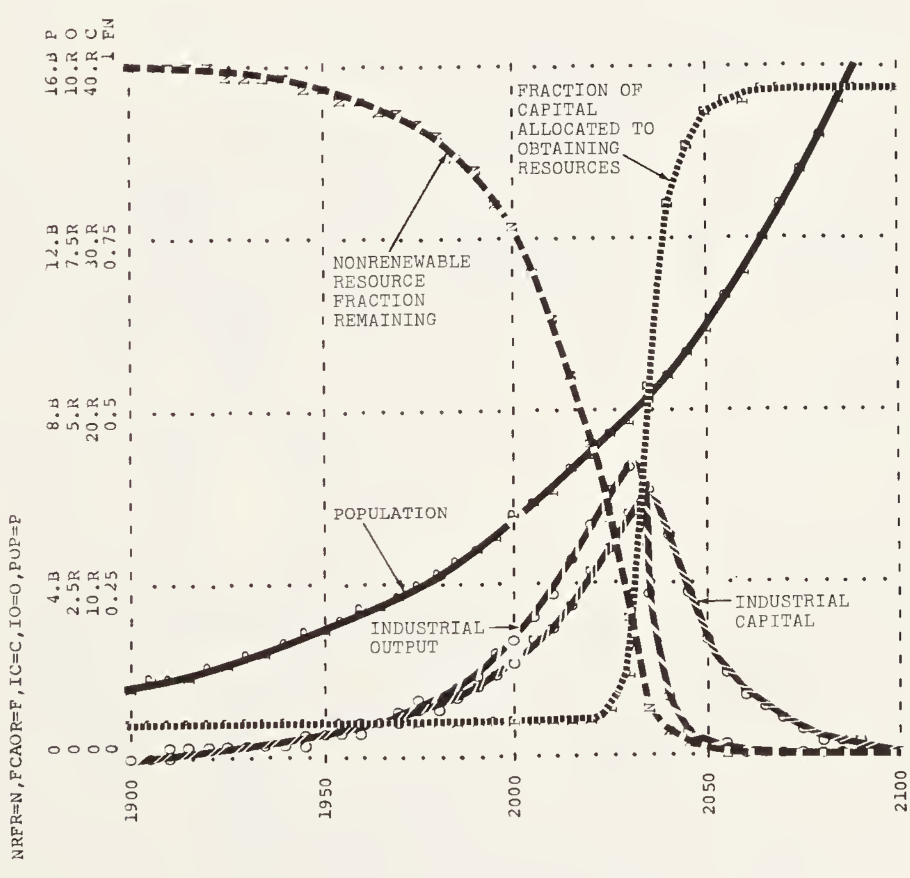


Figure 5-28 Run 5-3: The effects of cost-reducing technologies on the behavior of the nonrenewable resource sector

Yet, by encouraging continued exponential growth in resource consumption, they hasten the day when substitutes or recycling technologies will be needed.

Run 5-4 (Figure 5-29) shows the effects of implementing a resource-conserving technology in 1975 that reduces by a factor of four the amount of resources used per capita. This technology is modeled by changing the nonrenewable resource utilization factor NRUF from its normal value of 1 to 0.25 in 1975. Such a policy postpones the decline in industrial output for about 40 years.

It is apparent from Runs 5-3 and 5-4 (Figures 5-28 and 5-29) that cost-reducing and resource-conserving technologies are effective in postponing a decline in industrial output, but they are unable to prevent such a decline altogether in this simplified model. A resource shortage may be prevented within the time horizon of this model, however, by combining a policy of improving resource technologies with socioeconomic policies that affect other sectors of the model. For example, Run 5-5 (Figure 5-30) shows the behavior of the sector with both cost-reducing and resource-conserving technological advances and with zero population growth in 1975. In this run the stabilization of population reduces the growth in resource usage, allowing industrial capital IC and industrial output IO to continue to grow unhindered during the model run. The behavior of the

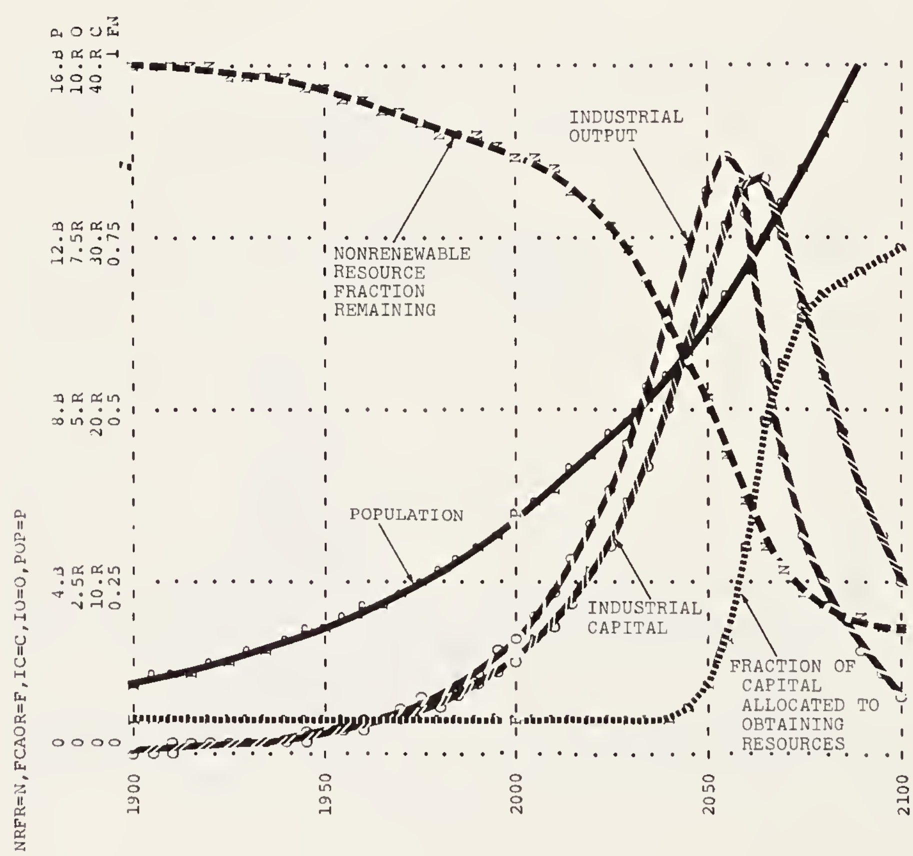


Figure 5-29 Run 5-4: the effects of resource-conserving technologies on the behavior of the nonrenewable resource sector

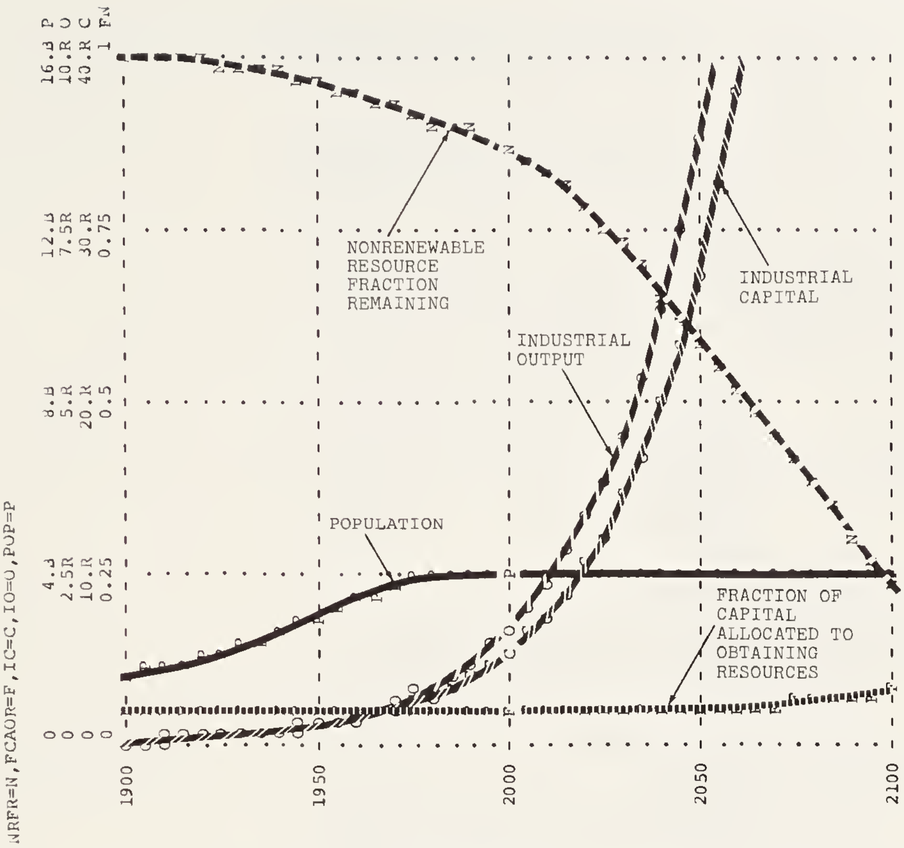


Figure 5-30 Run 5-5: The effects of zero population growth and advanced technological policies on the behavior of the nonrenewable resource sector

nonrenewable resource sector would be further stabilized if policies limiting the growth in industrial capital IC were implemented in this run. As will be shown again in Chapter 7, the long-term decline in industrial output IO caused by the increased cost of nonrenewable resources can be avoided only through a combination of technological and growth-reducing policies.

APPENDIX: PROGRAM LISTING

```
          RESTR
          *        NONRENEWABLE RESOURCE SECTOR WITH EXOGENOUS INPUTS
          NOTE
129       L        NR.K=NR.J+(DT)(-NRUR.JK)
          N        NR=NRI
          C        NRI=1E12
130       R        NRUR.KL=(POP.K)(PCRUM.K)(NRUF.K)
131       A        NRUF.K=CLIP(NRUF2,NRUF1,TIME.K,PYEAR)
          C        NRUF1=1
          C        NRUF2=1
132       A        PCRUM.K=TABHL(PCRUMT,IOPC.K,0,1600,200)
          T        PCRUMT=0/.85/2.6/4.4/5.4/6.2/6.8/7/7
133       A        NRFR.K=NR.K/NRI
134       A        FCAOR.K=CLIP(FCAOR2.K,FCAOR1.K,TIME.K,PYEAR)
135       A        FCAOR1.K=TABHL(FCAOR1T,NRFR.K,0,1,.1)
          T        FCAOR1T=1/.9/.7/.5/.2/.1/.05/.05/.05/.05/.05
136       A        FCAOR2.K=TABHL(FCAOR2T,NRFR.K,0,1,.1)
```

```
T       FCAOR2T=1/.9/.7/.5/.2/.1/.05/.05/.05/.05/.05
NOTE
NOTE    EXOGENOUS INPUTS TO THE NONRENEWABLE RESOURCE SECTOR
NOTE
NOTE    POPULATION
NOTE
A       POP.K=CLIP(POP2,POP1.K,TIME.K,ZPGT)
A       POP1.K=POPI*EXP(GC*(TIME.K-1900))
C       POPI=1.65E9
C       GC=.012
C       POP2=4E9
C       ZPGT=2500
NOTE
NOTE    INDUSTRIAL CAPITAL
NOTE
L       IC.K=IC.J+(DT)(ICIR.JK-ICDR.JK)
N       IC=ICI
C       ICI=2.1E11
R       ICIR.KL=(IO.K)(1-FIOAA-FIOAS-FIOAC)
C       FIOAA=.12
C       FIOAS=.12
C       FIOAC=.43
R       ICDR.KL=IC.K/ALIC
C       ALIC=14
NOTE
NOTE    INDUSTRIAL OUTPUT
NOTE
A       IO.K=(IC.K)(1-FCAOR.K)/ICOR
C       ICOR=3
A       IOPC.K=IO.K/POP.K
NOTE
NOTE    CONTROL CARDS
NOTE
N       TIME=1900
C       PYEAR=1975
SPEC    DT=1/PLTPER=5/LENGTH=2100
PLOT    NRFR=N,FCAOR=F(0,1)/IC=C(0,4E13)/
X       IO=O(0,1E13)/POP=P(0,1.6E10)
NOTE
NOTE    PARAMETER CHANGES FOR THE RESOURCE SECTOR RUNS
NOTE
RUN     FIGURE 5-25: RESOURCE SECTOR STANDARD RUN
C       NRI=2E12
RUN     FIGURE 5-26: DOUBLE RESERVES
T       FCAOR2T=1/.3/.1/.065/.06/.055/.05/.05/.05/.05/.05
RUN     FIGURE 5-28: COST-REDUCING TECHNOLOGIES
C       NRUF2=.25
RUN     FIGURE 5-29: RESOURCE-CONSERVING TECHNOLOGIES
C       ZPGT=1975
T       FCAOR2T=1/.3/.1/.065/.06/.055/.05/.05/.05/.05/.05
C       NRUF2=.25
RUN     FIGURE 5-30: ZPG AND NEW TECHNOLOGIES
```

REFERENCES

Adelman 1970 — Adelman, M. A. "Economics of Exploration for Petroleum and Other Minerals." *Geoexploration* 8:131–150.

AGA 1970 — American Gas Association. *Gas Facts, 1970.* New York, 1970. Annual.

AMM 1970 — American Metal Market Co. *Metal Statistics 1970.* New York: Fairchild Publications, Inc., 1970.

API 1967 — American Petroleum Institute, Independent Petroleum Association of America, Mid-Continent Oil and Gas Association. *Joint Association Survey of Industry Drilling Costs.* 1959–1967 eds.

Ayres and Kneese 1971	Ayres, R. U., and A. V. Kneese. "Economic and Ecological Effects of a Stationary Economy." *Annual Review of Ecology and Systematics* 2 (1971).
Barnett and Morse 1963	Barnett, H. J., and C. F. Morse. *Scarcity and Growth.* Baltimore: Johns Hopkins University Press for Resources for the Future, 1963.
Behrens 1971	Behrens, William W. "The Dynamics of Natural Resource Utilization." Paper presented at the 1971 Summer Computer Simulation Conference, July 1971, Boston, Mass., sponsored by the Board of Simulation Conferences, Denver, Colorado.
Brooks 1967	Brooks, D. B. "The Lead-Zinc Anomaly." *Society of Mining Engineering Transactions*, June 1967.
Bureau of Mines 1970	U.S. Bureau of Mines. *Mineral Facts and Problems, 1970.* Washington, D.C.: Government Printing Office, 1970.
Cloud 1969	Cloud, Preston. "Mineral Resources from the Sea." In CRAM 1969.
CRAM 1969	*Resources and Man: A Study and Recommendations* by the Committee on Resources and Man of the Division of Earth Sciences, National Academy of Sciences–National Research Council, with the cooperation of the Division of Biology and Agriculture. San Francisco: W. H. Freeman, 1969.
Energy Study Group 1965	United States. Energy Study Group. *Energy Research and Development and National Progress.* Washington, D.C., 1965.
Forrester 1971	Forrester, J. W. *World Dynamics.* Cambridge, Mass.: Wright-Allen Press, 1971.
Hubbert 1967	Hubbert, M. K. "Degree of Advancement of Petroleum Exploration in the United States." *Bulletin of the American Association of Petroleum Geologists* 51 (1967).
Lansberg et al. 1963	Lansberg, H. L., et al. *Resources in America's Future.* Baltimore: Johns Hopkins University Press, 1963.
Lovering 1969	Lovering, T. S. "Mineral Resources from the Land." In CRAM 1969.
Materials Policy Commission 1952	Materials Policy Commission. *Resources for Freedom.* Washington, D.C.: Government Printing Office, 1952.
Meadows 1970	Meadows, D. L. *The Dynamics of Commodity Production Cycles.* Cambridge, Mass.: Wright-Allen Press, 1970.
Minerals Yearbook 1970	United States. Bureau of Mines. *Minerals Yearbook.* Washington, D.C.: Government Printing Office, 1970 (and preceding years).
Naill 1973	Naill, R. F. "Discovery Life Cycle of a Finite Resource: A Case Study of U.S. Natural Gas." In *Toward Global Equilibrium: Collected Papers,* edited by Dennis L. Meadows and Donella H. Meadows. Cambridge, Mass.: Wright-Allen Press, 1973.
NCMP 1972	United States. National Commission on Materials Policy. *Towards a National Materials Policy: Basic Data and Issues.* Interim report. Washington, D.C : Government Printing Office, April 1972.
NPC 1971	National Petroleum Council Committee on U.S. Energy Outlook. *U.S. Energy Outlook: An Initial Appraisal, 1971–1985.* Vol. 1. Washington, D.C.: National Petroleum Council, 1971.

Potter and Christy 1962	Potter, N., and F. T. Christy, Jr. *Trends in Natural Resource Commodities.* Washington, D.C.: Resources for the Future, 1962.
Randers 1971	Randers, Jorgen, and D. L. Meadows. "The Dynamics of Solid Waste Generation." *Technology Review,* March/April 1972.
U.N. 1970	United Nations. Department of Economic and Social Affairs. *Statistical Yearbook, 1969.* New York, 1970.
U.S.D.C. 1969	United States. Department of Commerce. *U.S. Economic Growth.* Washington, D.C.: Government Printing Office, 1969.
USGS 1973	U.S. Geological Survey. *United States Mineral Resources.* Geographical Survey Professional Paper 820. Washington, D.C.: Government Printing Office, 1973.
WBA 1970	International Bank for Reconstruction and Development. *World Bank Atlas.* Washington, D.C., 1970.

6
Persistent Pollution Sector

Dennis L. Meadows, and Jay Martin Anderson

6.1 INTRODUCTION

The set of important environmental problems created by man is large and diverse. Figure 6-1, taken from a conceptual scheme presented by Brubaker (1972), lists twenty-three environmental problems in order of ascending gravity.

Amenity Considerations	Human Health Effects	Human Genetic and Reproductive Effects	Effects on Ecological System and the Earth's Life Supportive Capacity
Litter	Air pollution-combustion products	Radioactivity	Human occupancy of biospace
Noise	Water pollution:	Pesticides	Ocean threats:
Odor	Pathogens	Industrial chemicals	Pesticides
Air, visibility aspects	Nitrates		Oil
Water quality, recreational aspects	Industrial chemicals		Other chemicals
City, aesthetic aspects	Pesticides (through food chain)		Erosion
City, convenience and efficiency aspects	Radioactivity		Fertilizers and damage to mineral cycling
Country, aesthetic aspects	Heavy metals		CO_2, albedo, and climate
Access to country and nature			Heat rejection, local aspect and global aspect

Figure 6-1 A spectrum of environmental problems associated with demographic and material growth
Source: Brubaker 1972, pp. 186–188.

Many of the problems listed in Figure 6-1 either are unrelated to variables in World3 or are dealt with in other sectors of the global model. For example, none of the problems listed as amenity considerations have any direct influence on the variables included in World3; the effects of pathogens or of air and water pollutants on human health are highly dependent on population density and thus are dealt with in the population sector through the lifetime multiplier from crowding; the effects of erosion and air pollution on agricultural productivity are represented in the agriculture sector; and the effects of thermal emissions or of increases in atmospheric carbon dioxide (CO_2) or albedo on long-term global weather patterns will most likely manifest themselves over a time period greater than that of interest in our study and thus were excluded from our analysis.

When these problems are subtracted from those listed in Figure 6-1, there still remains a substantial group of material pollutants of potential importance to the world system over the next hundred years. The long-term behavior of these pollutants has been modeled explicitly in the World3 pollution sector. These persistent material pollutants include industrial and agricultural chemicals, radioactive isotopes, and heavy metals. Although few time-series data on the effects of these materials are available, and comprehensive cross-sectional data are nonexistent, the dynamic effects of persistent materials in the world system appear to be similar in several important ways:

1. Each is released through industrial or agricultural activity.
2. The impact of each material on man or the ecosystem has already been proved adverse in local areas.
3. Each material has been dispersed around the globe.
4. Each persists long enough to influence the components of the biosphere for years or decades once it is released into the environment.

The impact of persistent, man-made pollutants on the global biosphere will depend on both the pollutants' total level and the changing chemical composition of that level over time. The future mix of pollutants may be changed relatively rapidly in response to factors not explicitly represented in World3. It is certainly impossible to predict that mix in advance, especially since society has not yet identified all the components of the present stream of effluents that are persistent material pollutants—new ones are frequently discovered. Because the mix of pollutants is so indeterminate, the pollution sector is restricted to an aggregated representation of the globe's persistent pollution burden. We did not differentiate among specific materials but constructed the model to represent one generalized persistent pollution level. Our inability to make any precise statements about the composition of pollutants over the long term and the scarcity of comprehensive data on the long-term effects of persistent materials decidedly lessened the number of meaningful assumptions that could be incorporated in the pollution sector. Thus this sector of World3 is much less complex than the sectors representing global population, agriculture, and industrial and service output.

An aggregated model of pollution cannot be used to make precise forecasts of the levels and impacts of specific materials, nor is it useful in describing the current "quality" of the environment. Instead, the purpose of the persistent pollution sector is to represent in general terms the dynamic characteristics of the physical processes governing the generation, transportation, concentration, and assimilation of persistent, harmful materials that are released through agricultural and industrial activities. Our primary objective was to provide a conceptual dynamic structure that could capture the qualitative behavior of persistent pollutants in the world system.

Even as a very general model, the pollution sector addresses several important questions:

1. If material output and population continue to grow, what could be the global impact of future persistent material burdens on the behavior of other sectors in the world system?
2. Can technological programs, initiated in response to perceived pollution levels, be implemented in time to avoid substantial damage from the presence of persistent materials?
3. What effects on the ultimate global pollution level might be caused by various delays in society's efforts to stop the increase in the generation of persistent pollutants after the level has passed some critical threshhold?

4. What could happen to pollution levels if the natural pollution absorption mechanisms of the ecosystem were themselves degraded by pollution?
5. How sensitive is any estimate of future relative pollution levels to errors in assumptions about the magnitude of important delays and coefficients in the persistent pollution sector?

The answers to these questions depend both on the underlying geological and biological characteristics of the global ecosystem and on the nature of future social goals, decisions, and technological achievements. Although they are not yet fully understood, the physical characteristics do, in theory, lend themselves to prediction. But there is no possibility of predicting long-term social responses with great accuracy. Heightened social concern, more stringent legislation, and improved technologies can be expected to influence the future location, level, and composition of persistent pollution. Technological change may alleviate or exacerbate future pollution problems in ways that cannot currently be anticipated. Thus we represented the physical determinants of pollutant flows endogenously in the pollution sector and tested the future effects of conceivable changes in social and technical policies through exogenous changes in the model's structure and coefficients. As a consequence of omitting explicit assumptions about changes in society's response to pollution, none of the outputs of this sector can be used as the basis for a prediction of what *will* happen. The model can only lead to such statements as, "*If* these values, policies, and technologies are adopted, the most likely behavior of the system will be. . . ." Although the sector as modeled cannot be used to identify optimal pollution policies, it can indicate many policies that will not have the desired effects.

In this chapter we first present empirical data illustrating the observed behavior modes of persistent pollutants in the world system (section 6.2). We then provide a set of basic concepts that define persistent pollutants and the determinants of their dynamic behavior (section 6.3). The precise causal relationships of the World3 persistent pollution sector are then expressed graphically and in equation form in sections 6.4 and 6.5. In section 6.6 we present eighteen computer runs of the pollution sector with exogenous changes in its structure and coefficients. Simulations of the equations in this sector are presented to illustrate the behavior of the World3 pollution sector in response to different patterns of economic activity and population growth. Since the range of plausible values for each parameter is so large; sensitivity analyses are particularly important in the pollution sector. The influence of each parameter on the sector's behavior is thus tested to identify the most critical areas for further research. Finally we test the effectiveness of alternative policy responses to rising pollution and the damage it produces.

6.2 HISTORICAL BEHAVIOR MODES

Four dynamic attributes appear to characterize nearly all known persistent pollutants:

1. They are generated at increasing rates by industry and agriculture.
2. Their accumulated level in the global environment is increasing.

3. There is a significant delay between the time they are released into the environment and the time their full effects on the ecosystem finally appear.
4. They are concentrated as they pass to higher trophic levels in terrestrial and aquatic food chains.

Increasing Generation of Persistent Pollutants

Materials such as pesticides, chemical fertilizers, petroleum by-products, and heavy metals are widely used in the production of food and industrial goods. With rising population and technological advance, the number and the quantity of the materials being used has increased substantially. Figure 6-2 illustrates the historical global production of six toxic heavy metals: chromium, lead, nickel, mercury, cadmium, and arsenic. The production of these materials increased an average of about 350 percent between 1945 and 1970, or 5 percent per year during that period. Over the fifteen-year period 1951–1966, global phosphate, nitrate, and pesticide use increased 75 percent, 146 percent, and 300 percent, respectively (SCEP 1970, p. 118). Global petroleum use has exhibited a historical increase of about 6 percent per year. The generation of radioactive materials as inputs to and by-products of energy production will expand enormously for at least the next thirty years. The projections summarized in Figure 6-3 suggest that the growth rate in nuclear waste generation will be between 15 and 20 percent per year over the foreseeable future.

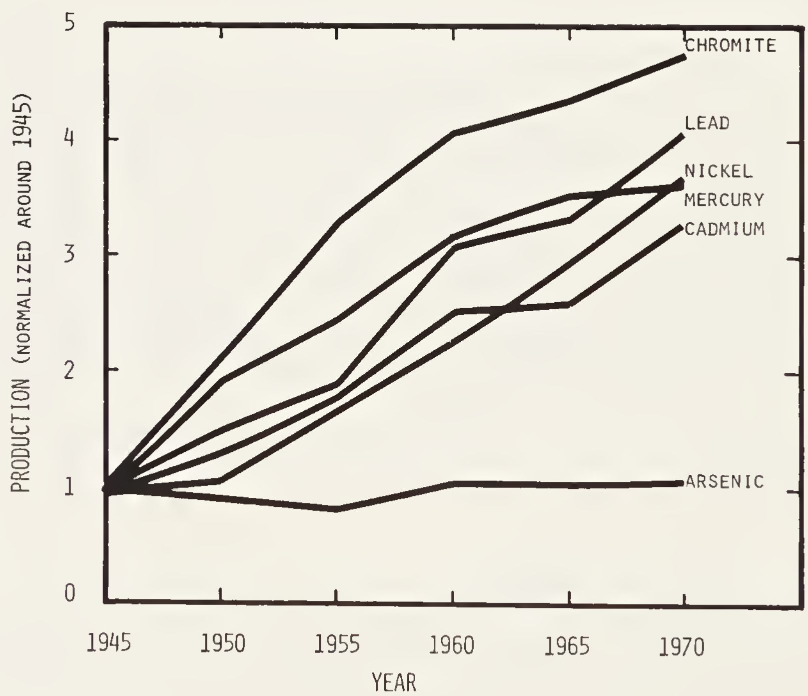


Figure 6-2 Growth in the global production of six toxic heavy metals, 1945–1970
Source: Production data from *Commodity Yearbook* 1950–1970.

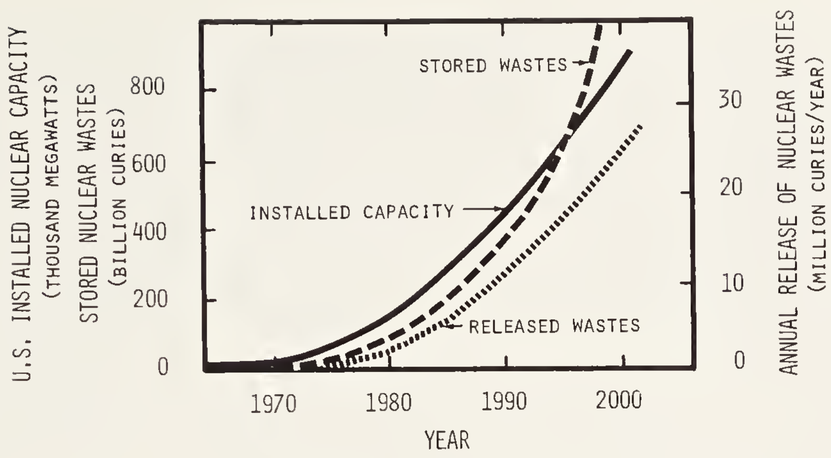


Figure 6-3 Projected generation of radioactive wastes from the operation of U.S. nuclear power plants, 1970–2000

Sources: Installed capacity to 1975 from AEC 1971; installed capacity to 2000 from Starr 1971; stored nuclear wastes calculated from specifications for 1.6-thousand megawatt plant in Calvert Cliffs, Maryland.

It is generally anticipated that these trends will continue. Even if the per capita consumption rates were to remain constant, the projected growth in population would bring substantial increases in the production of persistent materials. However, three factors combine to increase their use at an even faster rate than the rate of population growth alone. First, increasing affluence leads each individual to demand more energy, food, and material goods. For example, global annual petroleum production is expected to reach four times its 1960 level by 1980, although the global population will not quite double over that period (Figure 6-4).

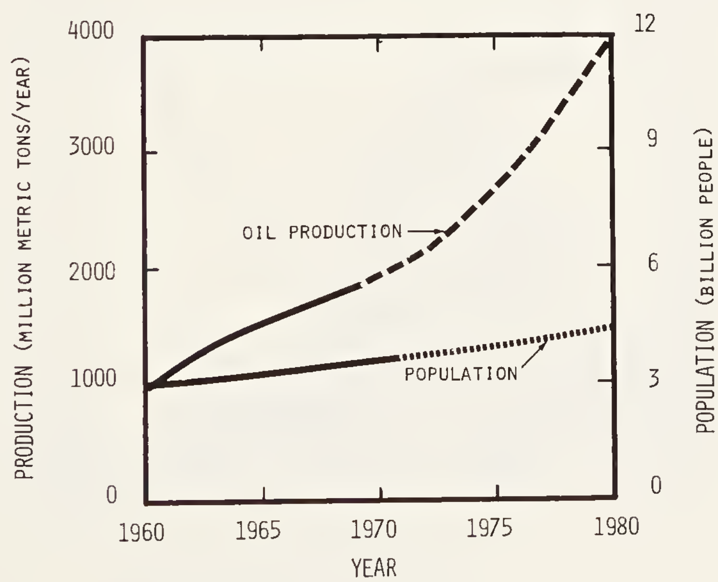


Figure 6-4 Actual and projected global crude oil production and human population, 1960–1980

Sources: Oil production data from SCEP 1970, p. 266; population data from U.N. 1969, p. xxvii.

Second, constraints on the supply of some productive factors will cause increases in the use of other material inputs proportionately far greater than the increase in the total product. An important example of this influence is found in the production of food. Because arable land is in short supply in most nations, increases in chemical and capital inputs do not produce proportional gains in food production. During the period 1951–1966 world food production increased only 34 percent, far less than the 75–300 percent increases in the inputs of phosphate, nitrates, and pesticides mentioned (SCEP 1970, p. 118). These trends may continue, for Figure 6-5 illustrates the sixfold increase in pesticide use expected to be necessary to double the present global food production, an increase that must be achieved within thirty years to maintain even the current inadequate food standards.

Third, man-made materials are often longer-lived and potentially more harmful than the natural materials they replace. On the basis of research on the product substitutions that have occurred over the past twenty-five years, Commoner has concluded:

> Evidence leads to the general conclusion that in most of the technological displacements which have accompanied the growth of the United States economy since 1946, the new technology has an appreciably greater environmental impact than the technology which it has displaced.[Commoner 1972]

The substitution of radioisotopes for fossil fuels, synthetic fibers for wool and cotton, detergents for soap, and plastics for paper and wood are examples of this third factor

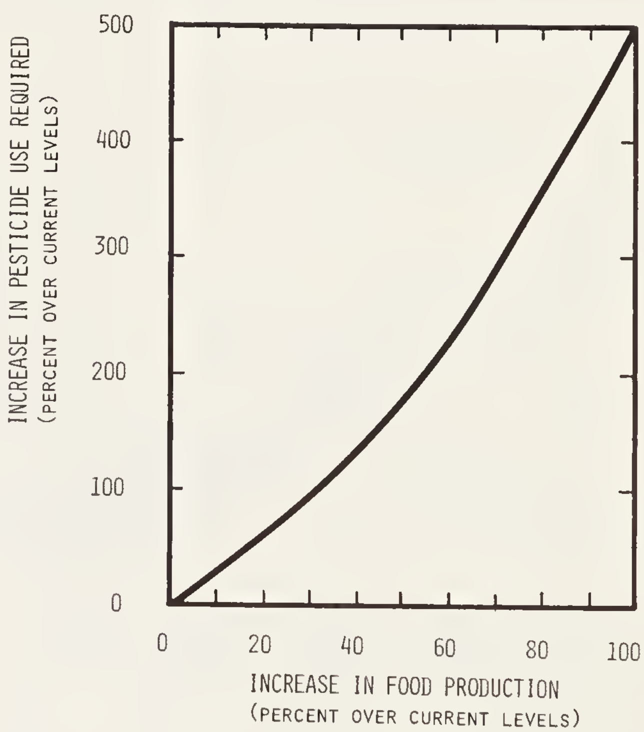


Figure 6-5 Pesticides required to increase food production on land now under cultivation in Africa, Latin America, and Asia (except mainland China and Japan) Source: Data from SCEP 1970, p. 282.

contributing to an increase in the use of persistent materials proportionately far greater than the increase in population or economic activity.

An increase in the production and use of persistent materials is, in itself, not a sufficient cause for concern. Damage will result only if the materials are toxic, released to the environment, transported to a sensitive part of the biosystem, and sufficiently concentrated to interfere with natural biological processes. Thus any assessment of global pollution must also examine historical patterns associated with the transmission and the concentration of persistent materials.

Transmission Delays

The movement of materials through the global ecosystem is governed by the physics of particulate and molecular transportation in water and air streams and by the biological processes of absorption and degradation in living tissues. None of these processes act on the total quantity of any pollutant instantaneously. Often they act in sequence as the material is transported through the environment and within each food chain. Thus one would expect to observe a transmission delay between the time a persistent pollutant is released into the environment and the time it appears elsewhere in the ecosystem. The delay should depend both on the geographical distance and on the number of trophic levels involved.

When the geographical distances involved are large the transmission delays may be several years in length. One illustration of a persistent pollutant transmission delay is shown in Figure 6-6, where data on the annual level of strontium-90 (Sr-90) in New York City drinking water are compared with a tally of worldwide atmospheric nuclear tests. The figure suggests delay of about two years between the peak in the

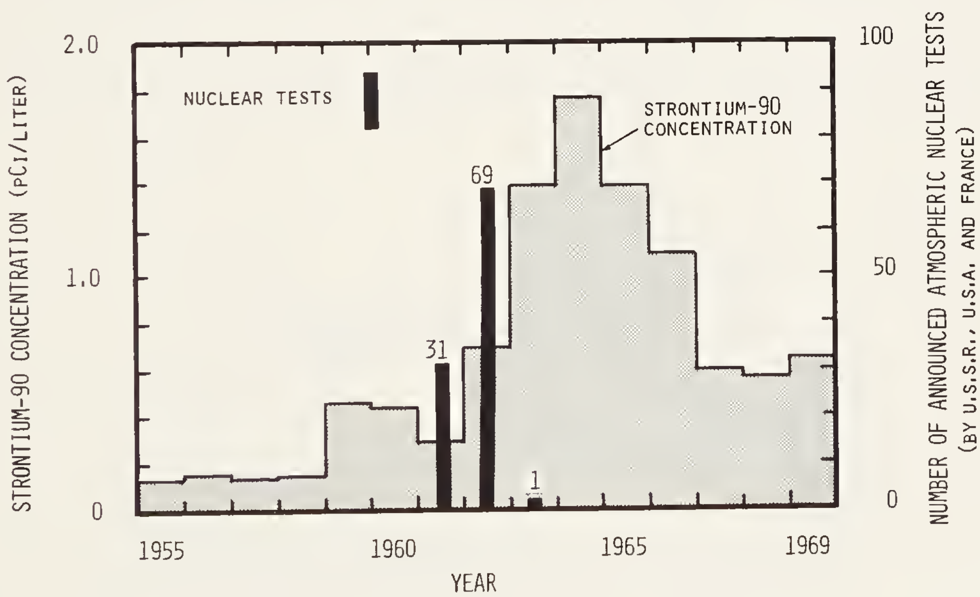


Figure 6-6 Yearly average strontium-90 concentrations in New York City drinking water, 1955–1970, versus number of announced atmospheric nuclear tests by the United States, the USSR, and France, 1961–1963

Sources: Data on number of tests from Facts 1964; water contamination data from EPA 1972.

number of tests and the maximum level of strontium-90 in the water. The time involved in the concentration of the pollutant in various life forms also adds to the total transmission delay. Because strontium-90 tends to be absorbed and eliminated very slowly from the human body, there would be an even longer delay between the date on which the greatest amount of the isotope was released into the environment and the time at which the concentration of strontium-90 would reach its maximum level in the body tissues of humans who had drunk the contaminated water.

The delay associated with movements through a food chain is illustrated by another study of persistent radioactive materials, one in which the materials are traced as they move up several trophic levels in a very confined ecosystem. In Figure 6-7 the radioactive material fed into a forest plant is shown to reach its maximum level 1.0 week after the start of the experiment. The concentration of radioactive pollutant in herbivores feeding on the plant peaks one week later, while the level of radioactivity in the predators that consume the herbivores is still rising after 6.0 weeks, five weeks after the peak in the application of the material.

Persistent chemicals exhibit transmission delays similar to those observed in radioactive materials. The authors of two studies of DDT flows have pointed to the delays inherent in the transport of that pesticide through air and water (Harrison et al. 1970, Woodwell et al. 1971). Our simulation substudies of DDT and mercury also provide information on the transmission delays associated with the movement of these materials through the global environment. Simulations of our two submodels are presented

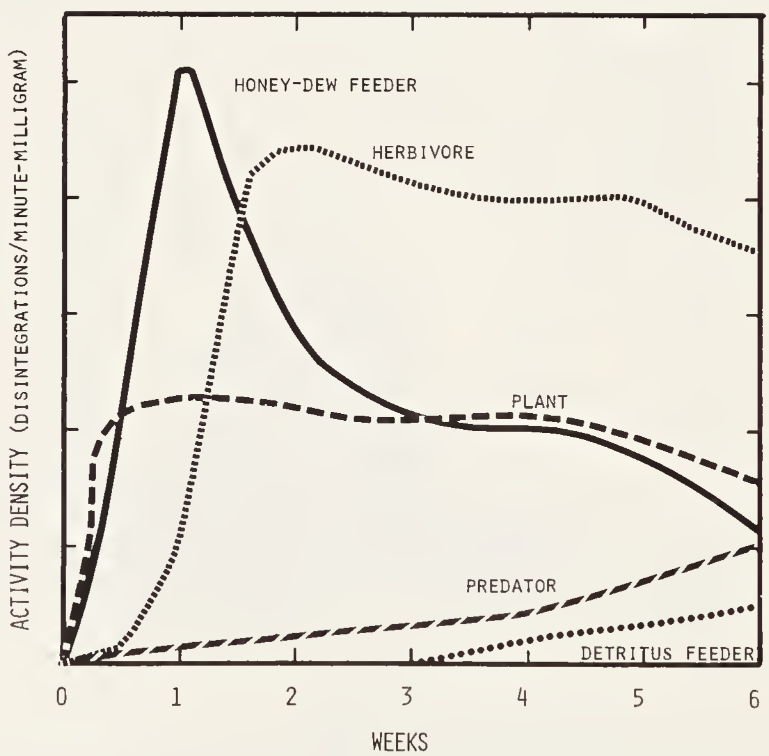


Figure 6-7 Levels of radioactivity present in different species over time after application of a radioisotope to one plant in a small ecosystem
Source: Odum 1971, p. 462.

later in this chapter to supplement the preceding information as a basis for estimating an appropriate range of transmission delays for inclusion in the world model pollution sector.

Geological and biological factors are not the only sources of delays influencing the flow of persistent materials through the global ecosystem. Social delays in identifying pollution problems, designing appropriate responses, obtaining social consensus on the need to act, and implementing decisions also influence the level of persistent pollution present at any time. Social delays are not incorporated explicitly in the standard pollution sector of World3, but they are added to the model in several of the runs of section 6.6 where we analyze the relative effectiveness of alternative pollution control policies.

Biological Concentration of Persistent Materials

The third widely observed pattern in the behavior of persistent materials is the tendency of organisms at each level in a food chain to concentrate persistent materials, so that concentrations in species at the top of the chain may be far above ambient levels. Figure 6-8 summarizes data on strontium-90 levels in various parts of a freshwater ecosystem after low-level radioactive wastes were introduced into the water of a nearby lake. After equilibrium was attained, the higher species on the food chain were found to have concentrations of strontium-90 between 1,000 and 3,900 times those found in the water. The data presented in Figure 6-9 reveal a similar behavior in the concentration of DDT.

Man occupies a comparatively high position on both aquatic and terrestrial food chains. Thus his own body load of persistent materials will generally be much greater than the ambient level. This fact is illustrated by the levels of DDT found in human adipose tissue. Various studies of human tissue have found DDT residues present in concentrations between 2.3 parts per million by weight (ppm) in Germany in 1958 and 26 ppm in India in 1964 (Wayland 1966). The latter concentration is higher than

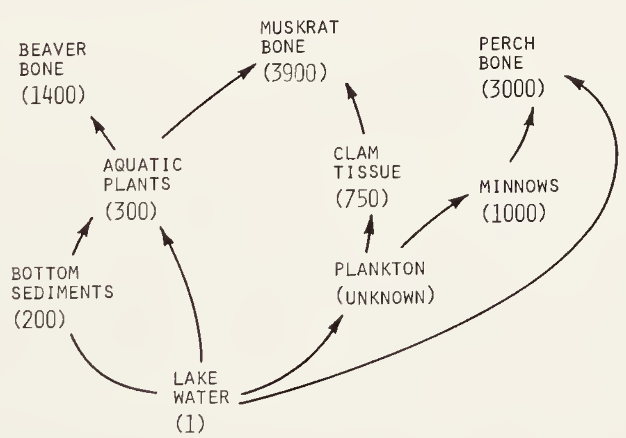


Figure 6-8 Concentrations of strontium-90 in various trophic levels of a small lake contaminated with low-level atomic wastes (average strontium-90 concentrations are expressed relative to the level of the isotope in lake water)
Source: Odum 1971, p. 460.

Level	Organism	DDT Concentration (parts per million)
Level 1	Water plant	0.08
	Plankton	0.04
	Marsh plants:	
	shoots	0.33
	roots	2.80
Level 2	Cricket	0.23
	Mosquito	0.30
	Clam	0.42
	Mud snail	0.26
	Bay shrimp	0.16
	Silversides	0.23
	Eel	0.28
	Fluke	1.28
	Blowfish	0.17
	Minnow	0.94 to 1.24
Level 3	Billfish	2.07
	Terns	3.15 to 6.40
	Osprey egg	13.8
	Green heron	3.57
	Merganser	22.8
	Cormorant	26.4
	Gulls	3.52 to 75.5

Figure 6-9 Concentration (parts per million) of DDT in three trophic levels of a Long Island, New York, estuary
Source: Woodwell et al. 1967.

those found in most of the species listed in Figure 6-9. This tendency to concentrate persistent materials above ambient levels is particularly important since environmental levels appear to be increasing.

Rising Ambient Persistent Pollutant Levels

Many of the potentially harmful materials in industrial and agricultural production have essentially no impact on the global environment. They degrade quickly into harmless products or are isolated and disposed of permanently before they can enter global air or water streams or be incorporated in living tissues. A persistent material must be present widely and in significant quantities before it has a potential for global damage. The fourth historical behavior mode, an apparent general increase in the environmental level of persistent materials, is thus of special interest.

Time-series data are not available for many indices of the global persistent pollution load. However, where data do exist, they suggest rapid and widespread increases in the level of pollution. Lead and mercury concentrations in the Greenland icecap appear to have been increasing for at least the past several decades (Murozumi et al. 1969, Weiss et al. 1971). An analysis of successive rings in United States elm trees revealed a marked secular rise in lead concentrations. The rings added to trees during 1900–1910 were found to contain 0.12 ppm of lead, those from 1940–1947 contained 0.33 ppm, and those added during 1956–1959 contained 0.74 ppm (Schroeder and Balassa 1961).

The concentration of dissolved solids in fresh water is rising. In Lake Ontario, for example, the level of materials in solution has increased from 130 ppm in 1910 to 200 ppm in 1970 (Beeton 1970). In this case the growth in ambient levels will probably continue. An exhaustive study of future material flows in the U.S. environment employed a variety of assumptions about possible changes in the rate of population and economic growth and about the urgency with which abatement techniques will be developed. Under the most favorable assumptions, dissolved solids in U.S. water supplies would increase by 60 percent between 1970 and 2000. Under the least optimistic set of assumptions, the increase would be over 160 percent (Ridker 1972). The report did not present similar data on the possible abatement for other persistent pollutants. However, the analysis of shorter-lived materials is encouraging. With reduced rates of population and GNP growth and with strenuous abatement policies, many important classes of short-lived pollution, particularly air pollution, may be reduced in the United States before the year 2000 to levels lower than those existing in 1970.

The level of persistent materials in the ocean appears to be rising. A recent survey of marine contamination off the south and east coasts of the United States revealed that

> contamination covered 50 percent (80,000 square miles) of the survey area along the East Coast continental shelf; 80 percent (280,000 square miles) of the survey area in the Caribbean to the Gulf of Mexico; and 90 percent (305,000 square miles) of the survey area north of the Antillean chain. [NYT 1973]

The ubiquity of the increase in pollutants is illustrated by the presence of DDT in the Greenland icecap and by measurements of DDT residues in the body tissues of humans around the world. DDT was first applied in significant quantities in 1940. (Before 1940 there was, of course, no DDT anywhere in the ecosystem.) Evidence now suggests that the vast majority of all humans carry DDT residues in their body tissues (Wayland 1966). PCBs, another family of synthetic chemicals, have also been found in increasing amounts in the tissues of humans around the world (Jensen 1972).

Except for the synthetic chemicals, most persistent materials are also released to the global environment through natural sources. Many of the heavy metals are even required in trace amounts to support some life forms. However, there is no reason to believe that the natural emissions of persistent pollutants are increasing while, as we have already mentioned, human use of these materials is increasing rapidly. In fact, the amounts of at least 13 materials released into the globe's freshwater streams by man are already greater than the quantities of these materials released through natural processes (SCEP 1970, p. 116). It is clear that man's activities are the prime contributor to the increasing accumulation of persistent pollutants in the biosphere.

Materials released into the environment do not remain there forever to cause damage. Most materials are ultimately assimilated by the environment, that is, they are converted chemically or stored so that they cause no further harm. If the assimilation of these materials took place instantaneously, significant ambient levels would never be observed. One of the defining characteristics of persistent pollutants is that their assimilation proceeds relatively slowly. In the next section we discuss the important dynamic determinants of this assimilative process.

6.3 BASIC CONCEPTS

Fundamental Postulates of the Sector

The concept of pollution is intimately related to entropy and energy flows. One may usefully define a pollutant as a displaced natural resource whose entropy is so great that it can no longer be reclaimed economically. The entropy of a closed system will inevitably increase. We believe that the earth may be considered to be a closed system insofar as pollution is concerned. Thus we assumed in the persistent pollution sector that:

1. Materials will inevitably be released to the environment through man's industrial and agricultural activities; and the generation of pollution will tend to increase with growth in the physical scale of man's activities.
2. The global biosphere has only a finite capacity to degrade, that is, to assimilate, persistent materials.

Other considerations led us to postulate that:

3. There is a delay between the time a persistent material is first released into the environment and the time its full effects are felt in the biosphere.
4. The rate of assimilation of persistent materials is proportional to the quantity of such materials present in the environment.

Definition of Persistent Pollution

The term "pollution" is commonly used to denote any material or energy stream that either disrupts the natural processes of the ecosystem or impairs the aesthetic qualities of the environment. Thus DDT, particulate matter in the air, discarded aluminum beer cans, noise, and thermal emissions have all been identified as pollutants. Indices of the level of pollution are correspondingly diverse. Parts per million, particles per cubic meter, cans per acre, decibels, and British thermal units, respectively, might be used to measure these pollutants. In the world model our objectives required a much more restrictive definition of pollution and a more general measure of pollution quantities.

In the persistent pollution sector we focused on materials that may have a significant negative impact on the global biosphere, that is, on animal and plant life in all regions of the world, within the next hundred years. Thus we included only materials that cause damage to some form of life, are released through many different forms of industrial and agricultural activity, and are sufficiently long-lived that they may be transported through the global environment by the planet's air or water streams. We use the phrase "persistent pollutants" to denote this general class of materials. Our focus is similar to that adopted by the 1970 Study of Critical Environmental Problems (SCEP 1970), but our attention was directed to the implications of these materials for human health and soil fertility.

Because of the long time perspective of the model, we did not focus on a set of specific materials. Some of the current global persistent pollutants will be eliminated over the next hundred years. For example, there is already strong pressure to replace DDT with other, less stable chemical compounds, and new materials will also be added to the list of global hazards. Man creates many new materials every year and often discovers that substances already in wide use have harmful effects. Thus we formulated the persistent pollution sector to represent the generation, transmission, concentration, and assimilation of materials with common dynamic attributes rather than with specific chemical identities. Six families of materials that exemplify the general class of materials represented in the pollution sector are radioactive wastes; heavy metals; suspended particulates and aerosols, including asbestos; fertilizers; pesticides; and other persistent synthetic chemicals.

Our definition of pollution permits only an imprecise specification of the units by which to measure persistent pollution levels and flows. The absolute level of persistent pollution in the model and the flows of pollutants are measured in units derived from nonrenewable resource units and agricultural input units and are weighted according to their toxicity. The index used to relate the level of pollution to life expectancy, soil fertility, and the pollution assimilation half-life is not an absolute measure. It is, instead, expressed in relative terms, or "index units." One index unit is any quantity and mix of persistent materials equivalent in biological impact to the total of all persistent materials present in the environment in 1970. Thus the index of pollution in any year equals the level of persistent pollution in that year, a variable, divided by the level of persistent pollution in 1970, a constant. Obviously, any variable related to persistent pollution will also be related to the persistent pollution index.

Pollution levels of many different magnitudes and compositions can have the same biological impact and thus be equal when measured in index units. Because of our definition, changing the chemical mix of one index unit of pollution may alter the dynamic behavior of the pollution's transmission and degradation, but its eventual biological impact would, by definition, remain the same. Since an index unit of pollution can have different transmission delays and different assimilation rates at different times, conclusions derived from World3 had to be valid for a wide range of values for these two parameters.

Assimilative Capacity of the Global Environment

The level of pollution in World3 represents the accumulation of all persistent materials in areas where they can cause damage to human health, food-producing species, or the soil. Thus materials in the air, in water, in topsoil, and in living tissues are all represented by this level. Once they appear in the environment, materials remain in the persistent pollution level until they are assimilated, that is, altered chemically or permanently sequestered so that they can cause no further harm to any life form.

Assimilation in the real world occurs in three general ways: nuclear disintegration, deposition, and degradation. Radioactive materials disintegrate; particulates and chemicals absorbed on soil particles may be deposited where they cause no harm; and chemicals and solid waste may be degraded through a chemical reaction, such as oxidation, or by some natural biochemical process. A useful measure of the rate at which a material disappears from the environment is the material's assimilation half-life, which is the period of time required for half of the initial amount of the material to disappear from the environment.

The half-life of any material assimilated by disintegration or deposition is essentially constant and a function of the material and the physical processes involved. The half-life of a chemically or biologically degraded material may, however, depend upon the quantity of the material present. In biological or chemical degradation, some substrate plays the role of initiating the breakdown of a pollutant. Chemical kinetic considerations can be used to show that the degradation half-life of a material may increase with its concentration. This effect is compounded if increases in the pollutant actually poison the degradative system, decreasing the effectiveness of the degrading substrates.

The Function of Technology in the Persistent Pollution Sector

The amount of pollution present in the ecosystem can be altered by changing the persistent pollution generation, appearance, or assimilation rate. The harm caused by persistent materials can be altered by changing the composition or the location of pollutants in the environment. New technical capabilities can be expected to affect each of these factors in varying degrees, depending upon the mix of pollutants present. Any technology developed in response to observed environmental damage will presumably decrease the rate of generation, increase the transmission delay, and decrease the effective assimilation half-life. Technologies developed for other purposes, such as increased food production or resource extraction, may inadvertently have the opposite effects. In analyzing the persistent pollution sector of the world model, we examined the effects of the possible results of different technological advances:

1. Decreasing the amount of pollution generated at any level of industrial and agricultural output. This change would correspond to a change in production processes or to improved emission controls.
2. Increasing the delay between the time the pollution is generated and the time its full impact is felt in the biosphere. This change could be brought about by, for example, transferring industrial operations to remote localities or by improving the storage facilities for nuclear and other wastes.
3. Increasing the rate at which the pollution is assimilated. This change represents the impact of such measures as the oxygenation of waste-bearing water or the substitution of shorter-lived chemicals for persistent pesticides.

4. Reducing the effects of persistent pollution on land fertility or on the average life expectancy of the population. This change represents a decrease in the average toxicity of effluents.

6.4 CAUSAL STRUCTURE

The preceding sections have described several concepts that appear to be important in governing the amount of persistent materials present in the environment over the long term. In the persistent pollution sector of World3 we employed the following set of assumptions to interrelate these concepts:

1. Persistent pollution is generated as a result of industrial and agricultural activities—the greater the per capita use of nonrenewable resources by industry, the greater the pollution generated each year per capita; the greater the capital intensity of agricultural production, the greater the persistent pollution generated per cultivated hectare per year.
2. There is a delay between the time a persistent material is generated and the time its full impact is exerted on the biosphere. A "transmission delay" contains materials that have been generated but have not yet fully affected the biosphere. As materials are transferred from the transmission delay to the level of accumulated pollution, they begin to affect plant and animal life.
3. The amount of accumulated pollution is determined by the integration of the difference between past rates of pollution appearance and pollution assimilation.
4. The amount of pollution assimilated per time period is directly proportional to the total accumulated level of pollution and inversely proportional to the assimilation half-life. Materials destined to be assimilated before they affect the biosphere are simply not counted in the calculation of the pollution generation rate.
5. The assimilation half-life of pollution may increase as the total level of pollution increases.

These assumptions are represented in the causal-loop structure shown in Figure 6-10. The causal links connecting the persistent pollution sector with the other sectors of World3 are represented by dashed arrows in that figure. The equations describing the generation and flow of persistent pollution are presented in this chapter; the equations describing the effects of accumulated persistent pollution on the human population and on agricultural productivity are presented in Chapters 2 and 4, respectively.

The causal relationships influencing persistent pollution generation are not involved in any feedback loop internal to this sector. Pollution generation is assumed to increase if population, agricultural inputs per hectare, arable land, or per capita resource usage increases (see Chapters 2, 4, and 5 for descriptions of these variables). The effects of these four variables are modified by a set of five parameters that represents the fractions of industrial resources and of capital inputs to agriculture that are persistent materials, the toxicity of the industrial and agricultural materials

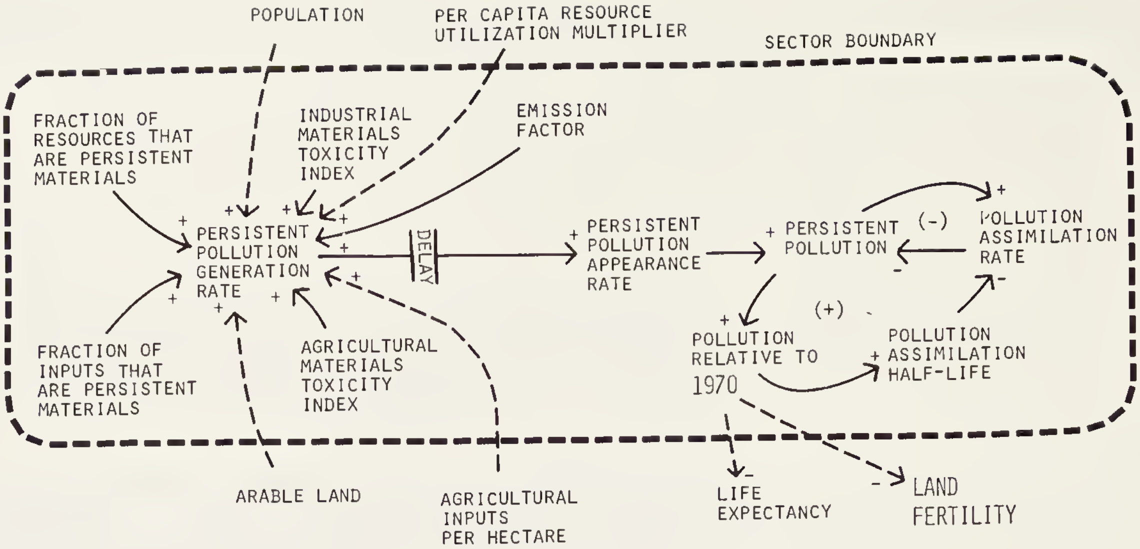


Figure 6-10 Causal-loop structure of the pollution sector

used, and the fraction of resources used in industry and agriculture that is emitted into the environment.

The effects of persistent pollution on the biosphere are not immediately influenced by the persistent pollution generation rate. As explained earlier, the physical and biological properties of material transportation and concentration introduce a delay between the time a pollutant is released and the time it is located and concentrated in ways that decrease human life or soil fertility. The transmission delay incorporates in World3 the lagged effects of both concentration and transmission.

The total level of persistent materials in the environment is the sum of the pollution level and the contents of the transmission delay. The pollution level is simply the integration of all past differences between the appearance and the assimilation of persistent materials. The behavior of pollution assimilation is determined by the two feedback loops shown in Figure 6-10. Consider first the negative feedback loop. If pollution rises and the assimilation half-life remains constant, the rate of pollution assimilation will also rise; as the rate of pollution assimilation rises, pollution will tend to decrease. This negative feedback loop constitutes a control mechanism that acts to decrease the level of persistent pollution to zero. It is dynamically analogous to the population–death rate loop in the population sector and to the depreciation relationships influencing industrial and service capital.

The second feedback loop has no analogue elsewhere in the model. Since this loop is positive, it tends to amplify any rise in pollution. Rising pollution lengthens the assimilation half-life by interfering with natural degradative processes; the increase in the half-life depresses the pollution assimilation rate and reinforces the rise in pollution. Since the negative loop will always dominate the positive loop, the endogenous behavior of the pollution sector is exponential decay in the level of pollution. The positive loop simply determines the time constant of that decay. The relationships enclosed within the dashed line of Figure 6-10 are defined in section 6.5. The effects of pollution on life expectancy and land fertility are described in

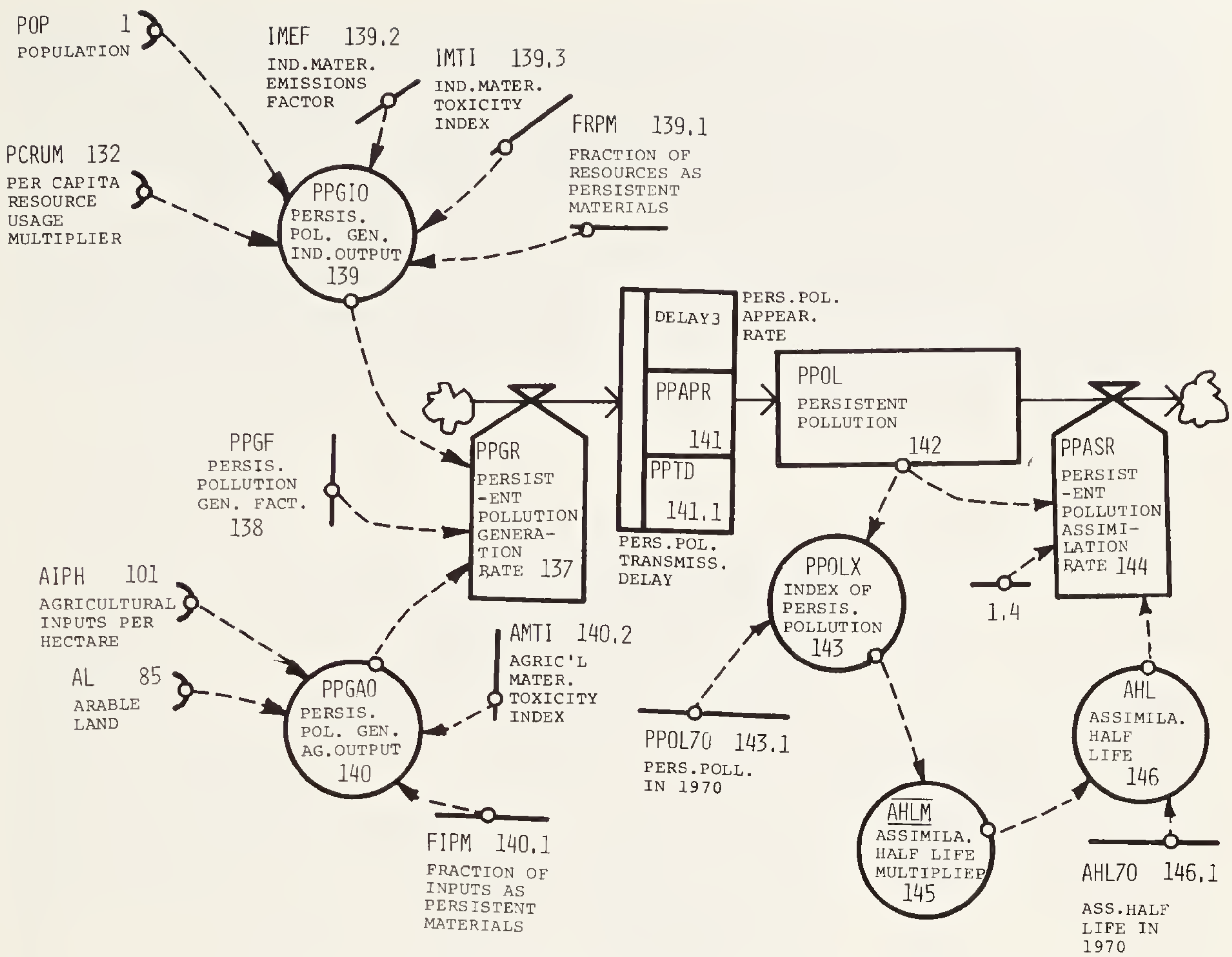


Figure 6-11 DYNAMO flow diagram of the pollution sector

Chapters 2 and 4, respectively. The full DYNAMO flow diagram of the relationships in the pollution sector is shown in Figure 6-11.

6.5 DESCRIPTION OF EQUATIONS

In this section the DYNAMO equations for the persistent pollution sector are explained in detail. In the discussion we shall employ data from case studies presented in the literature, a theoretical model of pollution assimilation, and two of our pollution substudies (Randers 1973, Anderson et al. 1973). These substudies illustrate in more detail the dynamic behavior of two materials, DDT and mercury, representing general classes of persistent pollutants, pesticides, and heavy metals.

Persistent Pollution Generation Rate PPGR Although persistent pollutants may sometimes be chemically similar, there is a fundamental dynamic difference between those resulting from industrial activity and those released in the production of food. The first are inadvertent wastes that are released into the environment by accident or because no one is willing to pay the cost of abatement. Industrial emissions are often composed of materials that would have some economic value if they were available as inputs to further production. Agricultural pollution, on the other hand, is a consequence of the deliberate dispersal of materials in the environment. Pesticides and fertilizers are useful to farmers only when they are present in sufficient concentration in specific areas of the environment. As a result, both the current causes and the future control of the two pollutant streams involve radically different procedures and incentives. We therefore separated the generation of persistent pollutants into two categories: persistent pollutants generated from industrial output PPGIO and persistent pollutants generated from agricultural output PPGAO. The persistent pollution generation rate PPGR is the sum of PPGIO and PPGAO.

```
PPGR.KL=(PPGIO.K+PPGAO.K)*(PPGF.K)                        137, R
    PPGR   - PERSISTENT POLLUTION GENERATION RATE
               (POLLUTION UNITS/YEAR)
    PPGIO  - PERSISTENT POLLUTION GENERATED BY
               INDUSTRIAL OUTPUT (POLLUTION UNITS/YEAR)
    PPGAO  - PERSISTENT POLLUTION GENERATED BY
               AGRICULTURAL OUTPUT (POLLUTIONUNITS/YEAR)
    PPGF   - PERSISTENT POLLUTION GENERATION FACTOR
               (DIMENSIONLESS)

PPGF.K=CLIP(PPGF2,PPGF1,TIME.K,PYEAR)                     138, A
PPGF1=1                                                   138.1, C
PPGF2=1                                                   138.2, C
    PPGF   - PERSISTENT POLLUTION GENERATION FACTOR
               (DIMENSIONLESS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    PPGF2  - PPGF, VALUE AFTER TIME=PYEAR
               (DIMENSIONLESS)
    PPGF1  - PPGF, VALUE BEFORE TIME=PYEAR
               (DIMENSIONLESS)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
```

To assist the analyst in testing the effects of alternative control policies, a persistent pollution generation factor PPGF is included in the equation for the persistent pollution generation rate PPGR. When TIME equals the chosen policy year PYEAR, the value of PPGF shifts from PPGF1 to PPGF2. Under normal circumstances both parameters will be equal to 1.0 and PPGF will not influence the behavior of the model. Reducing PPGF below 1.0 during a simulation corresponds to introducing pollution abatement procedures in industry and agriculture that do not decrease resource consumption. Thus PPGF should be decreased only to represent policies in which the normal effluent is converted to nontoxic, nonpersistent, or permanently sequestered material. A policy of capturing an effluent and recycling it into another use would reduce both the outflow and the net inflow of resources. A recycling policy should be represented by setting PPGF=1.0 and by setting NRUF<1.0 to reduce the resources used per capita.

Persistent Pollution Generated by Industrial Output PPGIO We defined the persistent pollution generated by industry PPGIO as the leakage of persistent materials into the environment from the flow of resources used in producing industrial output.

Since industrial output is consumed or invested in services and industry, persistent effluents from all three uses are included in PPGIO. For example, beryllium released to the environment through the smelting of metals (industry), mercury that escapes during the manufacture of paper (industry), mercury compounds released by medical laboratories (services), asbestos released from home insulation and brake linings (services), and insecticides consumed in home pest control (consumption) are all included in persistent pollution generated through industrial output.

The generic factors governing the rate of industrial pollution generation are:

1. The total usage rate of natural resources, that is, per capita resource usage times population (PCRUM×POP).
2. The fraction of the total resource flow that is in the form of persistent materials FRPM.
3. The fraction of the persistent material flow that is released into the environment, that is, the industrial materials emission factor IMEF.
4. The toxicity of the materials, that is, the industrial materials toxicity index IMTI.

If the product of the last three factors always equaled 1.0, we could link pollution generation directly to resource utilization. However, the persistent material fraction, the emission fraction, and the toxicity index can all vary independently from the total resource usage rate. Thus we chose not to represent the resource usage rate and the pollution generation rate as elements in a single, conserved material subsystem.

```
PPGIO.K=PCRUM.K*POP.K*FRPM*IMEF*IMTI                    139, A
FRPM=.02                                                 139.1, C
IMEF=.1                                                  139.2, C
IMTI=10                                                  139.3, C
    PPGIO   - PERSISTENT POLLUTION GENERATED BY
                INDUSTRIAL OUTPUT (POLLUTION UNITS/YEAR)
    PCRUM   - PER CAPITA RESOURCE USAGE MULTIPLIER
                (RESOURCE UNITS/PERSON-YEAR)
    POP     - POPULATION (PERSONS)
    FRPM    - FRACTION OF RESOURCES AS PERSISTENT
                MATERIALS (DIMENSIONLESS)
    IMEF    - INDUSTRIAL MATERIALS EMISSION FACTOR
                (DIMENSIONLESS)
    IMTI    - INDUSTRIAL MATERIALS TOXICITY INDEX
                (POLLUTION UNITS/RESOURCE UNIT)
```

The curve relating the per capita usage rate of nonrenewable resources PCRUM to industrial output per capita IOPC is described in Chapter 5. It is reproduced for reference as Figure 6-12. Because the curve is a nonlinear function of industrial output per capita, the persistent pollution generated by industrial output PPGIO cannot be expressed solely as a function of total industrial output. This important point may be illustrated by considering two hypothetical societies. One society has 10 people, an industrial output per capita of 1000 dollars per year, and thus an annual resource consumption of 6.2 units per person-year. The second has 100 people, with an annual industrial output per capita of 100 dollars per year and a yearly resource consumption of 0.42 units per person-year. Although the GNP of both societies is 10,000 dollars, the total resource consumption of the first society is about 1.5 times that of the second. If the persistent material fractions, the emission factors,

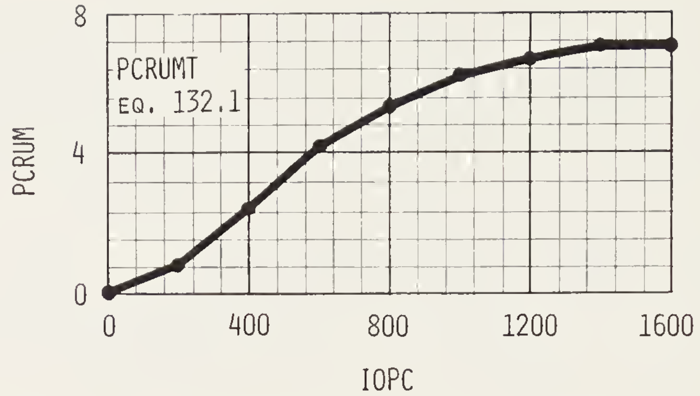


Figure 6-12 The relationship assumed, in Chapter 5, to exist between industrial output per capita and the annual per capita resource utilization.

and the toxicity indices of the two societies are equal, then the persistent pollution generation in the first society will be greater than that in the second.

While it is apparent that the industrial materials toxicity index IMTI, the industrial materials emission factor IMEF, and the fraction of resources that are persistent materials FRPM would have different values in industrialized and in agrarian societies, the lack of data, the long time horizon of the model, and their aggregated nature make it impossible to assign precise numerical values to the three parameters with great confidence. The following discussion thus aims primarily to provide an operational definition of the three factors in the equation defining persistent pollution generation from industrial output PPGIO and to illustrate the general considerations upon which their values depend. The discussion does not validate the set of exact numbers used for these three factors in the standard version of World3 model, but it does serve to establish the approximate magnitude of the real-world values.

To estimate the fraction of resources that is in the form of persistent materials FRPM, one might calculate the total weight of all materials produced in one year and then determine the relative fraction of the total that is composed of persistent materials. This calculation would require an analysis both of standard commodity production data and of those materials that are produced inadvertently. For example, the production of beryllium and other by-products in the smelting of metals is not included in published commodity production data. These by-products can be significant in absolute terms. For example, the mercury added each year to the environment through the combustion of fossil fuels is about 20 percent of the amount deliberately mined (Anderson et al. 1973).

Estimates of FRPM must also be based upon a consideration of the final chemical form of the resources consumed. For example, most petroleum is burned and produces only thermal energy and rather short-lived air pollutants. However, some petroleum is converted to chemical forms like PCBs and phenols that qualify as persistent materials. The U.S. refinery output in 1969 was about 1.4 billion barrels. About 98 million barrels, or 2 percent, of this output was in the form of petrochemical feedstocks that were converted ultimately into a wide variety of organic chemicals (Census 1971, p. 656). Not all organic chemicals are persistent pollutants, but some are among the most disruptive environmental contaminants. Nearly 100 percent of some materials, such as mercury, is consumed in a form that is a persistent material. Given the uncertainties in current data, no exhaustive analysis of final output streams is justified. We simply accepted 2 percent as a reasonable estimate of the fraction of all resources consumed today in forms that would be classified as persistent materials.

The industrial materials emission factor IMEF is an estimate of the fraction of all persistent materials mobilized by industrial activities that eventually enters the environment (excluding materials employed in agriculture). It includes materials released in all phases of resource use: mining, purification, transportation, production, use, disposal, and recycling. There are many intensive studies of the emissions associated with specific products and production processes, but few sources provide cross-sectional data. The most comprehensive information on current emissions is probably that in SCEP (1970, pp. 257–273) and Ridker (1972). However, neither source presents extensive projections of future emissions: Ridker provides estimates for only a limited number of materials in the United States for the year 2000; and SCEP simply states: ‘‘We were unable to find global estimates for the percentage of emissions controlled. There appear to be no general projections of industrial growth; therefore we have not estimated future emissions of pollutants’’ (SCEP 1970, p. 266.)

Here, again, illustrative examples may provide some idea of the relative magnitudes involved, but they cannot provide a definitive estimate of the global emissions as a fraction of all persistent materials currently used. In 1970 the global production of mercury from mines was about 284,000 flasks, or around 10,000 tons, a large amount of which ultimately entered the environment. Oil may contain on the average about one ppm by weight of mercury. Thus the global production of oil in 1970 would have released about 1,800 tons of mercury into the environment through combustion. In the United States, 20 percent of the annual consumption of lead is employed in gasoline (Moulds 1972, p. 673). Virtually all of that lead eventually enters the environment. In World3 we estimated the industrial material emission factor IMEF to be 10 percent. This appears to be a conservative estimate of the fraction of persistent materials that eventually escapes to the environment.

The industrial materials toxicity index IMTI is the most difficult of the three factors to define operationally. It expresses the biological impact of a unit of persistent material from industrial sources. Its role is analogous to the agricultural material toxicity index, which expresses the harmful biological effects of one unit of persistent material released through agricultural activities. In World3 the index of pollution PPOLX, not the absolute level of pollution PPOL, is used to determine the magnitude of pollution damage in the agriculture and population sectors of the model. Thus the absolute magnitudes of the toxicity indices for the persistent materials in industry and agriculture are unimportant, but their size relative to each other should be estimated as carefully as the data warrant.

The toxic heavy metals appear primarily in industrial emissions. The case for their harmful impact on human health is well established: an extensive if popular survey of literature on these metals is provided in Tucker (1972), and general discussions of the potential health effects from persistent materials are provided in Ehrlich and Ehrlich (1972), Brubaker (1972), and Lee (1972). Concern and knowledge about the health implications of persistent materials are increasing, but it is difficult to make a convincing case for any precise assumption about secular trends in the industrial materials toxicity index IMTI. However, the imminent increase in the generation of plutonium by fast breeder reactors is alone sufficient to increase the toxicity index. Each reactor will contain about 1,000 kilograms of plutonium, even though U.S. federal health standards in 1972 limited maximum body burdens of plutonium to 0.06 microgram per person. Because of the stronger case for harmful effects from industrial emissions we set the industrial materials toxicity index IMTI equal to 10, ten times the agricultural materials toxicity index AMTI.

Because of uncertainty about the long-term determinants of FRPM, IMEF, and IMTI, all three factors were simply held constant during our simulations. In reality none of these three factors are likely to be constant in different countries or over time. As synthetics replace natural fabrics and metals and as nuclear fuels replace fossil fuels, the fraction of resources in the form of persistent material FRPM will probably tend to increase. Emission factors may decline in the industrialized countries, but that trend will be offset to some extent by the low priority assigned to pollution control in the less industrialized countries. Since the total quantity of resources consumed in the less industrialized countries is increasing, the practices of the poorer countries are potentially important determinants of the globe's industrial pollutant burden. The relative toxicities of industrial and agricultural emissions in the future are equally uncertain. Thus, in view of our limited knowledge about the nature and future direction of possible future variations in these factors, no specific, elaborate assumption about these three factors appears to be any better than the simple approximation that they are constant.

Persistent Pollution Generated by Agricultural Output PPGAO To avoid double counting we distinguished between agricultural and industrial pollution in terms of where the persistent materials were released into the environment rather than according to the chemical nature of the materials. For example, emissions associated with the manufacture of fertilizers or pesticides are defined as industrial pollutants. The pesticides and fertilizers themselves become pollutants only when they are released into the environment as agricultural inputs. We defined persistent pollution from agriculture PPGAO as the persistent materials that result from agricultural activities and remain in the soil, air, or water for more than a short period of time. The materials meeting those criteria are primarily organic chemicals employed as pesticides and herbicides; inorganic chemicals used as nutrients; salts; and small quantities of heavy metals, primarily mercury, used in fungicides. Since these materials are useful to farmers only when released into the environment, the emission factor is 1.0. It was therefore omitted from the equation defining PPGAO.

Three generic factors determine the rate of agricultural pollution generation:

1. The total usage rate of inputs to the agricultural sector, defined as agricultural inputs per hectare times arable land (AIPH×AL).

2. The fraction of the total inputs that consists of persistent materials FIPM.
3. The agricultural materials toxicity index AMTI.

Industrial pollution results from a flow of resources that we measured in "resource units." Agricultural pollution is created by the application of agricultural inputs, measured in "dollars per hectare-year." Thus both the agricultural materials toxicity index AMTI and the fraction of inputs that are persistent materials FIPM differ somewhat from their counterparts employed in the equation for industrial pollution.

Whereas we examined the production rates of various resources, measured in tons, to obtain a crude index of the fraction of resources in the form of persistent materials FRPM, in the agriculture sector we were interested in the fraction of the total dollars of agricultural inputs that is in the form of persistent materials. In the equation for industrial pollution the toxicity index IMTI serves to convert resource units into standard persistent pollution units. In the agriculture sector the agricultural materials toxicity index AMTI is a factor that converts dollars of inputs into standard persistent pollution units.

The fraction of agricultural inputs that is composed of persistent materials FIPM depends both upon the fraction of the total agricultural inputs that is composed of fertilizers, heavy metals, and chemicals and upon the fraction of all these materials that remains for more than a few months in the soil, air, or water.

```
PPGAO.K=AIPH.K*AL.K*FIPM*AMTI                         140, A
FIPM=.001                                             140.1, C
AMTI=1                                                140.2, C
    PPGAO  - PERSISTENT POLLUTION GENERATED BY
               AGRICULTURAL OUTPUT (POLLUTIONUNITS/YEAR)
    AIPH   - AGRICULTURAL INPUTS PER HECTARE (DOLLARS/
               HECTARE-YEAR)
    AL     - ARABLE LAND (HECTARES)
    FIPM   - FRACTION OF INPUTS AS PERSISTENT MATERIALS
               (DIMENSIONLESS)
    AMTI   - AGRICULTURAL MATERIALS TOXICITY INDEX
               (POLLUTION UNITS/DOLLAR)
```

In the United States in 1968 the total inputs to the agriculture sector were valued at about 11.1 billion dollars (Census 1971, p. 593):

Repairs and operations of capital items	4.6 billion dollars
Fertilizer and lime	2.1 billion dollars
Miscellaneous inputs (including pesticides)	4.4 billion dollars
	11.1 billion dollars

The total U.S. production of pesticides and related chemicals was valued at about 850 million dollars (Census 1971, p. 718). Since most of these materials were used domestically and the value of heavy metal inputs was negligible, we assumed that approximately 30 percent of the total inputs to agriculture in the United States is composed of lime, fertilizers, and pesticides. Figure 4-31 indicates that this fraction may be about the same in less industrialized areas. However, most of these materials are not truly persistent. They are quickly degraded or absorbed in plant tissues and harvested. We could find no good basis for an estimate of the fraction of these materials that actually remains in the environment beyond one crop season. There-

Insecticide	Quantity on the Skin That Has Lethal Effects on 50 Percent of a Population (mg/kg)		
Phorate	2.5	–	6
Demeton	8.0	–	14
Parathion	7.0	–	21
Ethion	62.0	–	245
DDT			2,510

Figure 6-13 Toxicities of DDT and four alternative insecticides
Source: SCEP 1970, p. 281.

fore, we assumed that one-tenth of one percent of the materials remains in the environment long enough to become classified as persistent pollution. For the standard model simulations the fraction of inputs in the form of persistent materials FIPM was estimated to be 0.001.

Little information was available on which to base our estimate concerning the relative toxicity of industrial and agricultural materials. The toxicity of pesticides in common use appears to be increasing. Figure 6-13 provides information on the relative toxicities of DDT and four insecticides that are being substituted for it. The substitutes exhibit from 10 to 400 times the toxicity of DDT when ranked according to the milligrams of chemical that must be applied to the skin for each kilogram of body weight to produce death in 50 percent of a population.

The greatest part of the persistent materials released through agricultural activities are not pesticides but nutrients. These substances cause damage by suppressing the activity of soil organisms, by accelerating eutrophication of fresh water (thus reducing populations of food fish), and by contaminating groundwater used for human consumption. The first effect, the suppression of soil organism activity, is described briefly in Chapter 4. The second process was studied in detail in our substudy of eutrophication (Anderson et al. 1973). Nitrates in drinking water may be converted to nitrites by bacteria in the intestines of those consuming the contaminated water (Commoner 1971, pp. 78–90)—in babies the nitrites may lead to methemoglobinemia.

While the damage caused by agricultural pollution is important, it appears to be less severe than the effects of the heavy metals and the chemicals that compose industrial pollution. Thus the toxicity index of agricultural materials was defined equal to 1.0, an order of magnitude smaller than the estimated toxicity index of industrial materials.

Persistent Pollution Appearance Rate PPAPR Industrial and agricultural activities release persistent materials directly to the environment. However, the level of persistent pollution PPOL in World3 and the index of persistent pollution PPOLX do not refer to all materials in the environment but only to those persistent materials which are located and concentrated so that they exert a negative influence on living organisms. In most instances there is a delay, which depends on the material involved and on the location and the mode of its release, between the time a persistent material is first released and the time its damaging effects are widely felt in the biosphere. The delay is associated with the chemical and physical processes that govern the transport of materials through the environment and with the biological processes that cause materials to be concentrated as they pass through successive trophic levels. To incorporate this delay in the persistent pollution sector of World3 we defined a persistent pollution appearance rate PPAPR, which is a delayed function of the persistent pollution generation rate PPGR.

```
PPAPR.KL=DELAY3(PPGR.JK,PPTD)                        141, R
PPTD=20                                              141.1, C
    PPAPR   - PERSISTENT POLLUTION APPEARANCE RATE
                (POLLUTION UNITS/YEAR)
    DELAY3  - THIRD-ORDER EXPONENTIAL MATERIAL DELAY
    PPGR    - PERSISTENT POLLUTION GENERATION RATE
                (POLLUTION UNITS/YEAR)
    PPTD    - PERSISTENT POLLUTION TRANSMISSION DELAY
                (YEARS)
```

The effect of the transmission delay is to smooth and displace in time the effects on the biosphere of changes in the persistent pollution generation rate PPGR. The principal determinant of the delay's effect is the magnitude of its time constant, the persistent pollution transmission delay PPTD. This time constant is the average number of years spent by a unit of persistent pollution between the time of its generation and the time of its full impact on the biosphere. The dynamic influence of the delay function is illustrated in Figure 6-14, where hypothetical ''step'' and ''ramp'' increases and declines in the persistent pollution generation rate are related to the appearance rates they would produce. In Figure 6-14 the transmission delay is 20 years, its normal value in World3.

Even for individual materials the magnitude of the transmission delay is difficult to estimate from historical data because the lags in diffusion and concentration are generally confounded with delays in social perception and response. Case studies of mercurial poisoning in Japan and Sweden provide some information on the total length of the delays involved between the first release of mercury and the society's ultimate perception of its effects. Although these chronologies place upper limits on the transmission delay in these specific instances, they do not permit precise estimates of the length of time involved in the transmission and concentration of the mercury involved. Moreover, they only deal with instances in which the diffusion of mercury took place over small distances. Thus they include much shorter transmission delays than those existing for many globally distributed materials. The following summary of studies by Klein (1972) and Montague and Montague (1971) suggests that the mercury transmission delay in Minamata Bay was less than 3 years:

1950 Japanese factory begins discarding mercury into Minamata Bay.
1953 First case of alkylmercury poisoning, called ''Minamata disease,'' detected.
1956 Public health authorities aware of widespread Minamata disease.

1958 Pathology of Minamata disease identified.

1959 Connection between Minamata disease and mercurial effluent from factory established.

In another example (Johnels and Westermark 1969), Swedish scientists traced the use of mercurial fungicidal seed treatments to contamination of the food chain, including land-based, seed-eating birds and their predators:

1940 Mercurial seed treatment came to be extensively used in Sweden.

1950s Initial reports of mercury contamination in birds and their predators.

1965 Connection between mercurial seed dressings and contamination of the food chain is confirmed; the use of these seed dressings is halted.

In this instance it is clear only that the transmission delay was less than 10 years.

Notice that in these local cases the social response to pollution is delayed much more than the appearance of the pollution. For mercury in Japan the response delay was more than 6 years. In Sweden the response delay was 15 years. The response delay is not explicitly represented in the standard model, but is incorporated in simulation analyses of the pollution sector in this chapter and in Chapter 7. The

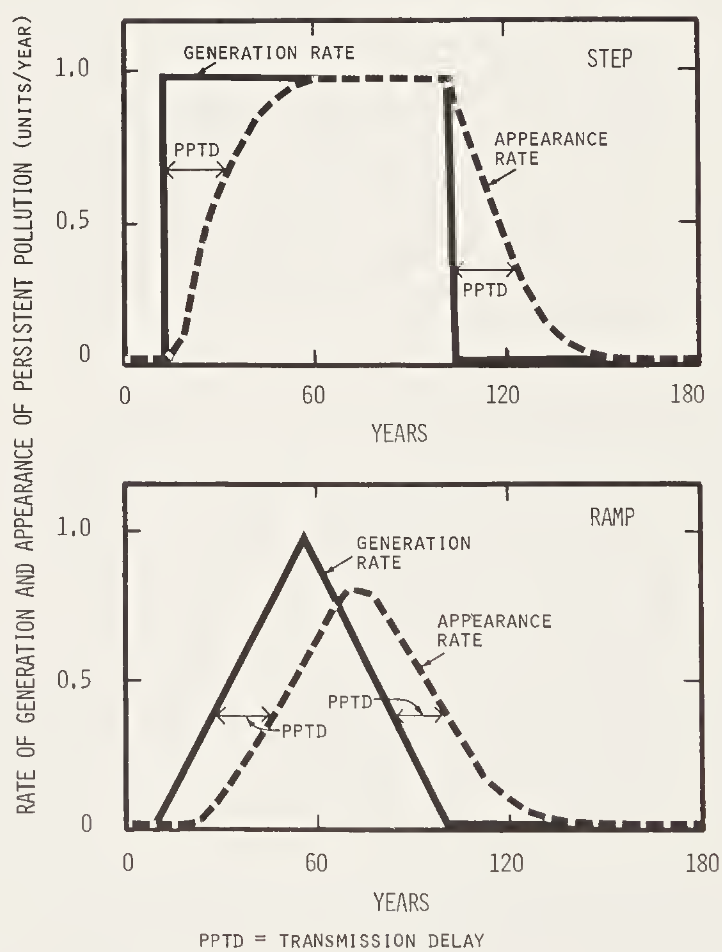


Figure 6-14 The relation between two persistent pollution generation rates and the persistent pollution appearance rates they would produce when the transmission delay is 20 years

simulations show that the social response delay has very important implications for policies intended to limit the damage caused by persistent materials.

More precise information on the magnitude of the transmission delays associated with characteristic persistent materials may be obtained through simulating the actual diffusion and concentration processes involved in the movement of these materials through the environment. To provide information on the transmission delays associated with several persistent materials we developed simulation submodels of DDT and mercury. These models are described in detail in the second volume of our report (Meadows and Meadows 1973). Here we will simply present the conclusions of each model without defending its structure or coefficients.

Earlier theoretical studies of DDT have indicated the presence of important lags in the movement of the chemical through the environment (Harrison et al. 1970, Woodwell et al. 1971). Our simulation model of DDT transport supports these findings and provides more detailed information on the probable magnitudes of the delays (Randers 1973). Figure 6-15 illustrates the delay that would be observed

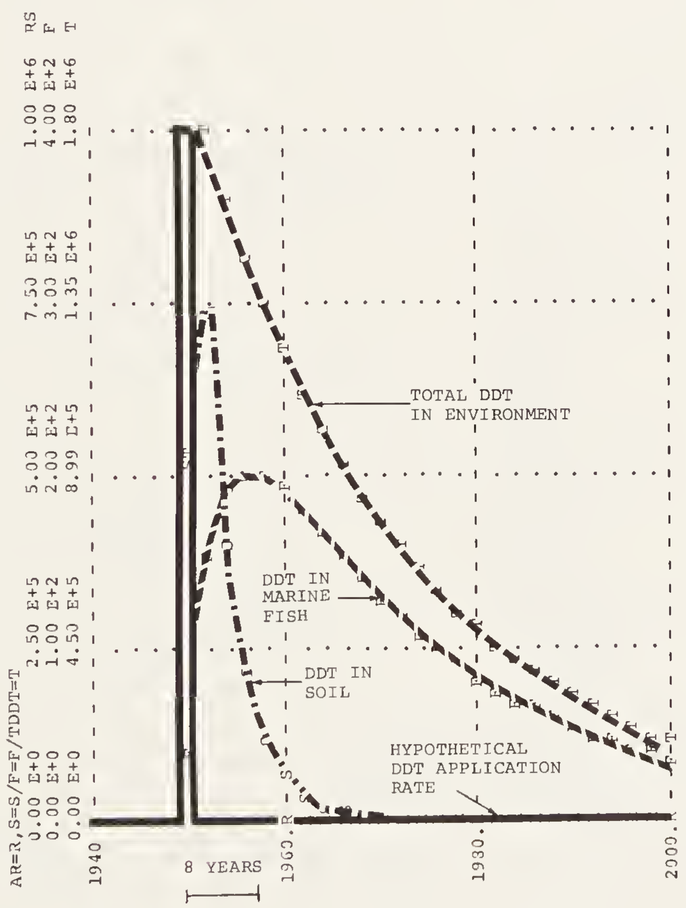


Figure 6-15 An illustration of the transmission delays associated with the diffusion of DDT through the global environment—the relation between the rate of DDT application over croplands and the level of DDT in marine fish tissue

Note: Appendix B to this chapter lists the changes required in the standard DYNAMO program of the DDT model to obtain the results illustrated in this figure.

between a pulse input of DDT over cropland and the subsequent level of the pesticide in the tissues of marine fish. The length of the transmission delay depends in part on the number of trophic levels involved in the movement and concentration of DDT; for example, there is a lag of about 8 years between peak generation rates and maximum levels of DDT in the second trophic level of marine fish. The peak concentration of DDT would occur somewhat earlier in fish than in fish-eating birds or man. DDT is transmitted to man through other paths as well. Delays along these other pathways could be either longer or shorter than those observed in the DDT model.

Mercury exhibits an even longer transmission delay than DDT. By slightly altering the model of global mercury flows described in Anderson et al. (1973), one can employ simulation to determine the time required for a pulse input of mercury, in the absence of all other natural or man-made sources, to travel through the environment. Figure 6-16 illustrates the results obtained when the revised model was used to simulate the effects of mercury added to the global environment in 1910. The con-

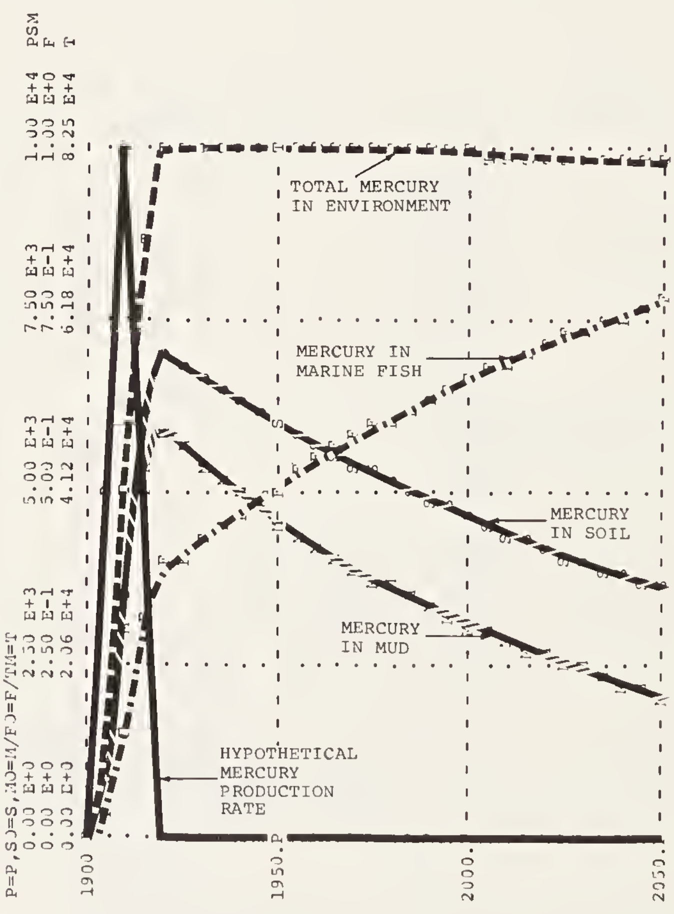


Figure 6-16 An illustration of the transmission delays associated with the diffusion of mercury through the global environment—the relation between the rate of mercury release to fresh water and the level of mercury in marine fish tissue

Note: Appendix B to this chapter lists the changes required in the standard DYNAMO program of the mercury model to obtain the results illustrated in this figure.

centration of mercury in mud and soil peaked within 5 to 10 years after the metal was released into the environment. However, even after 140 years the level of mercury in marine fish was still rising. Other studies suggest that the transmission delay in specific regions may be many times that indicated by the model run: "It is estimated that at the current rate of microbial action, the supply of mercury now at the bottom of Lake St. Clair, Michigan, will continue to be absorbed in to the food chain for several thousand years" (Wood 1972).

Until recently, significant quantities of radioactive materials were released by atmospheric nuclear tests. Figure 6-6 suggests a transmission delay of about 3 years for these materials.

Although their ultimate importance is not yet clear, stored radioactive wastes deserve mention as pollutants that may exhibit a very long transmission delay. By 1970 the U.S. Atomic Energy Commission had accumulated about 75 million gallons of liquid radioactive wastes in underground storage tanks.

> Many authorities now assume that the tanks can be relied upon only for about 20 years, the principal cause of failure being corrosion of welded seams. Even if it is assumed that a tank can be relied upon for about 40 years, the poisonous contents of those tanks would have to be transferred to new tanks more than 10 times before their radioactivity had died out enough for safe disposal. [Snow 1967]

If the tanks and the transfer procedures never fail, the transmission delay for these liquid radioactive wastes will be essentially infinite. None of the associated radioactivity will ever affect the biosphere. However, if accidents occur in the transfer, processing, or storage of these wastes, then the transmission delay is finite and equals the mean time to failure of the transfer and storage procedures. It is extremely difficult to estimate the severity, timing, or likelihood of such a release, though catastrophic consequences are at least conceivable, and small accidents are inevitable.

The transmission delay for radioactivity may in some instances be even longer than the lag introduced by storage. Radioactivity shares with some chemical substances, such as diesterstylbestrol, the ability to decrease the average lifetime of the generation following that actually exposed to the pollutant. Exposure to radioactivity may alter an individual's egg or sperm cells. When affected cells are employed in the conception of children, the children may inherit genetic defects that affect their health only after they mature. This factor alone adds fifteen or more years to the transmission delays of radioactive substances.

In summary, the transmission delay associated with the diffusion and the concentration of persistent materials in the biosphere is an important general characteristic of the pollutants' behavior. The delay may vary in specific instances from a year or less to many decades. The magnitude of the delay that characterizes the global burden of persistent materials will depend on the location and the mode of pollution generation, on the precise composition of the pollution level, and on the location and the nature of the affected organisms. These factors are not fully understood and will, in any event, change in the future in ways that cannot be fully anticipated today.

As an example, there will be a tendency for the composition of persistent pollution to shift as society discriminates against pollutants whose harmful consequences are more quickly apparent. The move in the 1960s toward increased reliance on nuclear reactors as a source of electric power illustrates this tendency. The transmission delays inherent in the diffusion of sulfur dioxide and other fossil fuel combustion products are very short. Thus the effects of these materials have already become apparent, and they are the objects of intense social concern. With the growing pressure to decrease fossil-fuel pollution, the relative importance of coal and oil in power generation will probably be substantially decreased as society increases its reliance on nuclear reactors. Reactor effluents are potentially much more dangerous, but their transmission delays are so long that the harmful consequences of reactor wastes are not yet fully perceived. Since society always prefers to shift the costs of present activities to the future, it should be expected that political processes will alter the composition of persistent materials so that the globe's average effective pollution transmission delay will increase. However, information about the strength or the relative importance of this effect was insufficient to warrant the incorporation of a secular trend in the equation defining the persistent pollution transmission delay PPTD. Therefore, we merely defined the delay as a constant and assigned it a value of 20 years in most of the World3 simulations.

Concluding this discussion, we quote from René Dubos, who writes eloquently of the potential effects of the pollution transmission delay:

> The point of importance here is that the worst pathological effects of environmental pollutants will not be detected at the time of exposure; indeed they may not become evident until several decades later. In other words, society will become adjusted to levels of pollution sufficiently low not to have an immediate nuisance value, but this apparent adaptation will eventually cause much pathological damage in the adult population and create large medical and social burdens. [Dubos 1968]

Persistent Pollution PPOL *and Index of Pollution* PPOLX Persistent pollution PPOL at time t is defined to be equal to the level of persistent pollution present in 1900, plus the accumulated difference between the persistent pollution that has appeared and that which has been assimilated between the year 1900 and time t.

```
PPOL.K=PPOL.J+(DT)(PPAPR.JK-PPASR.JK)                   142, L
PPOL=2.5E7                                              142.1, N
    PPOL   - PERSISTENT POLLUTION (POLLUTION UNITS)
    DT     - TIME INTERVAL BETWEEN CONSECUTIVE
               CALCULATIONS (YEARS)
    PPAPR  - PERSISTENT POLLUTION APPEARANCE RATE
               (POLLUTION UNITS/YEAR)
    PPASR  - PERSISTENT POLLUTION ASSIMILATION RATE
               (POLLUTION UNITS/YEAR)
```

To establish the initial value of persistent pollution we assumed that the generation rate PPGR, appearance rate PPAPR, and assimilation rate PPASR were all equal in 1900.* The generation rate in 1900 PPGR(1900) can be calculated from the initial values of the other model variables:

*We thus implicitly assumed that the level of persistent pollution PPOL was constant in the year 1900. Of course, there are essentially no data to support this or any other precise assumption about the value of the World3 pollution variables in 1900. However, the errors possibly introduced by this assumption create only a small transient, which disappears long before pollution has any significant influence on the other sectors of the model.

$$\begin{aligned}
PPGR(1900) &= (PPGIO(1900)+PPGAO(1900))(PPGF) \\
&= (PCRUM(1900)\times POP(1900)\times FRPM\times IMEF\times IMTI \\
&\quad +AIPH(1900)\times AL(1900)\times FIPM\times AMTI)\ (PPGF) \\
&= [.17\times 1.65E9\times .02\times .1\times 10+6.6\times .9E9\times .001\times 1]\times 1 \\
&= 5.6E6+5.95E6 \\
&= 1.16E7 \text{ persistent pollution units per year}
\end{aligned}$$

Since we assumed that the assimilation rate PPASR was equal to the generation rate PPGR in 1900, we could calculate the initial value of pollution PPOL in 1900. The pollution assimilation rate is equal to PPOL/(AHL × 1.4), where AHL is the World3 computer program abbreviation for assimilation half-life and 1.4 is a numerical correction factor explained later, in the section defining PPASR. Thus PPOL equals PPASR × 1.4 × AHL.

$$\begin{aligned}
PPOL(1900) &= PPASR(1900)\times 1.4\times AHL(1900) \\
&= 1.16E7\times 1.4\times 1.5 \\
&= 2.5E7 \text{ persistent pollution units}
\end{aligned}$$

The level of persistent pollution PPOL is measured in persistent pollution units, which are related to resource consumption and the application of agricultural inputs. We also defined a ratio scale for pollution which is an index of the pollution level at time t relative to its level in 1970. The influence of persistent pollution at time t on average life expectancy, soil fertility, and the assimilation half-life is expressed as a function of this index of pollution PPOLX:

```
PPOLX.K=PPOL.K/PPOL70                                    143, A
PPOL70=1.36E8                                            143.1, C
    PPOLX  - INDEX OF PERSISTENT POLLUTION
                (DIMENSIONLESS)
    PPOL   - PERSISTENT POLLUTION (POLLUTION UNITS)
    PPOL70 - PERSISTENT POLLUTION IN 1970 (POLLUTION
                UNITS)
```

The value of PPOL70 was determined by measuring the 1970 value of PPOL in the the standard run of the World3 model.

Persistent Pollution Assimilation Rate PPASR The equation for the persistent pollution assimilation rate PPASR is fully determined by one simple assumption and one definition. The assumption was derived in part from our detailed studies of the processes that cause the assimilation of DDT and mercury. On the basis of those pollution substudies we assumed that persistent materials disappear from the environment at a rate directly proportional to the total quantity of materials present. In other words, any given level of persistent materials present in the environment will decline asymptotically to zero.* All radioactive materials decay (are assimilated) exponentially. The reasons for assuming an exponential assimilation of other persis-

*However, if the persistent pollution appearance rate is greater than zero, the total amount of persistent pollution will not decline to zero. Even though each unit will ultimately disappear, new units may be added at the same rate or even faster than the old ones are assimilated.

tent materials are described in the following subsection, along with the determinants and numerical values of the assimilation half-life used in World3.

The assimilation half-life AHL was defined as the time period, measured in years, over which half of the initial amount of persistent material will disappear from the environment. The assumption and definition may be stated mathematically:

Assumption: $$\frac{dPPOL(t)}{dt} = \frac{-PPOL(t)}{C}$$

Definition: $$PPOL(t = AHL) = \frac{PPOL(t = 0)}{2}$$

From equation (6.1): $$\frac{dPPOL(t)}{PPOL(t)} = \frac{-dt}{C}$$

$$\ln[PPOL(t)] = C' - \frac{t}{c}$$

$$PPOL(t) = [PPOL(t=0)]e^{-t/c}$$

From equations (6.2) and (6.3):

$$PPOL(t=AHL)=PPOL(t=0)e^{\frac{-AHL}{c}} = \frac{PPOL(t=0)}{2}$$

Thus: $e^{AHL/c}=2$ or $AHL/c=\ln(2)$

and: $AHL/c=0.7$

$c=1.4\ AHL$

Therefore: $$\frac{dPPOL}{dt} = -PPOL/(1.4\ AHL)$$

Expressed in the DYNAMO format, equation (6.4) becomes:

```
PPASR.KL=PPOL.K/(AHL.K*1.4)                          144, R
    PPASR   - PERSISTENT POLLUTION ASSIMILATION RATE
                (POLLUTION UNITS/YEAR)
    PPOL    - PERSISTENT POLLUTION (POLLUTION UNITS)
    AHL     - ASSIMILATION HALF-LIFE (YEARS)
```

When the pollution appearance rate PPAPR is zero, one-half of the initial amount of persistent material will leave the environment over a time period equal to one assimilation half-life AHL; after an additional interval equal to AHL, one-fourth of the initial material will still remain, and so forth. The quantity remaining after the passage of a time interval equal to 7 half-lives will be less than 1 percent of the initial amount. Figure 6-17 illustrates the disappearance over time of 100 units of a persistent material with an assumed assimilation half-life of 1.5, 3, 5, and 90 years. Until the level of pollution has risen sufficiently to decrease the assimilative capacity of the environment, the numerical value for AHL employed in World3 is 1.5 years. As a consequence, when the pollution appearance rate is zero, half of the persistent materials will have disappeared from the World3 pollution level within 1.5 years of their appearance. So long as AHL equals 1.5 years, essentially all of the persistent pollutants will have been assimilated in World3 within 10 years after their appearance.

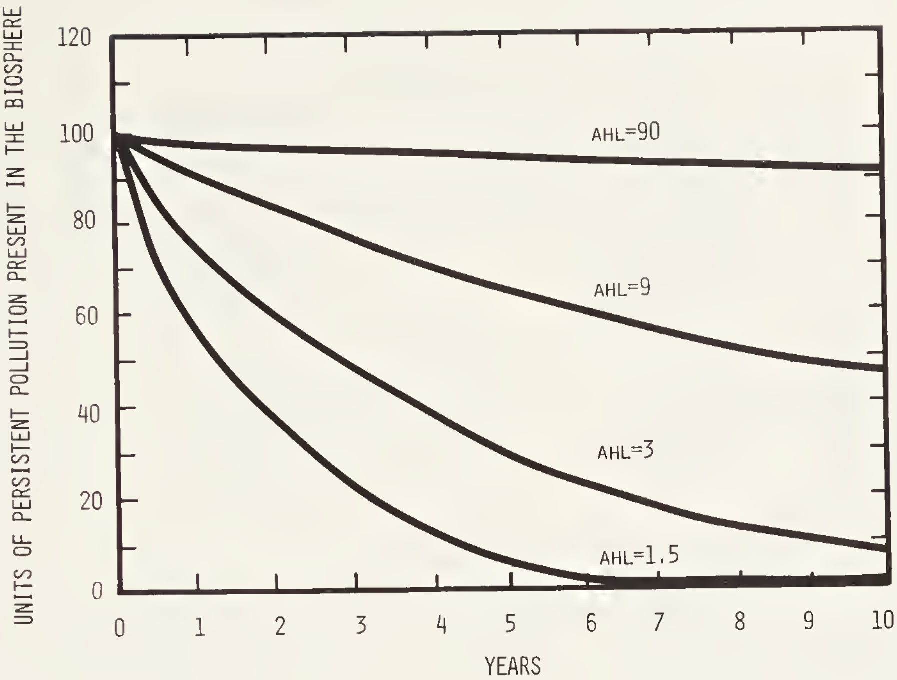


Figure 6-17 The assimilation of 100 units of persistent pollution with various values assumed for the assimilation half-life

Assimilation Half-Life AHL A basic postulate of the persistent pollution sector is that the rate of pollution assimilation at any point in time is directly proportional to the amount of pollution present in the global environment at that time. This assumption was used to derive the preceding expression for the persistent pollution assimilation rate PPASR. The half-life of the assimilation process need not be constant. In fact, the global average pollution assimilation half-life is affected by the composition of the existing pollution load, the geographical distribution of pollution, and the total amount of persistent pollution present in the environment. These three possible influences are discussed in this section to indicate the implications and the basis of our assumption in World3 that the assimilation half-life AHL is a variable that depends only on the level of the pollution present in the biosphere PPOL.

Because the global persistent pollution level will always be composed of materials with different half-lives, the real assimilation half-life will not be constant over time. Materials with very short half-lives disappear quickly. Thus the persistent pollution level PPOL will tend to become composed of materials with longer and longer assimilation half-lives.

This tendency may be illustrated by two simulation analyses of a very simple model of pollution accumulation and assimilation. The flow diagram of a model that simulates the decay of strontium-90 (Sr-90, half-life = 25 years) and molybdenum-93 (Mo-93, half-life = 2 years) is given in Figure 6-18. The program for the model is listed in the Appendix C to this chapter. Figure 6-19A presents a simulation of the model with no inputs of pollution and with initial values of 25 units of Sr-90 and 75 units of Mo-93. At first, the effective half-life of the total pollution level (Mo-93+Sr-90) is about 6 years. After 10 years, however, most of the persis-

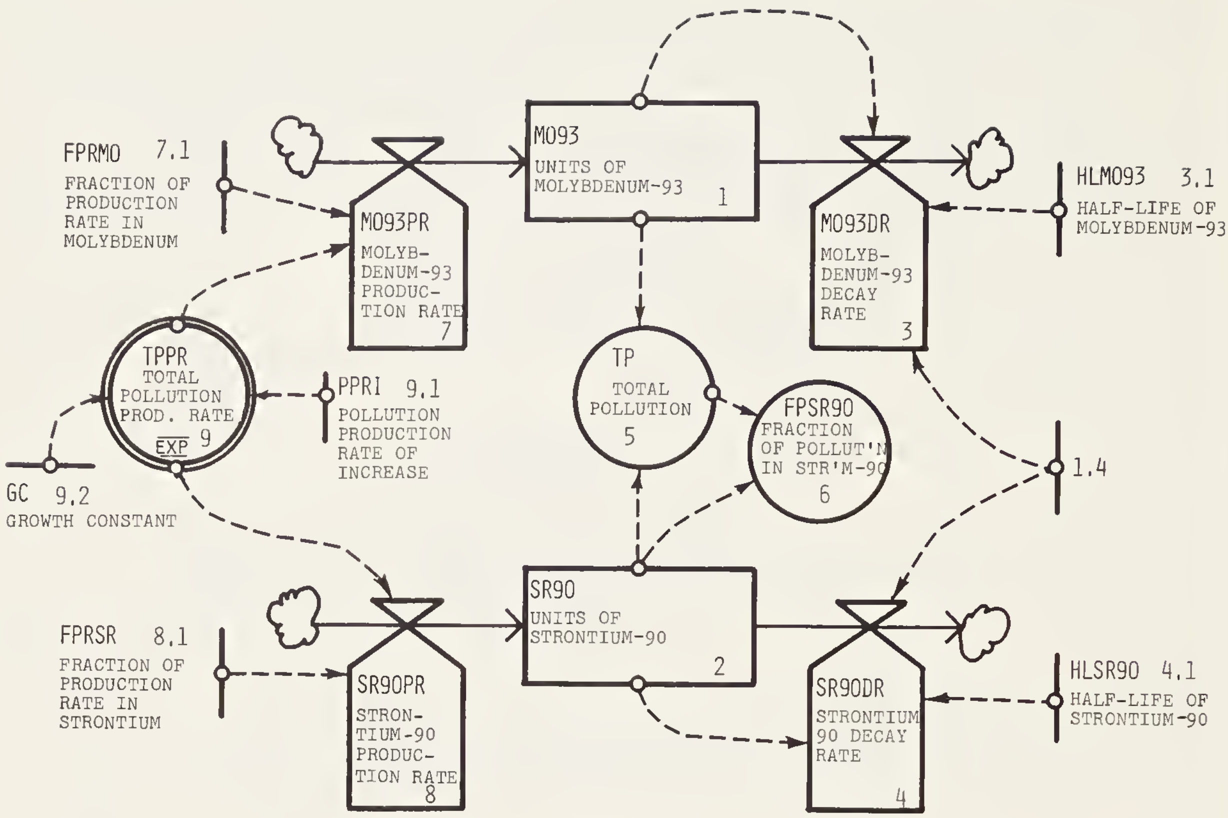
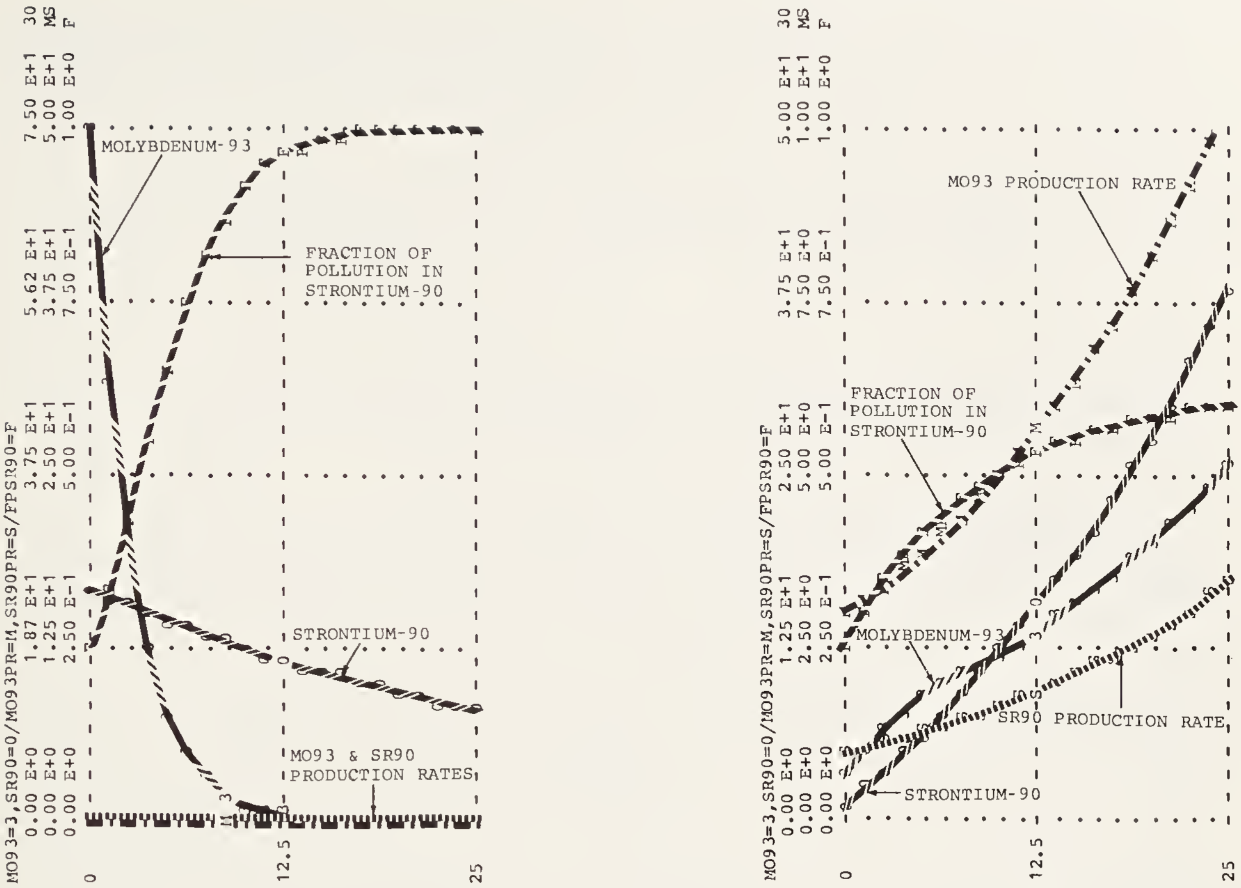


Figure 6-18 DYNAMO flow diagram of a simple model of pollution accumulation and assimilation
Note: Appendix C to this chapter lists the DYNAMO equations of this model.

tent pollution remaining in the system consists of Sr-90, and the effective half-life of the material is 25 years, the half-life of Sr-90. Figure 6-19B, the second simulation of this simple model, illustrates the shift in the composition of persistent pollution that takes place over time when pollution generation is increasing. We start with essentially no pollution in the system and with pollution increasing exponentially at 5 percent per year. Of this newly generated pollution, 75 percent is the short-lived Mo-93 and 25 percent is Sr-90. It can be seen that the composition of the total persistent pollution level gradually shifts from 25 percent Sr-90 to 65 percent Sr-90 at time = 25 years. Initially, the effective half-life of the total pollution is about 6 years; at year 25 it is nearly 20 years.

Although the tendency of effective half-lives to increase with composition changes is potentially important, we concluded that our current knowledge of the future composition of persistent pollution and of the assimilation half-lives that actually characterize persistent materials is too incomplete to warrant incorporating a time-dependent influence on the assimilation half-life in World3. Given the lack of data, incorporating in World3 a tendency for AHL to increase as a function of time due to shifts in the composition of pollutants would not improve the overall projective utility of the model. Although AHL does tend to increase during each simulation of World3, that increase is the consequence of continued growth in the generation and



A. the shift in the composition of total pollution over time with no inputs and initial ratios of 75 percent Mo-93 (halflife =2 years) and 25 percent Sr-90 (half-life = 25 years)

B. the shift in the composition of pollution over time with negligible pollution initially and exponentially increasing inputs of 75 percent Mo-93 (half-life = 2 years) and 25 percent Sr-90 (half-life = 25 years)

Figure 6-19 Secular shifts in the composition of total pollution in a simple two-pollution model when the half-lives of the two pollutants are unequal

appearance of persistent pollutants; it is unrelated to a shift in the global composition of persistent materials.

The second influence on the assimilation half-life in the real world is the geographical distribution of the pollutants. The rate of radioactive decay does not depend upon an isotope's concentration. However, where physical sedimentation, biological degradation, or chemical reaction is involved in the assimilation of persistent materials, the physical distribution of the pollutants may have a marked influence on the rate at which they can be assimilated. We chose to ignore this influence in formulating the equation for AHL in World3. By omitting any distributional parameter in the equation that defines AHL, we implicitly assumed that the future distribution of persistent materials around the globe will remain approximately as it was in 1970. While one can argue that the distribution of pollution sources will change in the future, the World3 pollution sector represents the effects of materials that persist long enough to be transported great distances by the globe's air and water streams. Thus the assumption of a constant distribution is not sufficiently in error to alter the utility of the pollution sector.

Assuming that the assimilation half-life AHL is only a function of the quantity of pollutant present, one could conceive of several different relationships between the two variables. Four possibilities are illustrated in Figure 6-20. Line A in each figure represents the case in which the half-life is constant and is independent of the total quantity of pollutant present. If the half-life is constant, the assimilation rate (shown by line A of Figure 6-20B) increases linearly with pollution. Line C (in Figures 6-20A and 6-20B) represents a case in which the assimilation half-life is constant over the lower range of pollution but rises quickly after pollution passes some threshold. In this case the assimilation rate rises linearly at first, as in the case represented by line A, but it ultimately begins to decrease as rising pollution forces the half-life toward infinity and the assimilation rate toward zero. Lines B and D in both figures correspond to other conceivable relationships.

We designed the World3 equations relating AHL to PPOL so that other analysts can easily incorporate the relationship they believe is most reasonable. Because the half-life of each radioisotope is independent of the isotope's quantity, the line relating half-life to the level of a radioactive pollutant is linear with slope zero and thus of the form specified by line A of Figures 6-20A and 6-20B. The relationship between the level of pollutant and the half-life of assimilation through deposition is unclear, though line A of Figures 6-20A and 6-20B may be a useful approximation for that mode of assimilation as well. For information about the form of the relationship between PPOL and AHL that is most appropriate for assimilation through chemical or biological degradation, we employed a simple model of the kinetics of degradation of a single pollutant. The casual reader may omit the mathematical derivation and proceed directly to equation (6.8) of this section.

Some forms of pollution degradation may be carried out by "degraders," which may be small molecules such as oxygen or water, large molecules such as enzymes,

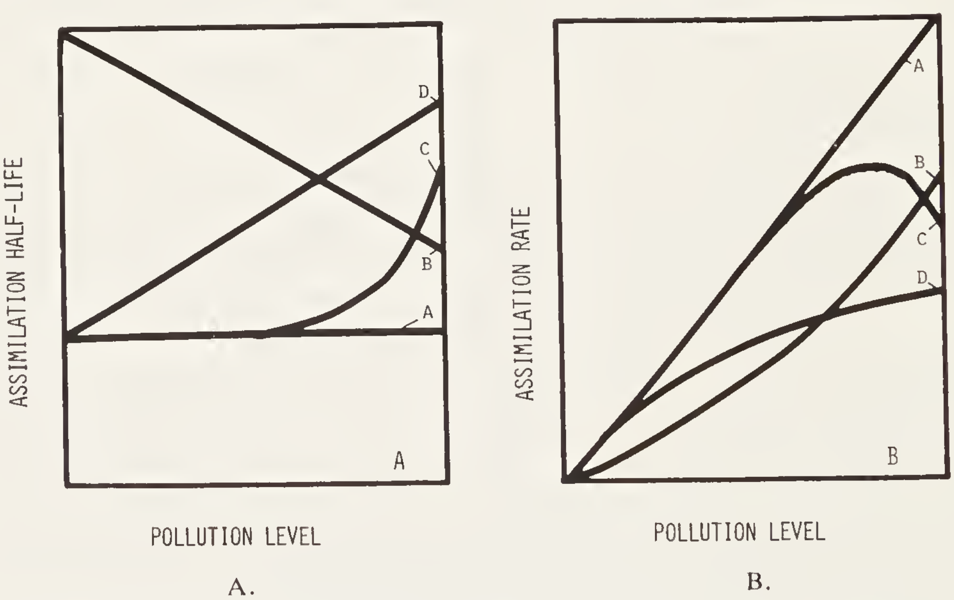


Figure 6-20 Alternative possible relationships between pollution level and assimilation half-life, together with the corresponding rate of pollution assimilation Note: PPASR = PPOL/(AHL × 1.4).

or entire organisms such as bacteria. For all these the process of pollution degradation could proceed in two steps as follows:

1. $$P + D \underset{k_1}{\overset{k_1'}{\leftrightharpoons}} PD$$

This is a reversible step in which a pollutant P and a degrader D form some kind of intermediate complex.

2. $$PD \underset{k_2}{\rightarrow} H + D$$

This is a step in which the complex PD decomposes irreversibly to yield a harmless species H and the degrader D. The degrader is then free for another catalytic cycle.

This formulation is identical to that proposed by Michaelis-Mention to represent enzyme-catalyzed kinetics (Fruton and Simmonds 1958). Following the usual pattern of chemical-kinetic analysis, one presumes a steady-state concentration of the complex PD:

$$\frac{d[PD]}{dt} = 0 = k_1 [P] [D] - k_1'[PD] - k_2 [PD], \tag{6.5}$$

where k_1, k_1', and k_2 are the rate constants for the indicated reactions. The total degrader concentration, uncomplexed and complex, [D*] is defined by:

$$[D^*] = [D] + [PD]. \tag{6.6}$$

From equation (6.5) at steady state the concentration of the complex PD is

$$[PD] = \frac{k_1[P][D^*]}{k_1' + k_2 + k_1 (P)} . \tag{6.7}$$

The rate at which the pollutant is assimilated PPASR is the rate of the second step in the reaction mechanism. Thus PPASR = k_2[PD] or

$$PPASR = \frac{k_1 k_2 [P][D^*]}{k_1' + k_2 + k_1 [P]} . \tag{6.8}$$

From equation (6.8) it is possible to calculate the pollutant's degradation or assimilation half-life AHL:

$$AHL = \frac{[P]}{PPASR\ (1.4)} = \frac{k_1' + k_2 + k_1 [P]}{k_1 k_2 [D^*] (1.4)} . \tag{6.9}$$

This theoretical model yields AHL as a linear function of [P], the concentration of the persistent pollutant, as shown by Figure 6-21, where $\alpha = (k_2' + k_2)/k_1 k_2 [D^*]$ (1.4) and $\beta = 1/k_2[D^*]$ (1.4).

Equation (6.8) is a general expression for pollution degradation for which there are two limiting cases. First, if pollution is small relative to the number of degraders, so that $(k_1' + k_2) >> k_1$ [P], then:

$$PPASR = \frac{k_1 k_2 [P][D^*]}{k_1' + k_2} \tag{6.10}$$

and

$$AHL = \frac{k_1' + k_2}{k_1 k_2 [D^*]\ (1.4)} , \tag{6.11}$$

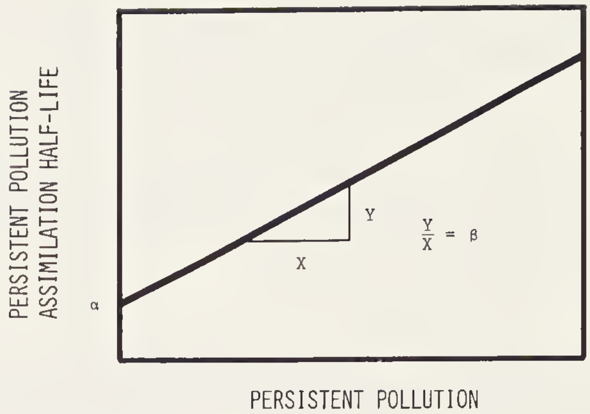


Figure 6-21 The theoretical linear relationship between the persistent pollution assimilation half-life and the level of pollution

indicating that pollution assimilation is proportional to the concentration of pollutants [P] and that the assimilation half-life AHL is constant (line A of Figure 6-20A). If, however, pollution is large relative to the number of degraders, so that $(k_1' + k_2) << k_1[P]$, then:

$$\text{PPASR} = \frac{k_1 k_2 [P][D^*]}{k_1 [P]} = k_2 [D^*]$$

and

$$\text{AHL} = \frac{[P]}{(1.4)\ (k_2)[D^*]},$$

which indicates that the degradation rate is no longer determined by the concentration of pollutants but only by the limited concentration of available degraders. In this case the assimilation half-life AHL is directly proportional to the pollutant level (line D of Figure 6-20A).

The foregoing arguments are based on the assumption of a constant total concentration of degraders [D*]. If this concentration changes, then the pollution assimilation rate will have a still more complex behavior. For example, biotic degraders, such as bacteria, may be poisoned by high levels of the pollutant. In this event, [D*] declines as [P] increases, and, from equation (6.9), the pollution assimilation half-life increases with increasing pollution [P] at a greater than linear rate (line C of Figure 6-20A).

An example of a case where the degrader concentration is apparently a function of pollutant levels is provided by the relation of mercury levels to the activity of methylating bacteria. Figure 6-22 presents empirical data suggesting that levels of mercury beyond a certain threshold actually decrease the activity of the bacteria that convert metallic mercury to its organic form. In this case the relationship between AHL and PPOL is indicated by line C of Figure 6-20A.

Even when the distribution and composition of pollution are assumed to be constant, the precise real-world relationship between the level of pollution and the assimilation half-life depends upon the relative importance of the three modes of assimilation—disintegration, deposition, and degradation—and on the magnitude of the half-lives of the individual persistent materials. There is little empirical basis for

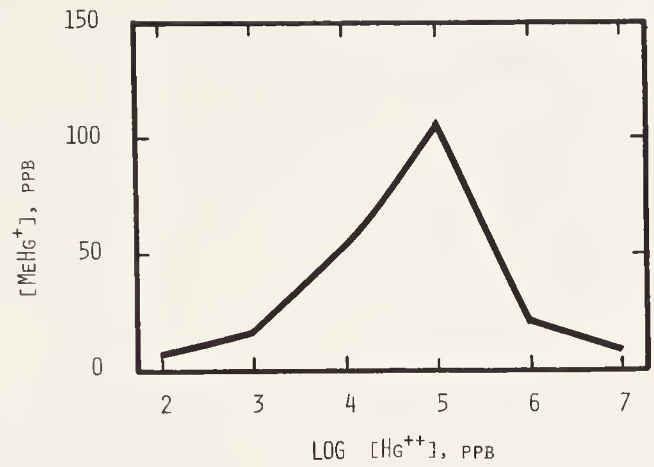


Figure 6-22 Maximum concentration of methylmercury [MeHG+] produced from a given concentration of mercuric ion [Hg++]
Source: Anderson et al. 1973.

projecting the future values of either factor over the next several decades. However, we could find no suggestion that persistent materials might be assimilated more quickly as their level in the global environment increases. Thus curve B of Figure 6-20A was not chosen to express the relation between AHL and PPOL. Instead we incorporated in World3 a linear relationship belonging to the same class as curve D of Figure 6-20A. However, because the relationship is highly uncertain, we made AHL a function of the pollution index PPOLX rather than of pollution PPOL itself.

While some set of precise equations must be developed to express the influence of the pollution level on AHL, it is important to develop the equations in a form suited to the low level of information actually available. To illustrate this important point we give two different statements expressing the same relationship between the level and the assimilation half-life of persistent pollution. The first suggests a rather comprehensive knowledge about the nature and the precise magnitude of all influences on the assimilation half-life. The second conveys a lower level of knowledge. We would say that the first statement implies a ratio scale for pollution and assimilation half-life. The second statement implies only an interval scale.* The DYNAMO equations appropriate for each scale are given below the corresponding statement.

1. Statement implying a ratio scale:

   The assimilative half-life of the biosphere is a linearly increasing function of the level of pollution present. When pollution is less than 10^8 units, the assimilation half-life will be 1.5 years. For each additional 25×10^8 units of persistent pollution beyond 10^8 units, assimilation half-life AHL will increase by 1.5 years.

   DYNAMO Equations:

   A AHL.K=TABHL (AHLT, PPOL.K,1E8,1001E8,250E8)
   T AHLT=1.5/16.5/31.5/46.5/61.5

2. Statement implying an interval scale for pollution and assimilation half-life:

   If persistent pollution rises to 1,000 times its level in 1970, the assimilation

*For a useful discussion of the difference between ratio and interval scales see Blalock 1960.

half-life would be about 40 times as great as it was in 1970.* The global assimilation half-life was about 1.5 years in 1970.

DYNAMO equations:

```
A AHL.K = AHL70 × AHLM.K
C AHL70=1.5
A AHLM.K=TABHL(AHLMT,PPOLX.K,1,1001,250)
T AHLMT=1/11/21/31/41
C PPOL70=1.36E8
A PPOLX.K=PPOL.K/PPOL70
```

Our information about the real world's current and potential assimilation capacity is based primarily on intuitive impressions, scattered data, and case studies. The interval-scale statement is closer to our current level of understanding than the ratio-scale statement. Existing information is not precise enough to connect absolute pollution levels directly with absolute values for the assimilation half-life AHL. However, there is some basis for guessing the percentage increase in the assimilation half-life that would be produced by different increases in PPOL. In the interval formulation one may easily change the value of the assimilation half-life in 1970, the value of persistent pollution in 1970, or the rate at which the assimilation half-life would increase with increases in the persistent pollution levels. Both DYNAMO expressions are numerically identical and would lead to the same model behavior, but the first equation does not clearly exhibit the components of the judgment that lead to the assessment of pollution's influence on AHL. We therefore chose the interval formulation. If more comprehensive and accurate information were available, the ratio expression would be preferred.

Since the assumptions underlying our formulation of AHL refer to the situation in 1970, the normalizing constant PPOL70 must always be equal to the value computed in World3 for persistent pollution PPOL in 1970. If any change is introduced in World3 that directly or indirectly influences the persistent pollution generation rate PPGR, transmission delay PPTD, or assimilation rate PPASR, and thereby the value of persistent pollution PPOL in 1970, the constant PPOL70 will have to be changed so that PPOLX will still retain the value of 1.0 in 1970. The standard value for PPOL70 was determined by simply simulating the standard version of World3 and setting PPOL70 to the value of PPOL observed in 1970. Since PPOL70 has a slight and indirect influence on the level of persistent pollution through AHL, several iterations were required to find the precise value of PPOL70 that caused PPOLX to be 1.0 in 1970.

Although current information is insufficient to make any accurate estimates of the effective assimilation half-life of global persistent pollution in 1970 AHL70, there are data that indicate the half-lives of individual persistent materials present in the environment in 1970. Figure 6-23 summarizes the estimates of the half-lives in soil of ten insecticides made by Nash and Woolson (1967). The estimated half-lives range from 4 to 13 years. It should be noted that these figures are not accurate estimates of the half-lives of these materials in the global environment, for disappear-

*To obtain equally spaced table intervals, DYNAMO programming conventions force the use of 1,001 instead of 1,000 as the upper bound of the AHLM table. Obviously, this difference has no effect on the model's behavior.

Insecticide	**Half-life in Soil (years)**
Aldrin	11
Chlordane	11
Endrin	11
Heptachlor	5
Dilan	6
Isodrin	5
Benzene hexachloride	4
Toxaphene	12
Dieldrin	9
DDT	13

Figure 6-23 Disappearance half-lives for ten insecticides in soil
Source: Data from Nash and Woolson 1967.

ance from the soil is a necessary but not a sufficient condition for disappearance from the global environment. Some fraction of the pesticides that vanished from the soil in Nash's tests must have been degraded and thus fully assimilated. The remainder may have simply evaporated and moved to other sectors of the global environment.

The difference between disappearance from only one sector and full assimilation by the global environment is illustrated by the simulation of our DDT model (Randers 1973), in which we followed the disappearance of the insecticide from the various sectors of the global environment after an initial pulse application in year 10 of the simulation (Figure 6-15). The residence half-life of DDT in the soil is seen to be about 2 years.* However, it takes fully 17 years to achieve a 50 percent reduction in the total amount of the chemical present in the environment: the air, soil, stream, ocean, and fish sectors of the model.

Figure 6-24 provides data on the half-lives of radioisotopes released in the liquid wastes of conventional pressurized water reactor nuclear power stations. The half-lives range from 20 hours to about 28 years. The concentration of these materials in the liquid effluents of reactors was extremely small in 1970, so they did not play a significant role in determining the effective assimilation half-life of the total global persistent material burden. However, both the growth in reactor usage and the tendency of longer-lived materials to increase in importance because of changes in the composition of persistent materials will increase the contribution of many elements listed in Figure 6-24 to the global pollution burden.

As a final illustration of the half-lives that characterize current components of the global persistent material burden, we refer again to our simulation of the mercury model (Figure 6-16). In the model's projection, only a small fraction of the total metal initially added to the environment disappears from the air, soil, mud, ocean, and fish sectors of the model after 140 years have elapsed. This long delay is likely to

*The discrepancy between our simulated estimate of half-life in soil and the larger figure obtained by Nash and Woolson (1967) is due to the higher rate of evaporation in the simulated system. Nash placed his DDT evenly throughout several inches of soil. Thus evaporation was less important in his test than in the real world.

Isotope	**Half-life**
H-3	12.3 years
Mn-54	300 days
Co-58	71 days
Co-60	5.2 years
Sr-89	50.5 days
Y-90	64.8 hours
Y-91	57.5 days
MO-99	67 hours
I-151	81 days
Cs-134	2.3 years
Te-152	78 hours
I-133	20.5 hours
Cs-136	13 days
Cs-137	27 years
Ba-140	12.8 days
La-140	40.5 hours
Ce-144	290 days

Figure 6-24 Half-lives of radioisotopes present in the liquid releases from a 1,000-megawatt pressurized water nuclear reactor
Source: Data from Wright 1970.

be characteristic of most heavy metals, which currently constitute an important portion of the globe's persistent pollution level. We could find no accurate means of weighing even the current components of pollution in an assessment of the effective half-life. We therefore chose a conservative figure of 1.5 years for the assimilation half-life of persistent pollution AHL in World3 in 1970.

Having assumed a linear relationship between the assimilation half-life AHL and the index of pollution* PPOLX and having specified the magnitude of AHL in World3 in 1970, we needed only to estimate the slope β of the line relating the two. For a specific pollutant the slope could in theory be calculated from the kinetic rate constants as indicated earlier. Where a wide variety of pollutants is involved, some other basis for an estimate had to be found. Our approach was to determine the dynamic significance of β, the slope of the line relating AHL and PPOLX.

Given our assumption that AHL is a linear function of PPOLX,

$$\begin{aligned} \text{AHL} &= \text{AHL70}\ (1 + \beta \times \text{PPOLX}) \\ &= \text{AHL70}\ (1 + \beta \times \text{PPOL/PPOL70}). \end{aligned}$$

Thus:

$$\text{PPASR} = \frac{\text{PPOL}}{\text{AHL70}(1 + \beta \times \text{PPOL/PPOL70})\ (1.4)}.$$

In 1970 the assimilation rate is:

$$\text{PPASR}\,(1970) = \frac{\text{PPOL70}}{\text{AHL70}(1 + \beta)\ (1.4)} \simeq \frac{\text{PPOL70}}{\text{AHL70} \times 1.4}.$$

*It should be noted that the AHL relationship assumed for the model runs is slightly nonlinear, for AHL is assumed to be constant at 1.5 years when PPOLX is less than 1.0. The resulting behavior is indistinguishable from an assumed linear AHL relationship.

The approximation is valid since we assume that β is substantially less than 1.0.

To estimate the approximate value of β, we may compute the maximum value for the assimilation rate PPASR, which occurs when the pollution level approaches infinity. If we allow pollution to grow toward infinity ($\beta \times \mathrm{PPOL} >> 1$), then:

$$\mathrm{LIM}_{\mathrm{PPOL} \to \infty}\ \mathrm{PPASR} = \mathrm{LIM}_{\mathrm{PPOL} \to \infty} \frac{\mathrm{PPOL}}{\mathrm{AHL70}(1 + \beta \times \mathrm{PPOL/PPOL70}\ (1.4)}$$

$$= \frac{\mathrm{PPOL70}}{\mathrm{AHL70}(\beta)\ (1.4)} = 1/\beta \times \mathrm{PPASR}(1970).$$

Thus, given a linear relationship between AHL and PPOL, at very high levels of persistent pollution PPOL, pollution assimilation PPASR becomes a constant independent of PPOL and equal to the reciprocal of β times the assimilation rate observed in 1970. This is just a restatement of the limiting case for assimilation found in the simple kinetic model derived earlier in this chapter. It is thus clear that β can be evaluated by intuitively estimating the relationship between the assimilation rate in 1970 and the maximum assimilation rate that could be sustained by the global environment. We assumed that the environment could assimilate up to 25 times the amount of pollutants it rendered harmless in 1970. Thus β was set equal to 0.04 in the standard version of the World3 program. However, we tested the sensitivity of the pollution sector's behavior mode to a variety of other assumptions about the maximum possible assimilation rate. It should be noted that so long as AHL is not zero, growth in the level of persistent pollution PPOL will accompany an increasing generation rate PPGR even if the assimilation capacity of the environment is assumed to be infinite. The form of the standard relationship between PPOLX and the multiplier on the assimilation half-life in 1970 AHL70 is shown in Figure 6-25.

```
AHLM.K=TABHL(AHLMT,PPOLX.K,1,1001,250)                    145, A
AHLMT=1/11/21/31/41                                       145.1, T
    AHLM    - ASSIMILATION HALF-LIFE MULTIPLIER
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    AHLMT   - AHLM TABLE
    PPOLX   - INDEX OF PERSISTENT POLLUTION
                (DIMENSIONLESS)

AHL.K=AHL70*AHLM.K                                        146, A
AHL70=1.5                                                 146.1, C
    AHL     - ASSIMILATION HALF-LIFE (YEARS)
    AHL70   - ASSIMILATION HALF-LIFE IN 1970 (YEARS)
    AHLM    - ASSIMILATION HALF-LIFE MULTIPLIER
                (DIMENSIONLESS)
```

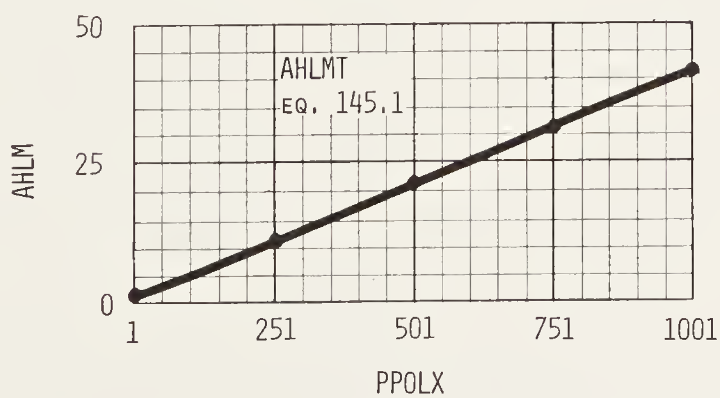


Figure 6-25 Table function of the relationship between PPOLX and the multiplier on the assimilation half-life in 1970 AHL70

That completes our description of the persistent pollution sector equations. The next section presents analyses of the sector's behavior under a variety of assumptions.

6.6 SIMULATION RUNS

The persistent pollution sector of the world model serves to convert information on resource use in industry and agriculture into a long-term projection of persistent pollution levels in the global ecosystem. In this section we examine the general behavioral characteristics of this conversion.

The following series of simulation runs illustrates the general dynamic behavior modes of the persistent pollution sector when it is driven by exogenous inputs affecting the generation of persistent pollution. These inputs are time-dependent functions of arable land AL, agricultural inputs per hectare AIPH, population POP, and the per capita resource usage multiplier PCRUM. First, we examine the behavior of the sector in response to pulse and step inputs to pollution generation. Next we show the behavior of the persistent pollution sector when driven by the historical values of the four inputs. The following three parts explore the behavior of the sector when past growth trends are assumed to continue through the year 2100. The last part examines the behavior of the sector if pollution generation stops growing and becomes constant at various points in the future. A complete DYNAMO program listing of the persistent pollution sector with exogenous inputs and a list of parameter changes for each of the following runs are included in Appendix A to this chapter.

Behavior in Response to Pulse and Step Inputs

Runs 6-1 and 6-2 (Figures 6-26 and 6-27) illustrate the behavior of the persistent pollution sector in response to pulse and step inputs in pollution generation. They indicate the roles played by the persistent pollution transmission delay PPTD and the persistent pollution assimilation rate PPASR in moderating the response of the persistent pollution level PPOL to changes in pollution generation PPGR. As will be shown later in this section, the transmission delay and the assimilation rate are of particular concern to policy makers, for both factors help determine the effectiveness of pollution control policies that act to reduce the generation of pollution.

Run 6-1 (Figure 6-26) shows the behavior of the sector in response to a hypothetical pulse input in pollution generation 20 years after the initiation of the run. This pulse represents the effect on the pollution sector of a pulse increase in any of the determinants of the persistent pollution generation rate PPGR (for example, in the agricultural inputs per hectare AIPH or in the toxicity of industrial materials IMTI). Before 1920 no pollution is generated in Run 6-1; initially, both the level of persistent pollution PPOL and the index of persistent pollution PPOLX are zero. In 1920 the persistent pollution generation rate PPGR rises to 10 billion units per year, remains there for one year, and then promptly falls to zero. Because of the assumed delay between the time a pollutant is first generated and the time it has had its full impact on the biosphere, the persistent pollution appearance rate PPAPR does not immediately respond to the sudden rise in PPGR. Instead, PPAPR rises gradually to

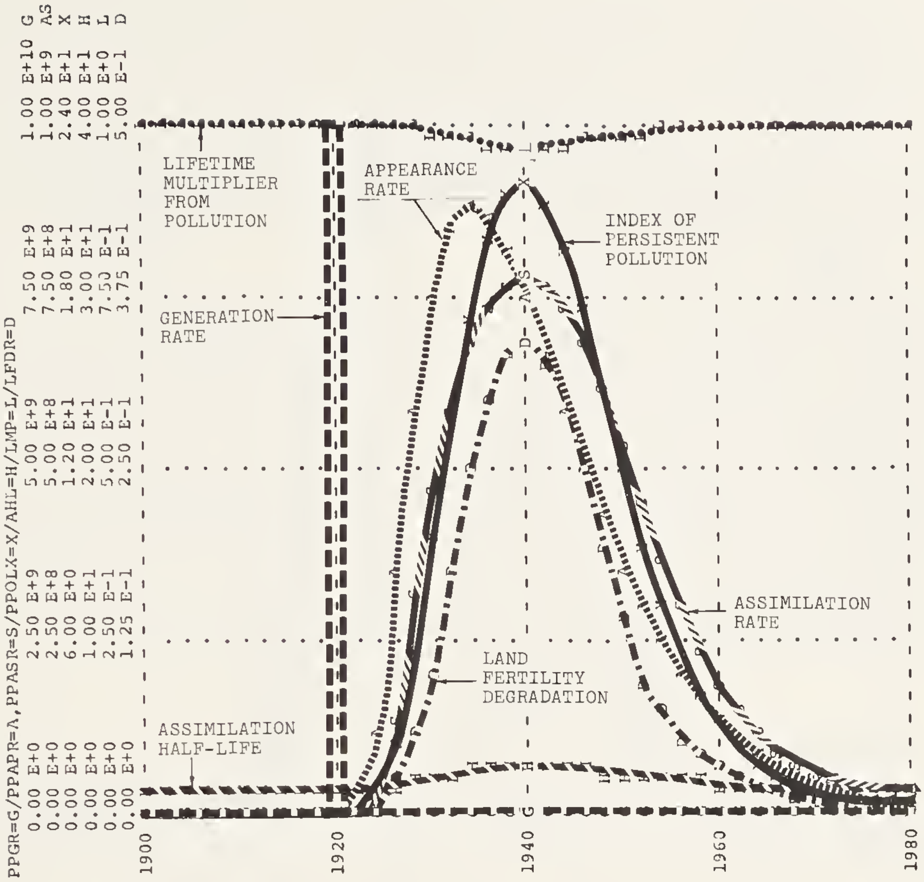


Figure 6-26 Run 6-1: behavior of the pollution sector in response to a pulse input in persistent pollution generation in 1920

a peak of 0.9 billion units per year 15 years after the occurrence of the pulse in pollution generation. Notice that the scales for PPGR and PPAPR in Run 6-1 differ by a factor of 10. If the scales were equal, the area under the PPGR and PPAPR curves would be equal, since no pollution is lost from the transmission delay.

The pollution assimilation process also introduces a delay whose magnitude is governed by the assimilation half-life. The half-life AHL varies between 1.5 years and 3 years in Run 6-1. The time of maximum persistent pollution assimilation occurs in 1940, 5 years after the peak in PPAPR. Because of the lag between appearance and assimilation, pollution tends to accumulate, and PPOLX rises. These two runs are synthetic and designed to display the behavioral properties of the pollution sector, not to forecast real-world behavior. Thus PPOLX has a slightly different meaning in Runs 6-1 and 6-2 than it does in the later runs of Chapter 6 and in simulations of the full World3 model. Here it is an index of the level of pollution relative to the PPOL value at 1970 in the standard run of World3. We did not adjust the value of PPOL70 in Runs 6-1 and 6-2 to equal the values of PPOL in 1970 for those two runs.

In 1940 the appearance rate drops below the assimilation rate, and both persistent pollution PPOL and the index of persistent pollution PPOLX begin to fall. PPOLX reaches its peak value 20 years after the occurrence of the PPGR pulse. It

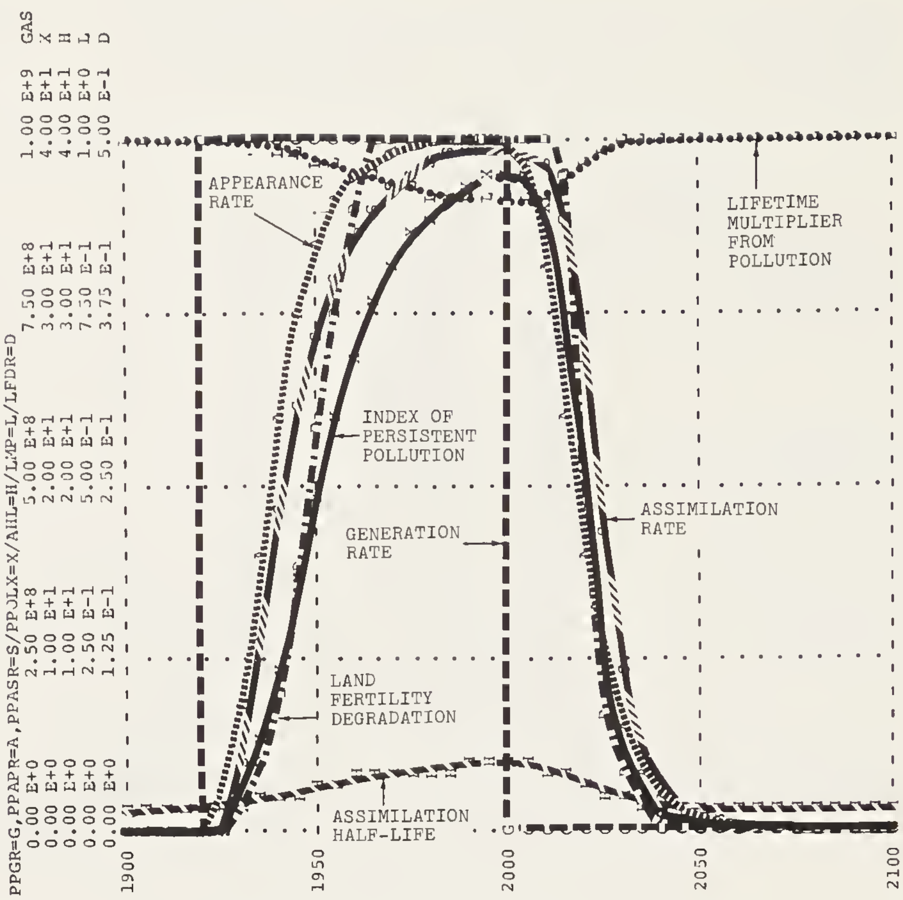


Figure 6-27 Run 6-2: behavior of the pollution sector in response to a step increase and decrease in persistent pollution generation

does not return effectively to zero until approximately 50 years after the last pollution was generated.

Run 6-2 (Figure 6-27) shows the responses of the persistent pollution sector to a step increase and subsequent step decrease in the generation of persistent pollution PPGR. Twenty years after the beginning of the simulation, PPGR suddenly increases to 1 billion units per year and remains constant at that high value for the next 80 years before dropping to zero in the year 2000. In Run 6-2 as in Run 6-1, the persistent pollution appearance rate PPAPR lags behind PPGR. Fifty-five years are required for PPAPR to rise enough to equal PPGR.

Seventy-five years after the step increase in pollution generation, the assimilation rate PPASR finally equals PPAPR, and both PPOL and PPOLX cease to grow. At this point PPOL equals approximately 5 billion units and PPOLX equals 38. The assimilative capacity of the environment is slightly impaired at this level of pollution, and the assimilation half-life AHL equals 4 years. If the generation rate PPGR were maintained at 1 billion units per year, no further change would occur in the system after the year 1995. The system is in dynamic equilibrium at that point. All flows are equal and the pollution level is constant.

However, in the year 2000 the simulated rate of pollution generation PPGR is assumed to drop suddenly back to zero. Again, the level of persistent pollution is slow to respond; only after 45 years do PPOL and PPOLX drop to zero. Note that the response pattern is asymmetric, with a faster response to pollution decrease than to pollution increase because of the variable delay time represented by the assimilation half-life AHL. This asymmetry results in part from our assumption that the assimilative capacity of the environment is not permanently impaired by high levels of pollution. Once pollution declines sufficiently, the assimilation returns to its former level.

Runs 6-1 and 6-2 are the results of entirely hypothetical patterns of pollution generation, but they illustrate several important dynamic properties of the pollution sector. Most important is the fact that a decline in pollution generation is not accompanied by a simultaneous decline in the level of pollution. The level of pollution may continue to rise for many years after pollution generation has declined. Second, because of the lag between the rate of appearance and the rate of assimilation, the pollution assimilation rate PPASR is always less than the pollution appearance rate PPAPR when the latter is rising. Thus a growing pollution appearance rate is always accompanied by increasing levels of pollution and hence increases in pollution damage.

Historical Run

Run 6-3 (Figure 6-29) shows the behavior of the persistent pollution sector when the sector is driven by historical values of arable land AL, agricultural inputs per hectare AIPH, population POP, and the per capita resource usage multiplier PCRUM. Figure 6-28 portrays the values of the exogenous inputs used to derive Run 6-3 for the 70-year period from 1900 to 1970. Over that interval all four inputs exhibit approximately exponential growth. Arable land AL grows at an average of 0.6 percent per year, from an initial value of 0.9 billion hectares in 1900 to a value of 1.4 billion hectares in 1970. Agricultural inputs per hectare AIPH increase from 6.6 to 45 dollars per hectare from 1900 to 1970, an average growth rate of 2.7 percent per year. Over that period population POP increases from 1.6 to 3.6 billion persons, an average growth rate of 1.2 percent. The per capita resource usage multiplier PCRUM rises from 0.17 in 1900 to its normalized value of 1.0 resource units per person-year in 1970, a growth rate of 2.5 percent per year. Note that since the rate of pollution generation is defined as the product of several growing factors, pollution generation PPGR always grows faster than any of its causes. The combined growth of these four inputs causes the persistent pollution generation rate PPGR to grow at an average rate of 3.6 percent per year, rising from 0.011 billion to 0.15 billion persistent pollution units per year over the 70-year period.

Run 6-3 also shows the behavior of the persistent pollution sector in response to the growth in the rate of persistent pollution generation PPGR from 1900 to 1970. Because of the persistent pollution transmission delay PPTD, the rising persistent pollution appearance rate PPAPR lags behind the persistent pollution generation rate PPGR by 20 years. The net growth in the level of persistent pollution (here represented by the index of persistent pollution relative to 1970 levels PPOLX) is determined by the difference between the persistent pollution appearance rate PPAPR

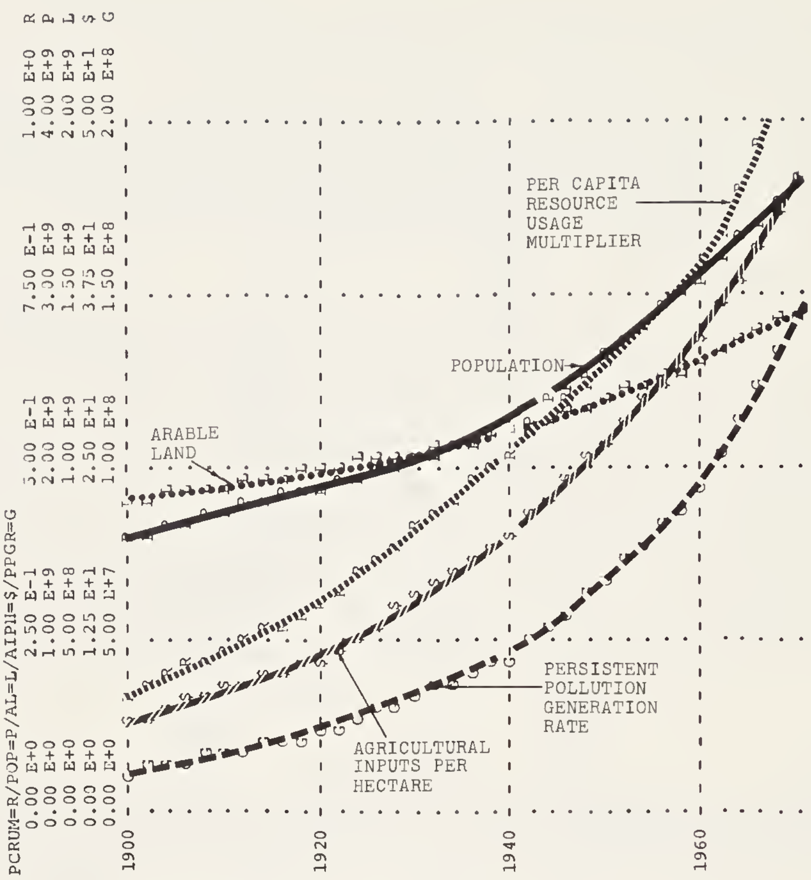


Figure 6-28 Inputs to Run 6-3, the historical run of the pollution sector

and the persistent pollution assimilation rate PPASR. This difference grows continuously as PPAPR rises, for even though PPASR is also increasing, it lags behind PPAPR by a constant 2.1 years (=1.4×AHL). This historical run was used to determine the value of PPOL70 that would make PPOLX equal 1.0 in 1970.

Although the index of persistent pollution PPOLX grows considerably during the 70-year period, we made the conservative assumption that historical levels of pollution have no significant adverse effects on any of the variables in the model. Run 6-3 shows that the assimilation half-life AHL remains constant at 1.5 years throughout the historical run, reflecting the assumption that 1970 levels of persistent pollution are not high enough to interfere with the pollution assimilation process. Run 6-3 also shows that the lifetime multiplier from pollution LMP remains constant at 1.0 during the 70-year period, indicating that the growing level of persistent pollutants has no deleterious effects on the life expectancy of the model population. The rate of degradation of land fertility LFDR increases slightly from 1900 to 1970, but the small 1970 value of 1 percent reduction in fertility per year is easily offset by land fertility regeneration through land maintenance in the model.

Behavior in Response to Continued Material Growth

Run 6-4 (Figure 6-31) shows the behavior of the persistent pollution sector when the material growth trends of the past 70 years are assumed to continue through the year 2100. Figure 6-30 illustrates the time-dependent behavior of the four exogenous

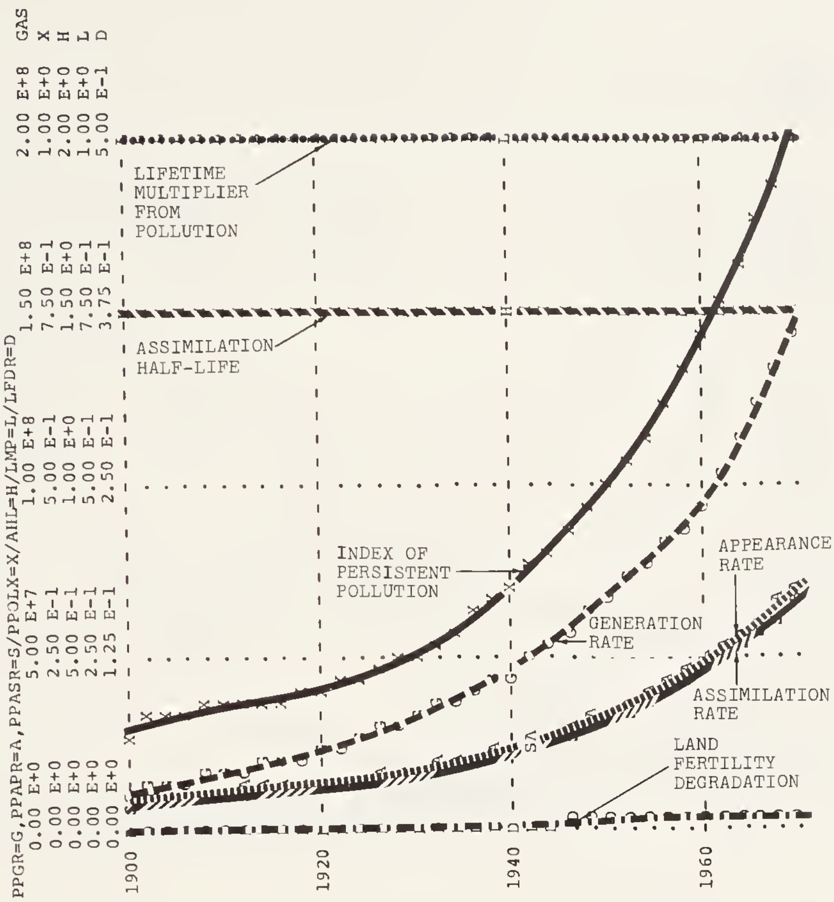


Figure 6-29 Run 6-3: historical run of the pollution sector

inputs assumed for this run. Both population POP and agricultural inputs per hectare AIPH are assumed to grow continuously at their historical rates of growth of 1.2 and 2.7 percent per year, respectively. Under this assumption, population exceeds 17 billion persons and agricultural inputs approach 1,500 dollars per hectare-year by the year 2100. Arable land is assumed to reach a maximum level of 2.7 billion hectares by the year 2060, almost twice the 1970 level. Per capita resource usage reaches its maximum value of 7 times the 1970 value by the year 2060 and then levels off, for it is assumed that, at levels of income above 1,400 dollars per person-year, increases in income will not be accompanied by any increase in per capita resource usage PCRUM. These four inputs generate the persistent pollution generation rate PPGR shown in Figure 6-31 which grows at an average rate of 3.2 percent per year over the 200-year period.

Run 6-4 (Figure 6-31) shows that the continued growth in pollution generation produces a ‘‘pollution crisis’’ within the 200-year time horizon of the model. As in Run 6-3 (Figure 6-29), the persistent pollution appearance rate PPAPR lags behind the growing persistent pollution generation rate by 20 years throughout the run, corresponding to the delay involved in the transfer of persistent pollutants to the biosphere. Before 1970 the index of persistent pollution PPOLX is relatively low in Run 6-4, and the pollution assimilation half-life AHL is constant. Thus PPOLX grows at the same rate as PPGR. After 1970, however, the accumulated persistent pollu-

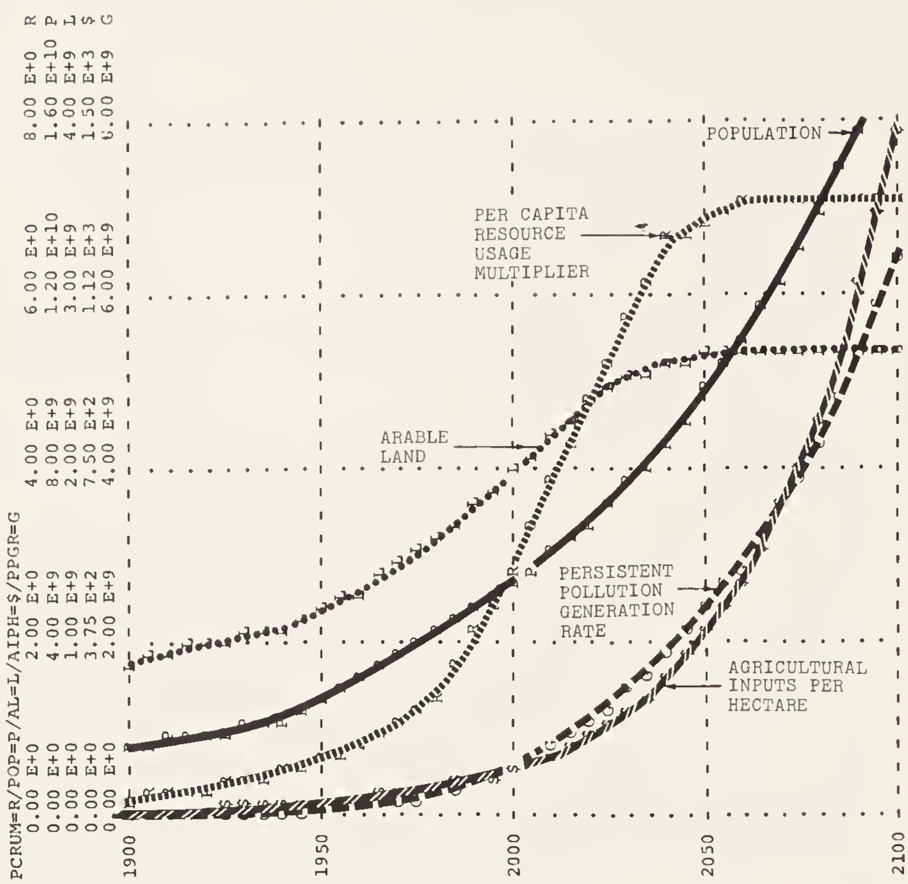


Figure 6-30 Inputs to Run 6-4 of the pollution sector when continued material growth is assumed

tants begin to interfere with the pollution assimilation process, and AHL begins to rise. This rise is practically imperceptible through the year 2030; thus the persistent pollution assimilation rate PPASR continues to rise almost as fast as PPAPR. After 2030, however, the higher levels of persistent pollutants significantly raise AHL. The increasing AHL causes PPASR to level off by the year 2100, reflecting the basic assumption that there is a finite upper limit to the rate of persistent pollution assimilation in the world ecosystem. In the standard formulation of World3, this maximum pollution assimilation rate is assumed to be about 25 times the rate of assimilation that occurred in 1970.

As the rate of assimilation levels off, there is accelerating growth in the level of pollutants, indicated by the increase in PPOLX, because the appearance rate PPAPR continues to grow exponentially over the 200-year period. The pollution index finally grows to levels that exceed the limits of the tables used to define the land fertility degradation rate LFDR and the lifetime multiplier from pollution LMP. Thus both variables suddenly level off in the year 2065. The resulting behavior mode of the pollution sector under conditions of continued material growth is exponential growth in the accumulation of persistent pollutants and considerable impairment of the environment's ability to assimilate pollution—conditions observed in the pollution crisis mode of World3.

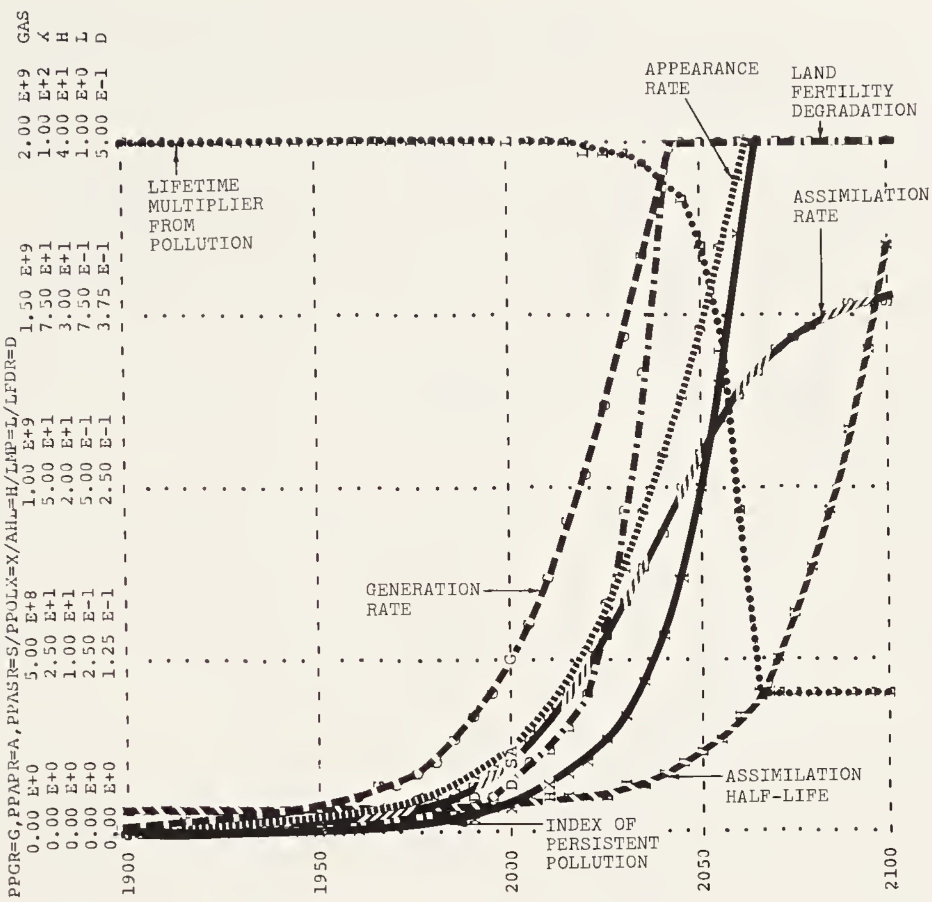


Figure 6-31 Run 6-4: behavior of the pollution sector in response to continued material growth

Run 6-4 also plots the steadily increasing damage associated with this pollution crisis. As persistent pollution grows beyond 10 times its 1970 level, the land fertility degradation rate LFDR increases very sharply, reaching its maximum rate of 50 percent per year after the year 2045. It is not possible in World3 to counteract such high levels of fertility degradation through investment in land maintenance. Thus during this phase of the pollution crisis there would be serious deterioration in the fertility of the arable land stock. As pollution exceeds by 40 times its 1970 level, the life expectancy LE of the population is significantly lowered. By the year 2065 the lifetime multiplier from pollution LMP reaches its minimum value of 0.2, indicating that the average life expectancy LE of the world population has been reduced by 80 percent. In the normal behavior exhibited by World3, these extreme values would never be reached, but, under the assumption of continued material growth and no corrective policies, high levels of damage are realized within a century.

Sensitivity Runs

The following set of runs illustrates the sensitivity of the persistent pollution sector's behavior to variations in our estimates of the section's parameter values. The behavior of any sector is judged insensitive to a parameter change over a given range if no value of the parameter within that range alters the basic behavior mode of the sector. In the case of the persistent pollution sector, the basic mode of behavior in response to the set of driving functions shown in Figure 6-30 is exponential growth in the index of pollution PPOLX. This behavior is exhibited by Run 6-4 (Figure 6-31), and that run will thus serve as our reference in establishing the sensitivity of the sector. Except when a change is specifically mentioned, the inputs illustrated in Figure 6-30 are those employed to obtain Runs 6-5 through 6-15.

Persistent pollution is assumed to have two negative effects outside the pollution sector. It affects the life expectancy LE of the population and increases the rate of land fertility degradation LFDR. Both LE and LFDR are defined as functions of PPOLX, the pollution level in the model relative to the pollution that exists in 1970. As a consequence we will not use changes in the absolute level of pollution PPOL to determine the sector's sensitivity to a revision in a parameter estimate. Instead we will examine the extent to which a different parameter value changes the behavior of PPOLX over time. Because PPOLX is renormalized for each run to equal 1.0 in 1970 of that run, the sector will be insensitive to any parameter change that simply alters PPOL by a constant factor throughout the course of the run. Only changes that cause the rate of growth in PPOL to differ over the course of the run from that existing in Run 6-3 will alter the time form of PPOLX.

This subtle, but important, point can be illustrated by changing the sector's parameter estimates in a way that merely alters PPGR and thus PPOL by a constant factor over the course of the entire run. Run 6-5 (Figure 6-32) presents the behavior of the persistent pollution sector when the inputs employed in Run 6-4 were revised to represent a different estimate of the toxicity indices of industrial and agricultural materials. As described in section 6.5, the toxicity indices are measures of the relative biological impact of persistent materials from industrial sources and agricultural activities. To obtain Run 6-5 the industrial materials toxicity index IMTI was reduced from 10 to 1, and the agricultural materials toxicity index AMTI was reduced from 1 to 0.5.

A reduction in both indices reduces the total amount of persistent pollution that is generated and eventually assimilated throughout the run; PPGR, PPAPR, and PPASR are significantly lower in Run 6-5 than in Run 6-4. As a consequence the level of pollution in 1970 is also lower, and it was thus necessary in Run 6-5 to decrease the value of the normalizing constant PPOL70. Once PPOLX is renormalized, its behavior is the same in Runs 6-4 and 6-5. We would not conclude that the behavior of the sector is sensitive to the changes we made in the toxicity indices. Since the rates of growth in the two components of pollution generation—persistent pollution generated by industrial output PPGIO and persistent pollution generated by agricultural output PPGAO—are somewhat different, reducing one of the toxicity indices to zero would slightly alter the time form of PPOL and PPOLX. However, the change would not be significant and would be, in any event, predicated on an unrealistic assumption about the nature of persistent materials.

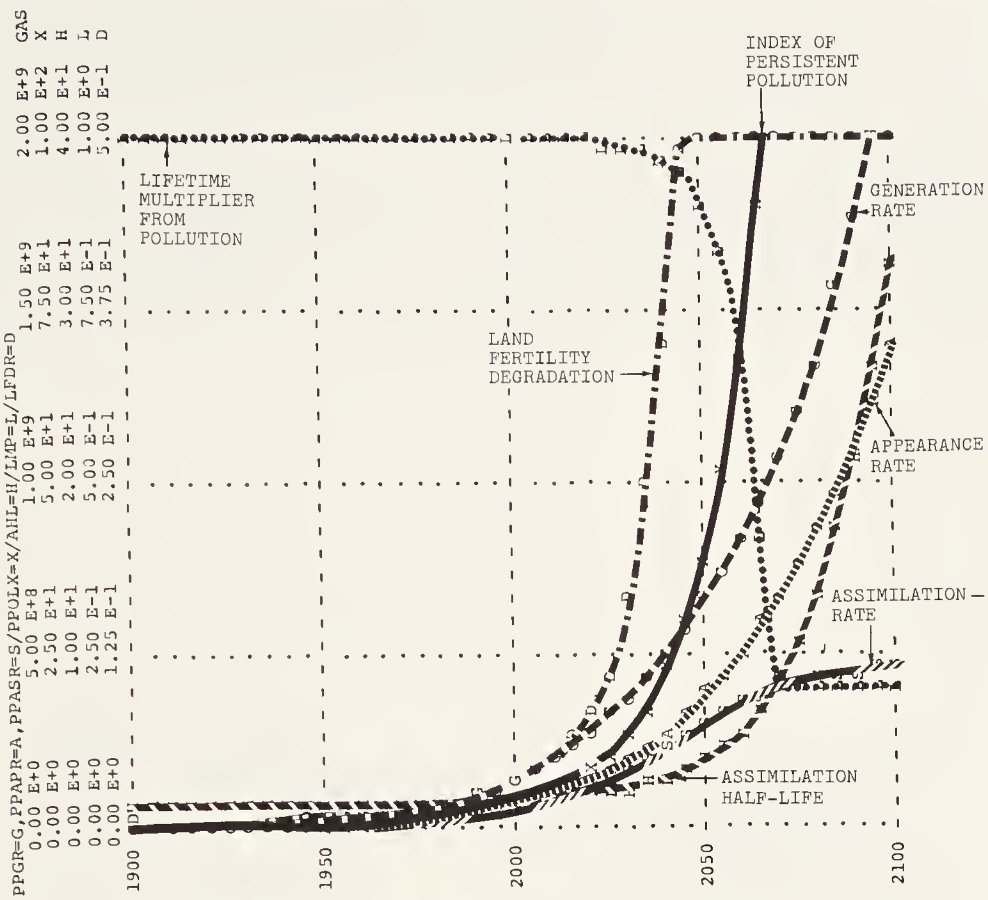


Figure 6-32 Run 6-5: behavior of the pollution sector with decreased toxicity indices

We assumed that most of the sector's parameters are constant over the course of the run. A specification error different from that analyzed in Run 6-5 could occur if there were future technological or social changes that altered the toxicity indices or other sector coefficients at some point beyond 1970. PPOL70 would not be altered by these changes and the time form of PPOLX could be influenced significantly. Later runs in Chapter 6 will illustrate the sector's sensitivity to changes of this sort. So long, however, as the specification errors are constant throughout the run, the insensitivity of the sector observed in Run 6-5 for changes in the toxicity indices is characteristic of the sector's response to other changes as well.

Runs 6-6 and 6-7 (Figures 6-33 and 6-34, respectively) show the response of the pollution sector to revisions in our estimate of the persistent pollution transmission delay PPTD. In Run 6-6, where the transmission delay is doubled to 40 years, the persistent pollution appearance rate PPAPR lags behind the persistent pollution generation rate PPGR by 40 years. In Run 6-7, where the transmission delay is halved to 10 years, PPAPR lags behind PPGR by only 10 years. However, in both runs, the behavior of PPOLX and its effects on life expectancy and land fertility are almost identical to the results shown in Run 6-4. An error in the estimate of the persistent pollution transmission delay PPTD has little effect on the rate of growth of these

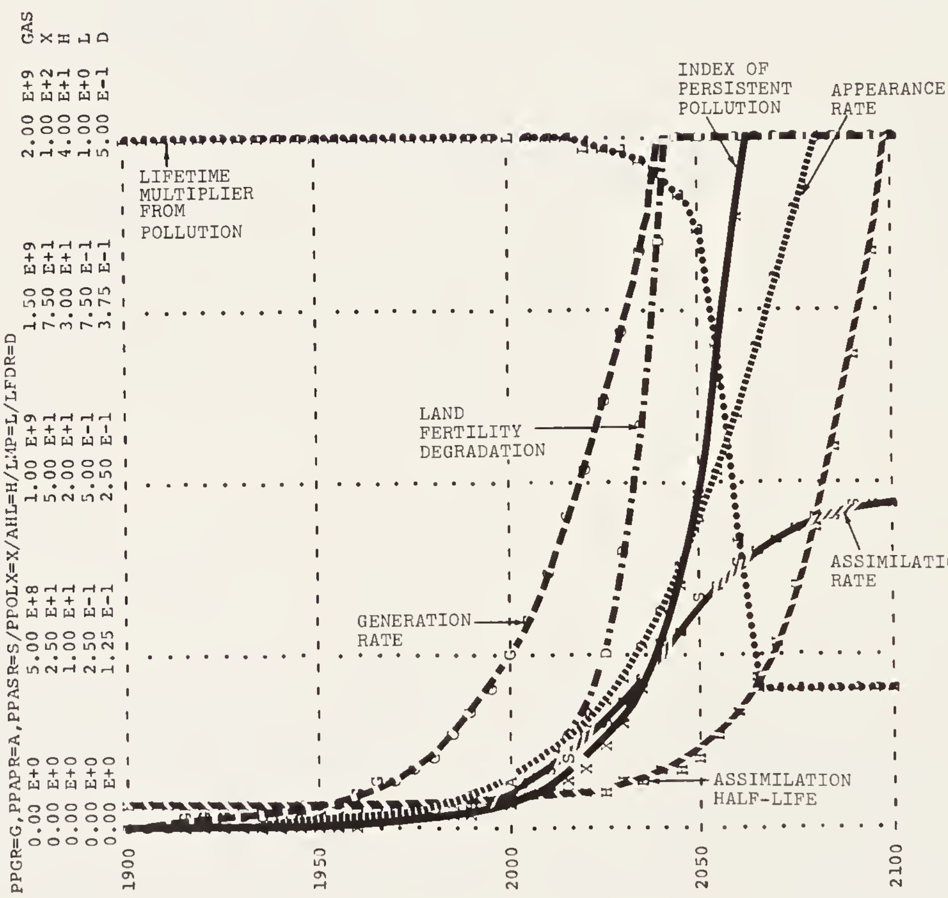


Figure 6-33 Run 6-6: behavior of the pollution sector when the estimate of the persistent pollution transmission delay is doubled

variables as long as we assume that the transmission delay remains constant throughout the model run. The following section explores the behavior of the model when this parameter (PPTD) is varied during the model run to represent the implementation of some new technological policy.

Runs 6-8 and 6-9 (Figures 6-35 and 6-36, respectively) test the sensitivity of the persistent pollution sector behavior shown in Run 6-4 (Figure 6-31) to different estimates of the relationship between the index of persistent pollution PPOLX and the assimilation half-life AHL. Run 6-8 assumes that, with increasing pollution, AHL

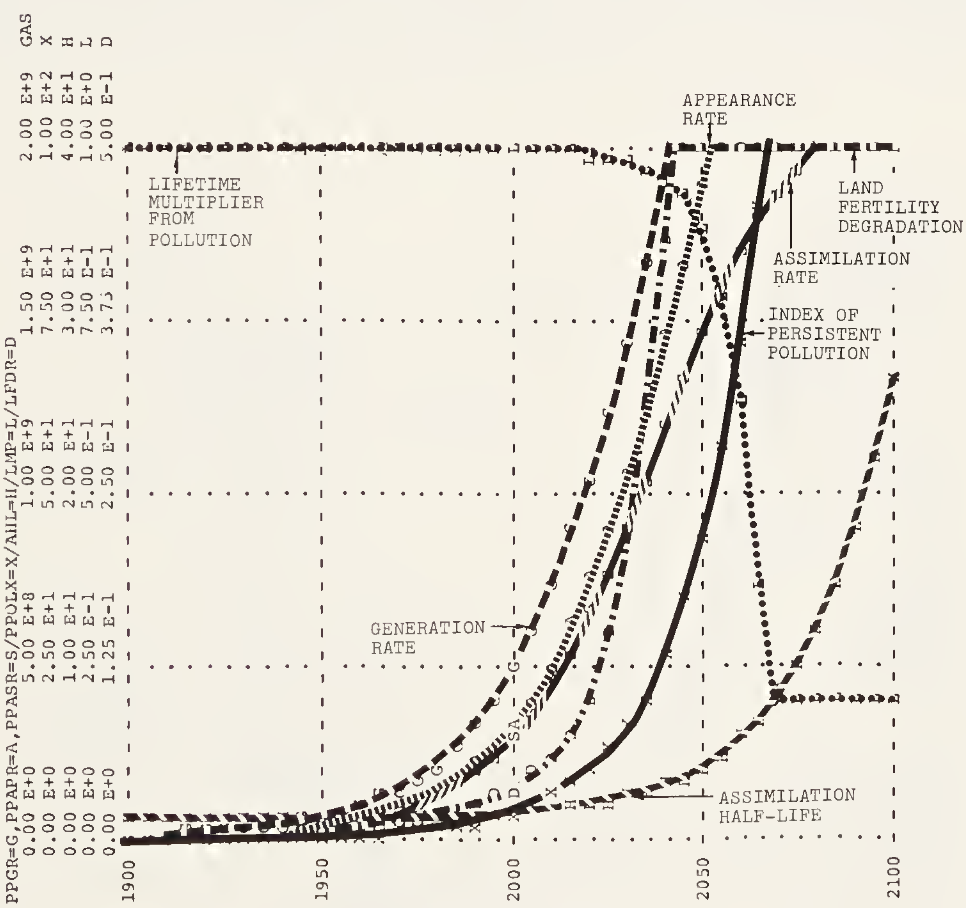


Figure 6-34 Run 6-7: behavior of the pollution sector when the estimate of the persistent pollution transmission delay is halved

will increase twice as rapidly as in Run 6-4. Thus the persistent pollution assimilation rate PPASR is always lower in Run 6-8 than in Run 6-4, and the upper limit to PPASR is cut by 50 percent to 12.5 times the 1970 level. Because of the lower PPASR, PPOLX grows more rapidly in Run 6-8 than in Run 6-4. The time of the maximum damage to life expectancy LE and land fertility LFERT occurs only 10 years earlier in Run 6-8 than in Run 6-4, however, and the basic mode of behavior is unchanged.

Run 6-9 (Figure 6-36) assumes that an increase in the accumulated level of persistent pollutants has no deleterious effects whatsoever on the assimilation half-life AHL. Thus AHL remains constant throughout Run 6-9, which means that there is no upper limit to the rate at which persistent pollutants can be assimilated by the ecosystem. Therefore, PPASR continues to grow throughout the model run, and PPOLX is significantly lower after the year 2000 than in Run 6-4. When no interference with the assimilation process is assumed, PPOLX grows at the same rate as PPGR, more slowly than in the reference run, and the severe pollution crisis observed in Run 6-4 does not occur within the time frame of Run 6-9. While the lower rate of persistent pollution growth in Run 6-9 is still sufficient to decrease LE and increase LFDR

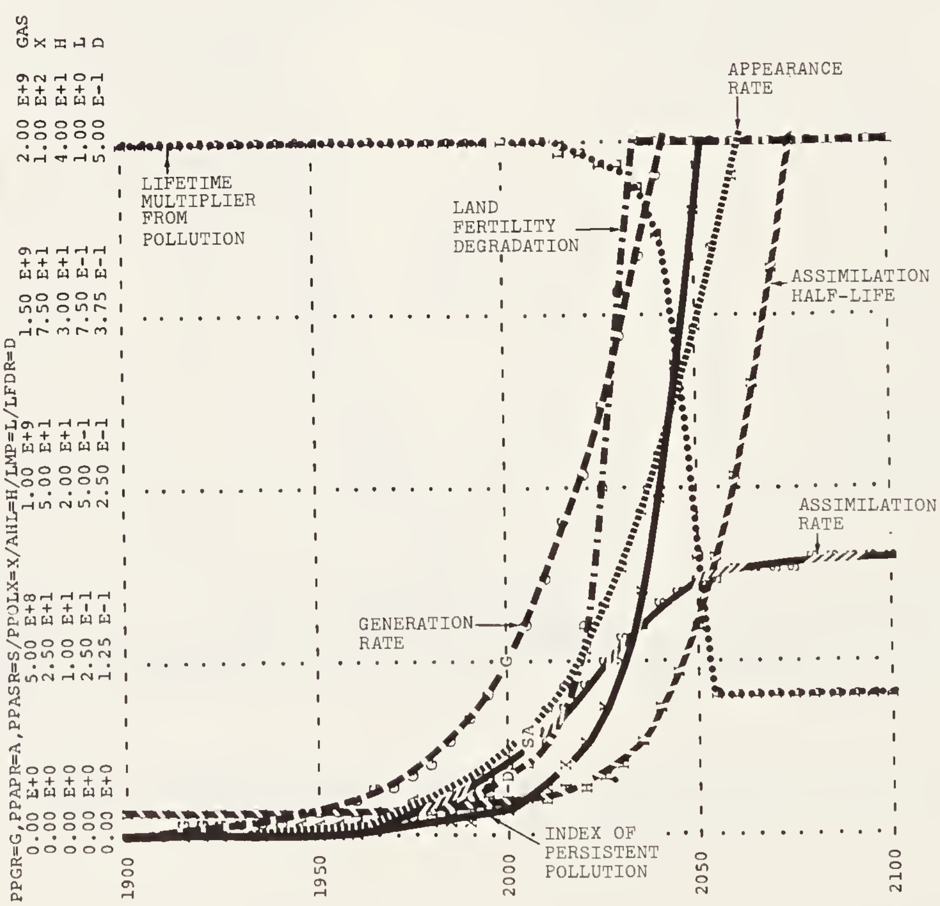


Figure 6-35 Run 6-8: behavior of the pollution sector when the assimilation half-life is assumed to increase twice as fast with a rising index of persistent pollution

within the 200-year time horizon of the model, the differences between Runs 6-9 and 6-4 are significant. Clearly, it is important to gain a better understanding of assimilative processes and limits in the real world.

The basic pollution crisis behavior mode shown in Run 6-4 is caused by continued increases in the rate of generation of persistent pollutants, coupled with an assumed limit to the rate of assimilation of those pollutants. This basic mode was altered significantly by only one of the five changes presented in this section. Only the change made in Run 6-9 affects one of the two basic causes of the pollution crisis. However, assuming that AHL does not increase with PPOLX is more than a simple parameter change: it is in reality a structural change that removes the positive feedback loop relating AHL, PPASR, and PPOL. The removal of this feedback loop implies that there is no finite limit to the rate of assimilation of persistent pollutants. It implies that the assimilative processes of the global environment could deal with a molecule of persistent material as effectively in the presence of 100 times the 1970 level of pollution as they did in 1970. With this assumption Run 6-9 shows that the growth rate of PPOLX is significantly reduced, confirming the general rule that changes in the feedback-loop structure of a dynamic model have a greater effect on a model's behavior than simple parameter changes.

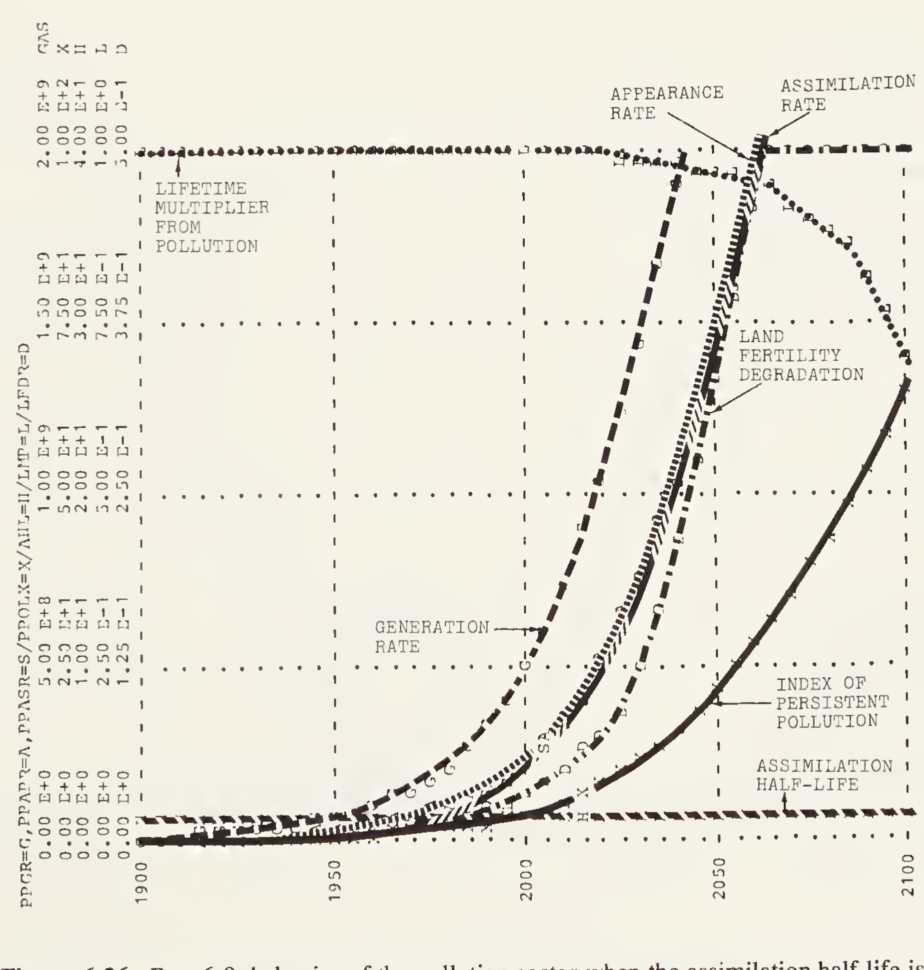


Figure 6-36 Run 6-9: behavior of the pollution sector when the assimilation half-life is assumed to be constant

Effects of New Technologies

Section 6.4 suggested four possible technological policies for pollution control: increasing the pollution transmission delay, increasing the rate of pollution assimilation, decreasing the damage caused by each unit pollution, and reducing the amount of pollution associated with each unit of resource or agricultural input. The following runs test the effectiveness of these four types of technological policies in avoiding the pollution crisis behavior shown in Run 6-4 (Figure 6-31). The exogenous inputs are again those portrayed in Figure 6-30, where continued material growth was assumed. In the real world, policies typically affect more than one relationship; the side effects and trade-offs of real-world policies are often complex and must therefore be modeled carefully when alternative policies are being considered. However, in the following runs we seek only to illustrate the behavior of the persistent pollution sector in response to several generic influences. Thus we assume that the changes we introduce influence only one sector relationship at a time.

Run 6-10 (Figure 6-37) shows the behavior of the persistent pollution sector if the persistent pollution transmission delay PPTD is doubled to 40 years in 1975 to represent the effects of technological advances that slow the transmission of persistent pollutants through the ecosystem. Such a change might be implemented in the real

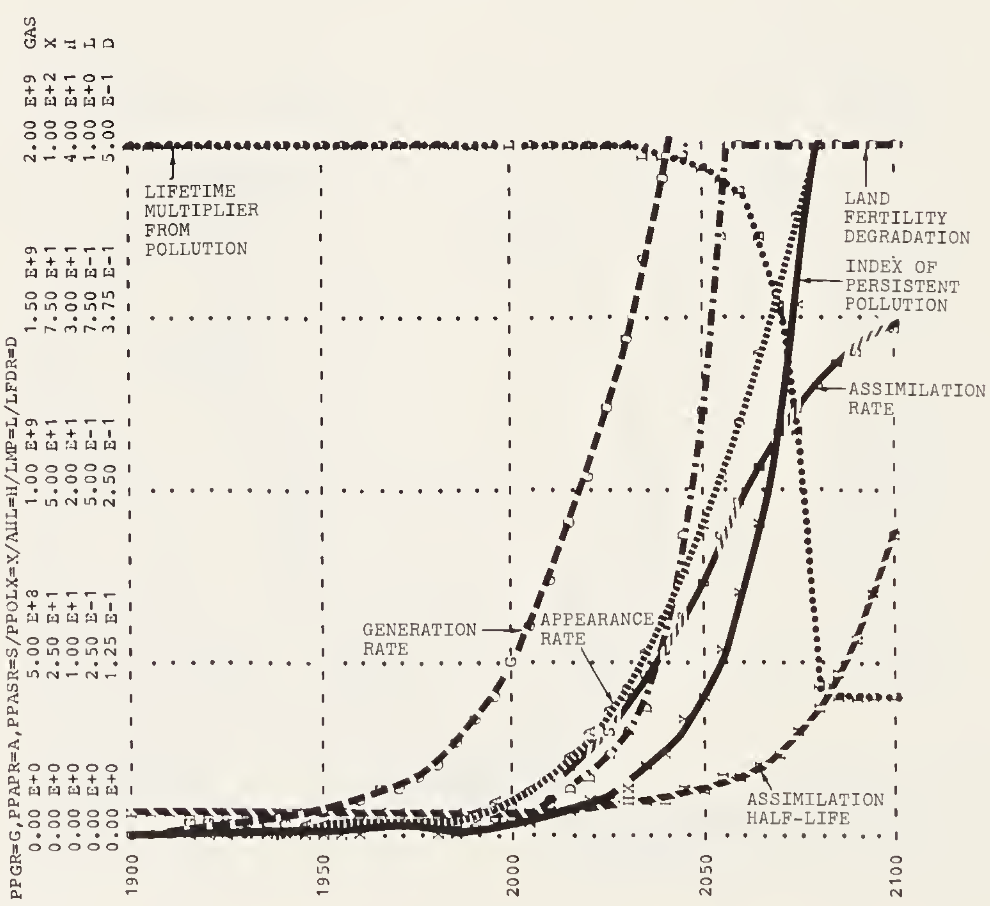


Figure 6-37 Run 6-10: behavior of the pollution sector in response to a doubling of the persistent pollution transmission delay in 1975

world by improved pollution storage techniques or by a shift in the geochemical characteristics of the persistent material emissions. Comparing Runs 6-10 and 6-4, indicates that this policy is effective only in the short term, postponing the rise of persistent pollutants for about 20 years. In the long run, continued growth in the generation of persistent pollutants PPGR counteracts the technological policy and causes PPOLX to grow exponentially. The net effect of this particular technological advance is to delay the damage portrayed in Run 6-4 by 20 years.

Run 6-11 (Figure 6-38) shows the effects of an advance in pollution assimilation technology implemented in 1975. In this run the assimilative limit of the ecosystem is doubled by reducing the effects of high levels of accumulated pollution on the pollution assimilation half-life AHL. As expected, the persistent pollution assimilation rate PPASR continues to grow for a longer period in Run 6-11 than in Run 6-4 because AHL remains lower in Run 6-11 than in Run 6-4. Even with increased assimilation technology, however, the growth in AHL is sufficient to raise the index of pollution PPOLX to 25 times its 1970 level by the year 2045. This value for PPOLX is two-thirds that observed in Run 6-4 in the same year. Doubling the assumed limit to the rate of pollution assimilation PPASR postpones the eventual impact on life expectancies LE and land fertility degradation LFDR by only 15 years.

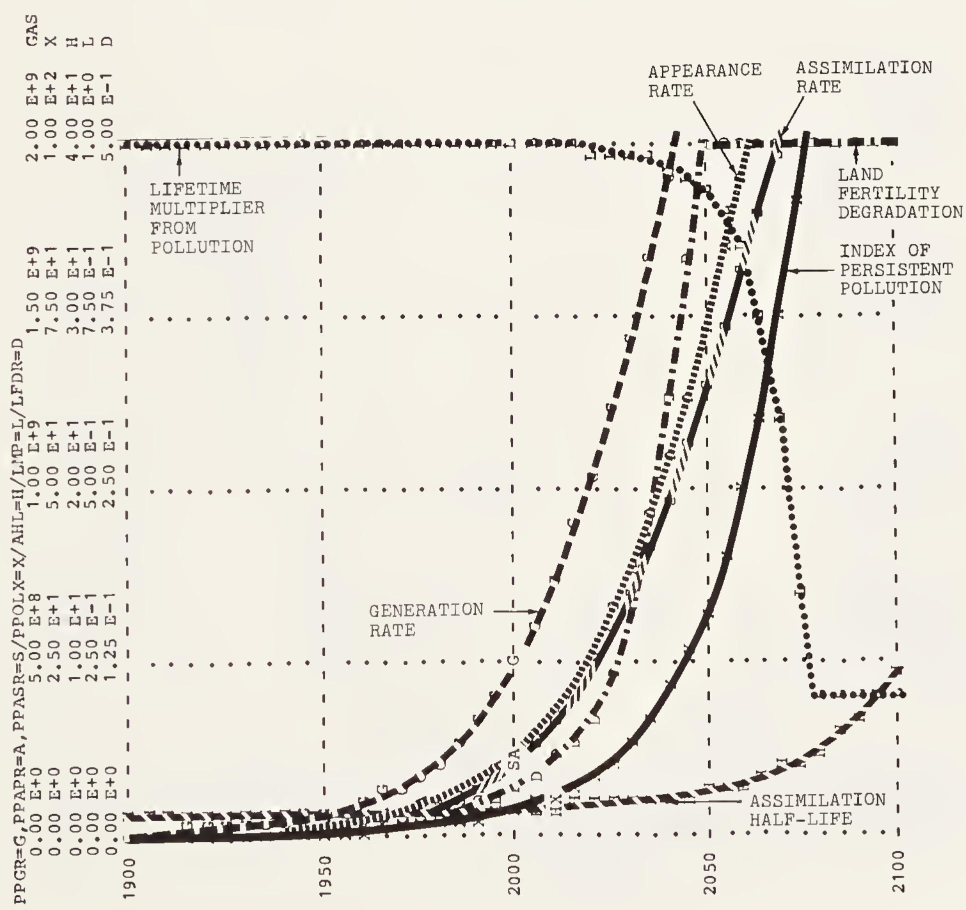


Figure 6-38 Run 6-11: behavior of the pollution sector in response to an advance in persistent pollution assimilation technology in 1975

In Run 6-12 (Figure 6-39), 1975 technological advances are assumed to reduce by 50 percent the effects of PPOLX on LE and LFDR. Here, although damage is indeed reduced at each level of the pollution index PPOLX, equivalent levels of damage are attained only 5 years later than in Run 6-4.

The fourth technological response designed to avoid the pollution crisis behavior is a reduction in the amount of persistent pollution generated per unit of industrial and agricultural output. Run 6-13 (Figure 6-40) shows the effects of a decrease in the amount of pollution generated per unit of output from both sources by a factor of 5 in 1975. The resulting decrease in the persistent pollution generation rate PPGR produces an overall decrease in the index of persistent pollutants PPOLX after 1975. Although the pollutant level is growing rapidly by the year 2100, pollution in that year is still low relative to 1970; thus accumulated pollutants do not interfere significantly with the assimilation process over the course of the run.

In Run 6-13 the pollution crisis is successfully avoided within the time frame of the model through large-scale implementation of pollution generation control technologies, which are assumed to be fully implemented in 1975, well before the damage from rising pollution levels has become evident. Run 6-14 (Figure 6-41) presents the effects of a more realistic model of the effects of pollution generation

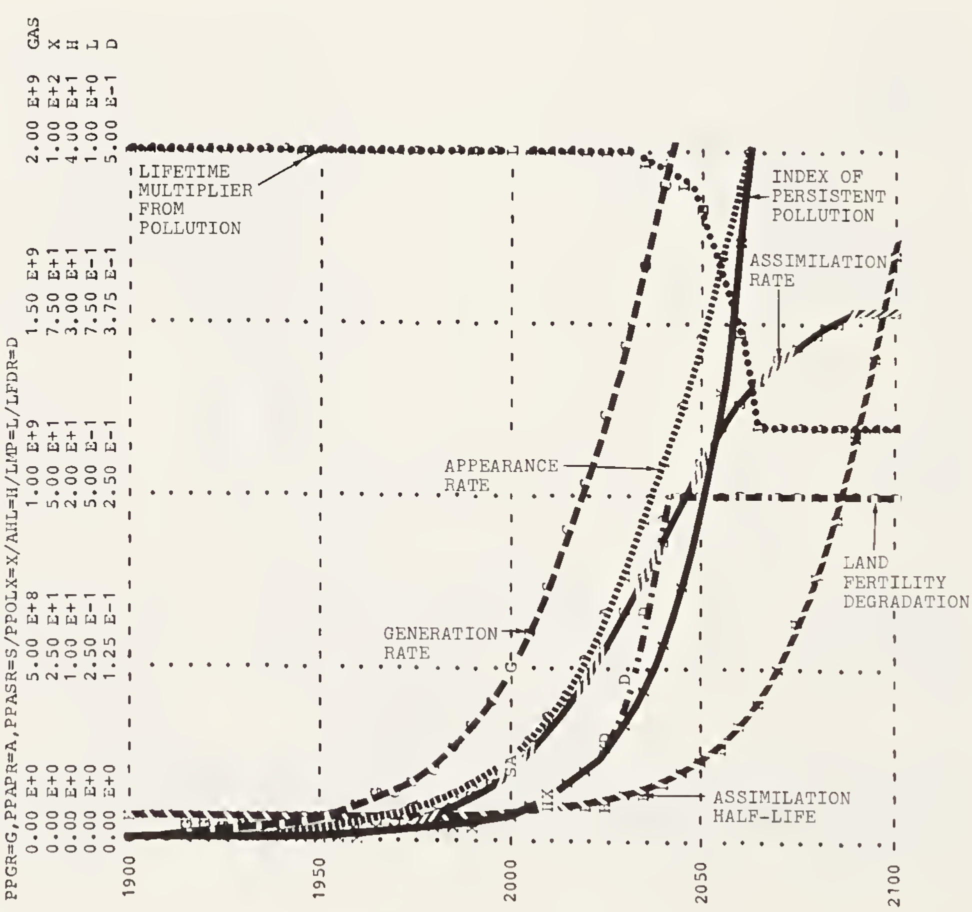


Figure 6-39 Run 6-12: behavior of the pollution sector in response to a 50 percent increase in human health and land fertility technology in 1975

control technologies. Run 6-14 incorporates an adaptive model of technological development: as pollution damage (here measured as a decrease in the lifetime multiplier from pollution LMP) is perceived, new pollution control technologies are developed. The effort applied to the development of new control technologies, measured in a percentage reduction of pollution per year, is proportional to the perceived pollution damage. As very high levels of damage are perceived (a 10 percent drop in life expectancies), new pollution control technologies are developed at their maximum rate, resulting in a 5 percent reduction each year in the amount of pollution generated per unit of output. Since we assumed that the new technologies are developed without cost, we do not lower the rate of growth of industrial output as pollution abatement techniques are implemented. Chapter 7 does include several runs in which the capital costs of new technologies are explicitly modeled. We also assumed that these new technologies are not immediately effective (we incorporated a ten-year delay between the development and implementation of new technologies). Figure 6-42 shows the structural additions assumed for this run.

Run 6-14, a more realistic model of the development of pollution generation control technologies, no longer avoids the pollution crisis observed in Run 6-13. In Run 6-14, pollution generation continues to grow without social constraint past the

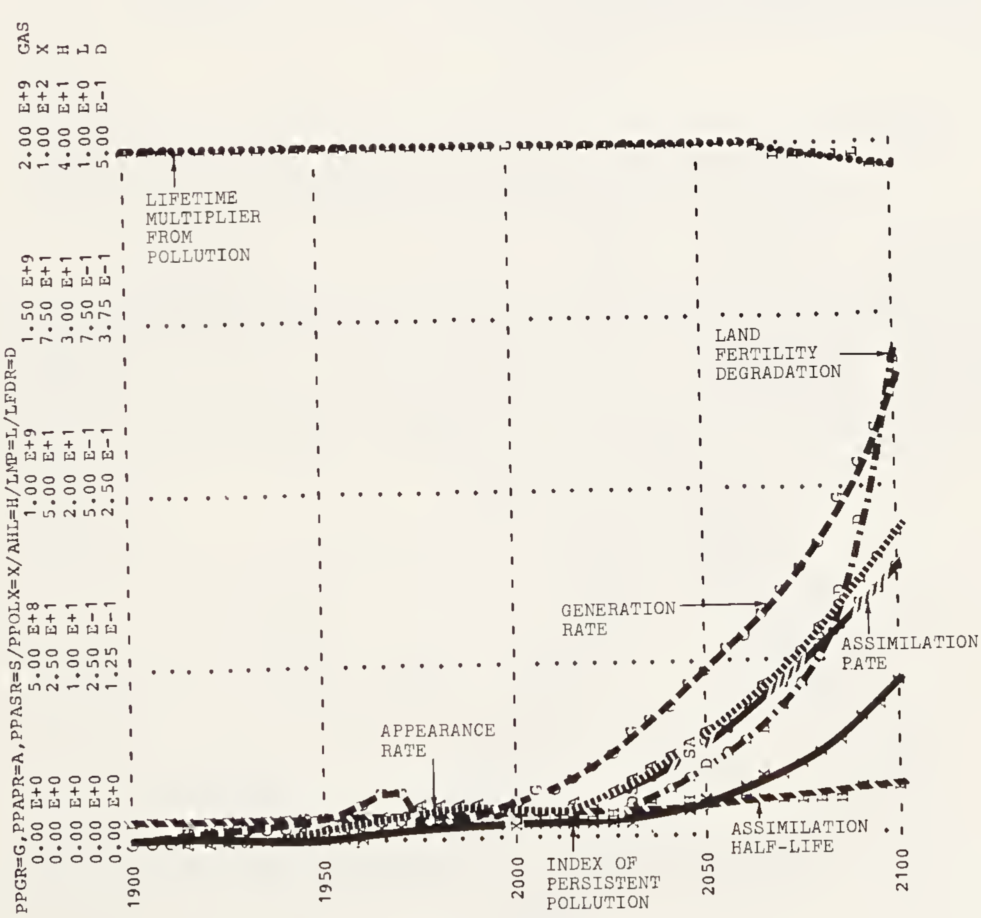


Figure 6-40 Run 6-13: behavior of the pollution sector in response to a sudden increase in persistent pollution generation control technology in 1975

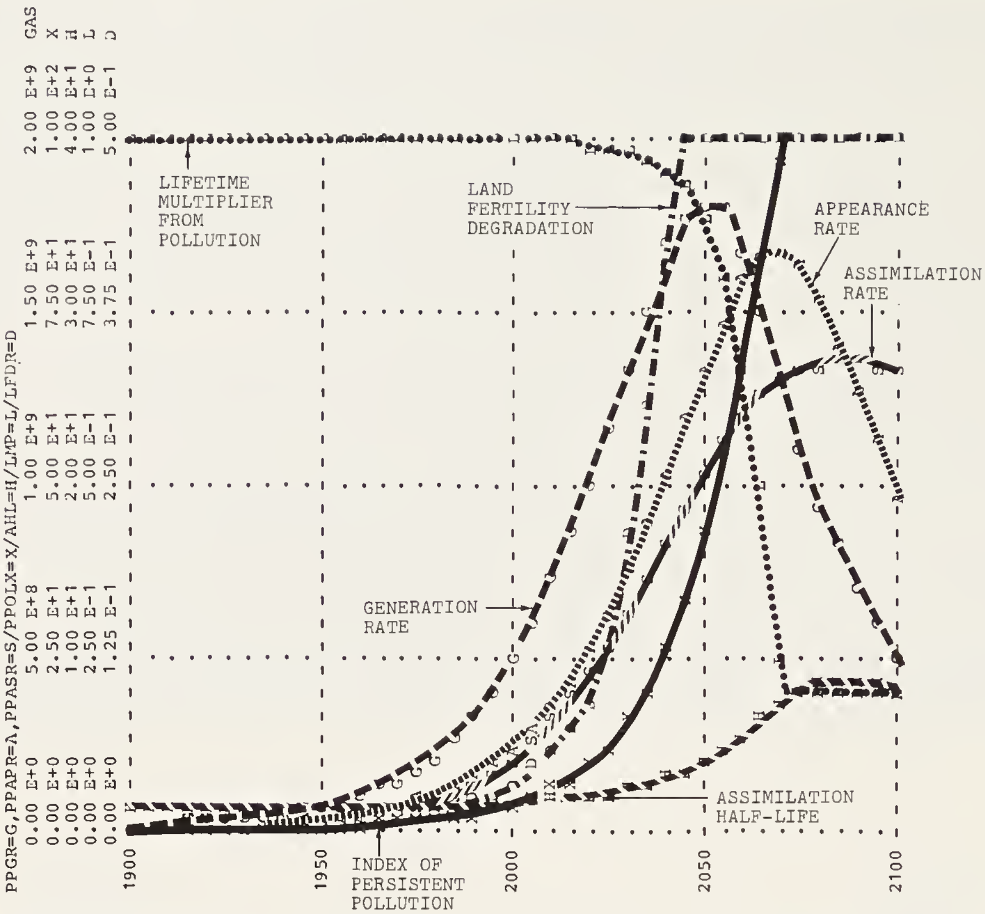


Figure 6-41 Run 6-14: behavior of the pollution sector in response to adaptive persistent pollution generation control technologies when the persistent pollution transmission delay is assumed to be 20 years

year 2020. Since no damage to life expectancies has been perceived, no pollution control technologies have been initiated. After 2020, however, the lifetime multiplier from pollution LMP begins to fall. As this effect is perceived, new pollution control technologies are developed and implemented; pollution generation PPGR thus peaks in the year 2050 and begins to decline thereafter. Because of the 20-year delay in

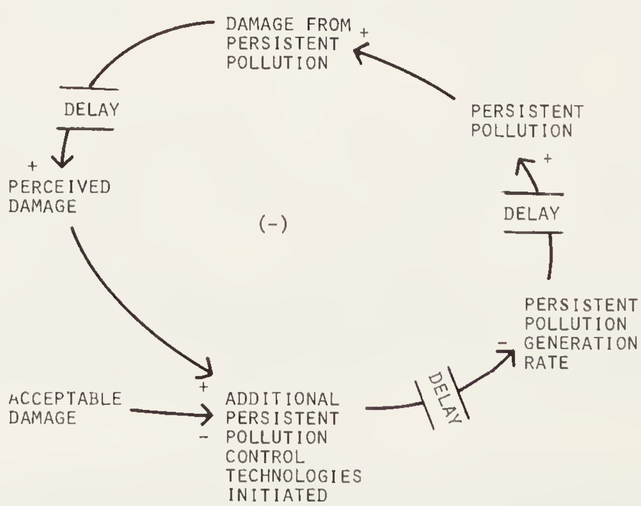


Figure 6-42 Causal-loop diagram of the structural additions designed to test the effects of adaptive persistent pollution generation control technologies

the appearance of persistent pollution, however, the persistent pollution appearance rate PPAPR does not peak until the year 2070. Even though the new pollution control technologies cause the generation of pollutants to decline rapidly after 2050, PPAPR continues to increase for 20 years thereafter, causing the index of persistent pollution PPOLX to continue growing. Persistent pollution does not begin to decrease until around the year 2085 (35 years after the decline in pollution generation), when PPAPR finally drops below PPASR.

The long delay in the response of the index of persistent pollution PPOLX to pollution control policies renders the assumed adaptive control policy ineffective. The lifetime multiplier from pollution LMP still reaches its minimum value, 0.2, during the course of the run. If new pollution control technologies are not developed until after significant damage has been observed, the long delays involved in reducing the pollution damage may allow persistent pollutants to remain above acceptable levels for several decades. In contrast to Run 6-14, an effective pollution generation control policy must anticipate those delays by reducing pollution generation well before pollution damage becomes evident (as in Run 6-13).

Run 6-15 (Figure 6-43) shows the behavior of the persistent pollution sector with the same adaptive pollution generation control policies employed in Run 6-14,

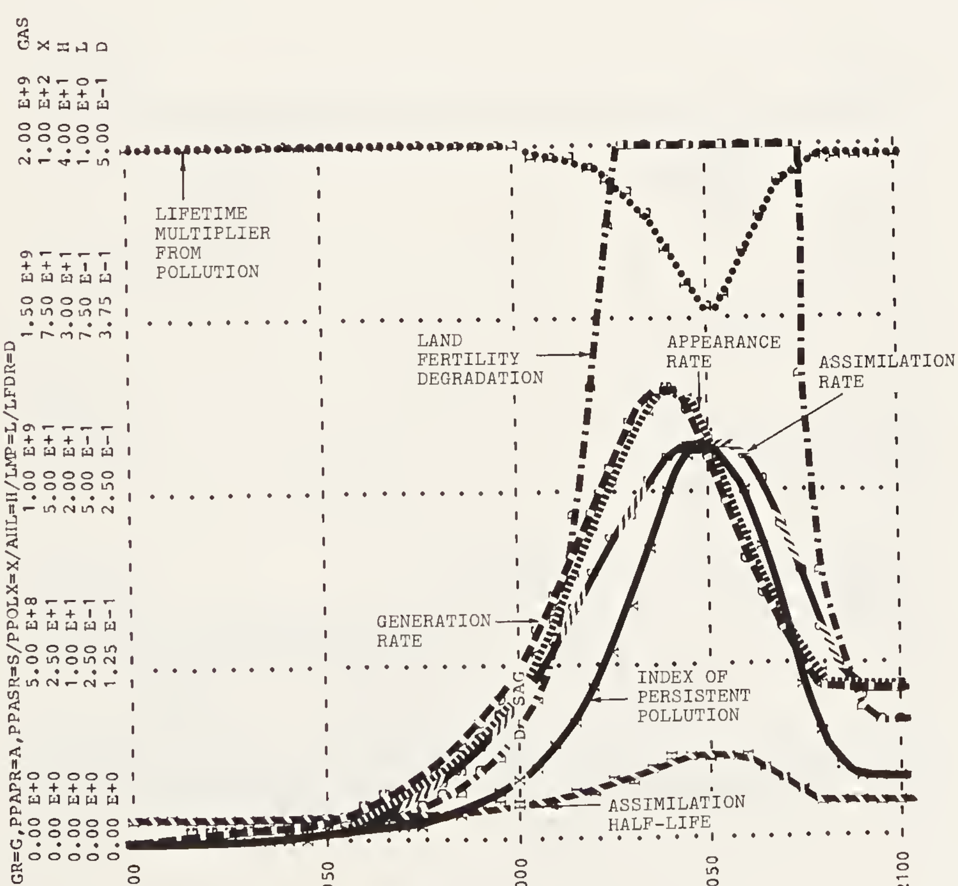


Figure 6-43 Run 6-15: behavior of the pollution sector in response to adaptive persistent pollution generation control technologies when the persistent pollution transmission delay is assumed to be 2 years

but with an assumed persistent pollution transmission delay of 2 years instead of 20 years. When the pollution transmission delay is assumed to be much shorter, the resulting overshoot in the behavior of the index of persistent pollution PPOLX is less severe than that shown in Run 6-14. However, because of the remaining delays in the perception of the damage and the development and implementation of the required new technologies, significant negative effects on LE and LFDR are incurred before the new technologies can effectively control the level of pollution.

Equilibrium Runs

Runs 6-16 through 6-18 (Figures 6-44 through 6-46) examine the behavior of the persistent pollution sector if past material growth trends are interrupted and the four causes of pollution generation level off. The technological policies described in connection with Runs 6-10 through 6-15 assumed no pervasive change in the material growth trends illustrated in Figure 6-31. The stabilization of demographic and material growth in Runs 6-16 through 6-18 is meant to simulate the results of socially oriented policies implemented to reduce the growth in population and in resource use.

Run 6-16 (Figure 6-44) shows the behavior of the persistent pollution sector when pollution-generating material growth is stopped in the year 2000 so that the

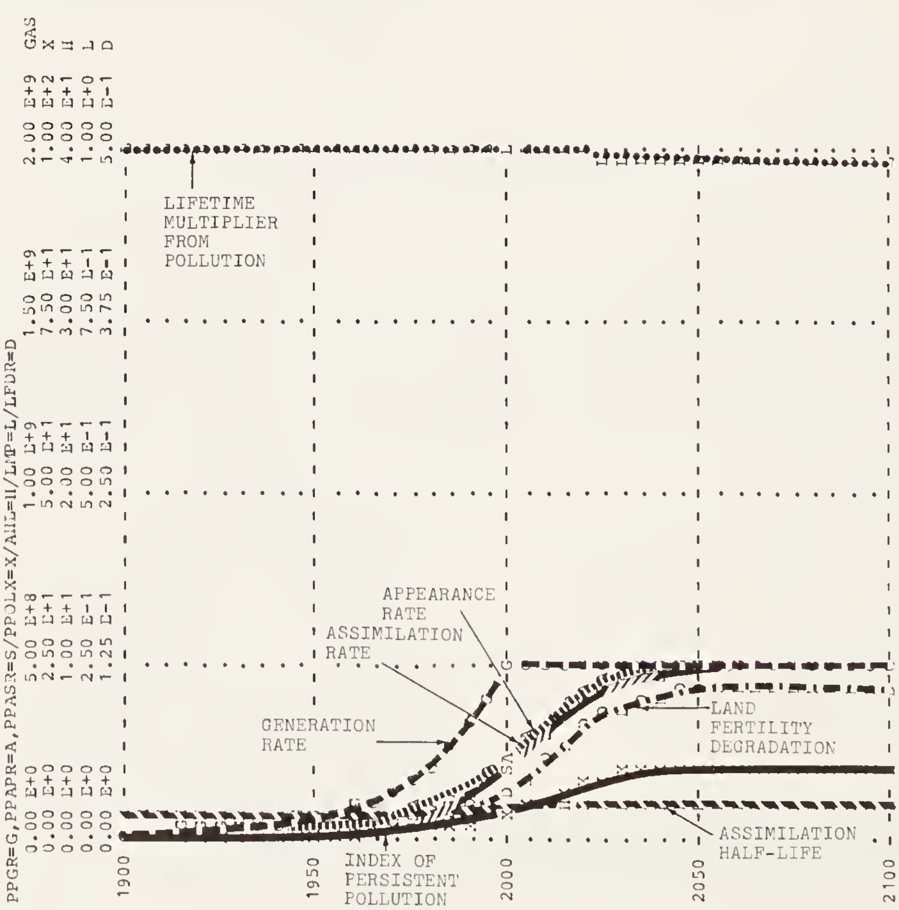


Figure 6-44 Run 6-16: behavior of the pollution sector when persistent pollution generation stabilizes in the year 2000

persistent pollution generation rate PPGR becomes constant after the year 2000. Because of the persistent pollution transmission delay, the index of persistent pollution PPOLX does not stabilize until approximately 30 years later. Still, when PPGR stabilizes in 2000, the final level of pollution is only 10 times that in 1970, and PPOLX is low enough to cause little or no damage to the globe's land fertility and to the population's life expectancy.

Run 6-17 (Figure 6-45) shows the effects of a 20-year postponement in the stabilization policies enacted in Run 6-16. Material growth is continued for an additional 20 years, to the year 2020, which permits roughly one doubling of the persistent pollution generation rate PPGR above its level in the year 2000. In this run the beginning of a pollution crisis is evident. As the level of pollution rises, the assimilation half-life AHL begins to rise, and persistent pollution accumulates even faster. In response to doubling PPGR, the level of pollution eventually stabilizes at a level 4 times the final level reached in Run 6-16. The high pollution levels in this run do cause considerable damage to the ecosystem, for the land fertility degradation rate LFDR is considerably increased and the lifetime multiplier from pollution LMP decreases significantly after the year 2020.

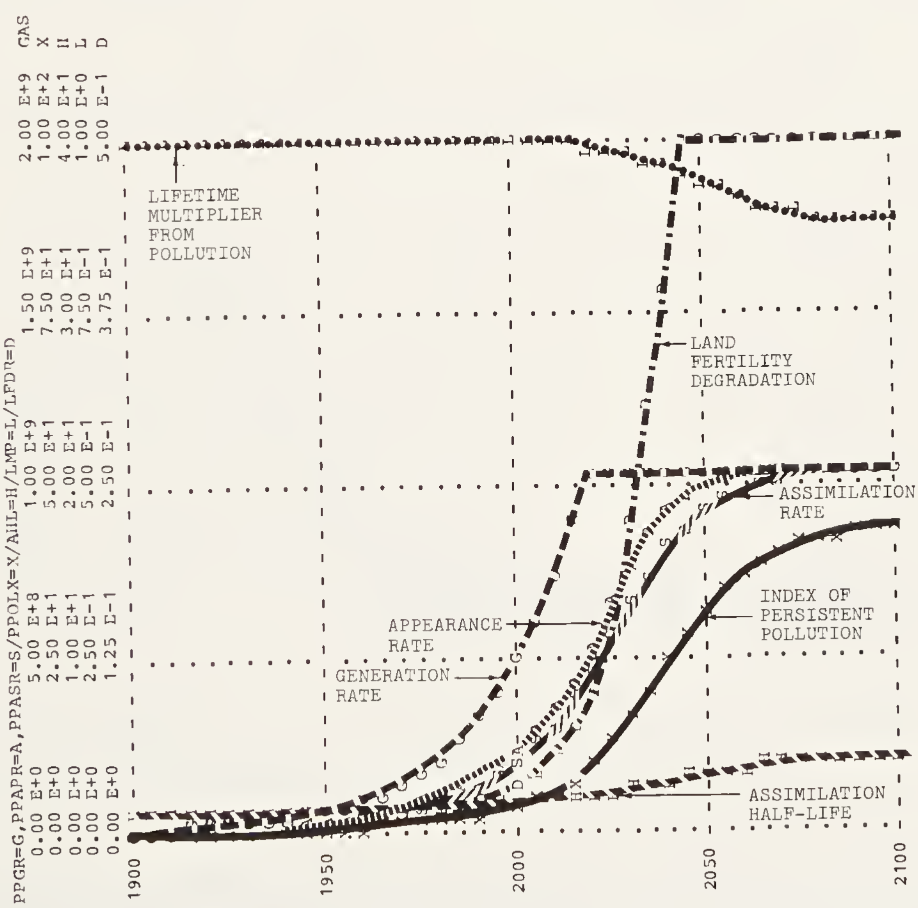


Figure 6-45 Run 6-17: behavior of the pollution sector when persistent pollution generation stabilizes in the year 2020

Run 6-14 (Figure 6-41) showed that the process of technological development might not succeed fully in avoiding the pollution crisis mode of behavior. In Run 6-18 (Figure 6-46) the adaptive pollution generation control technologies of Run 6-14 are combined with the social policies of Run 6-17 so that the generation of pollutants PPGR ceases to grow in the year 2020. This combination of social and technological policies is considerably more successful in avoiding high levels of damage than either policy implemented separately. In both Run 6-14 and Run 6-17, high pollution levels cause considerable damage to life expectancies and land fertility in spite of active technological policies. In Run 6-18, however, the social policies that stabilize pollution generation PPGR reduce the rate of growth of persistent pollution PPOL after the year 2020. As life expectancies begin to fall, new technological policies of pollution control are developed to further reduce the growth in persistent pollution. Because pollution generation has already leveled off before new technologies are implemented, the technological policies are much more effective.* These technologi-

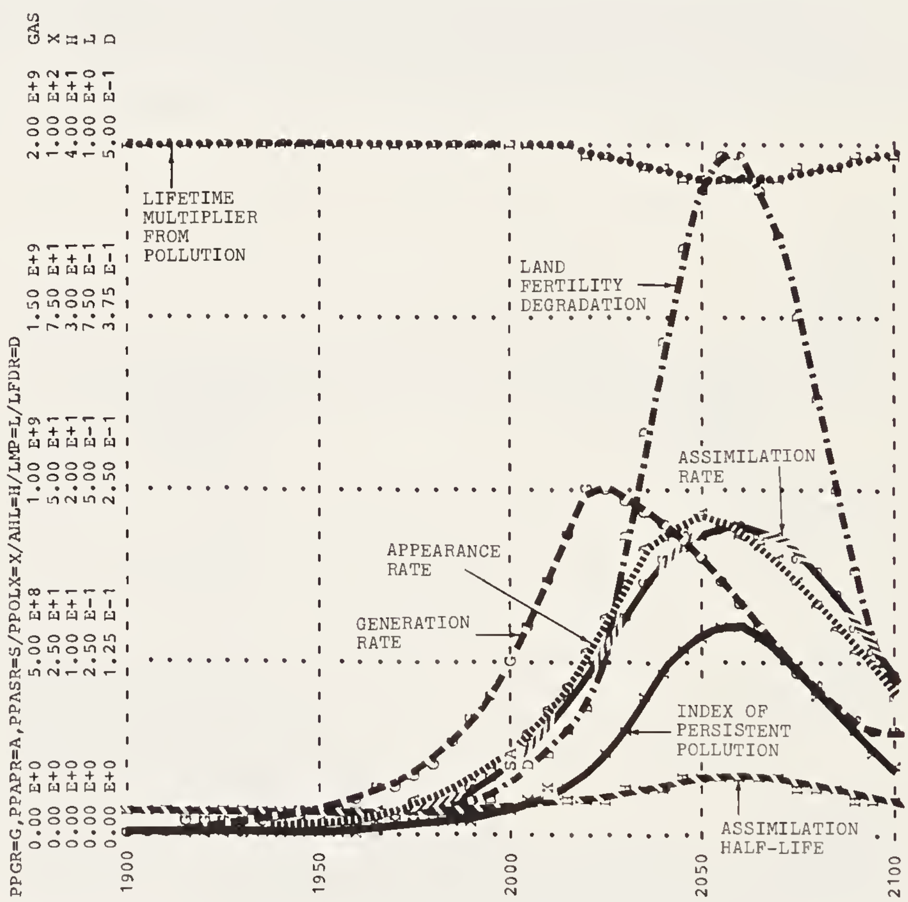


Figure 6-46 Run 6-18: behavior of the pollution sector when adaptive persistent pollution generation control technologies are combined with material equilibrium in the year 2020

*The land fertility degradation rate LFDR grows to high levels in Run 6-18 because new pollution control technologies are developed only in response to a decrease in life expectancies, measured by the lifetime multiplier from pollution LMP. A more realistic control policy might develop new pollution control technologies as a function of the damage to both life expectancies and land fertility.

cal policies are more successful when combined with growth-reducing policies because the long delays before the full effects of these new technologies are felt are much less critical to the behavior of the sector when pollution generation is no longer growing.

Summary

The preceding eighteen pollution sector runs illustrate several important behavioral characteristics of global persistent pollution as modeled in World3. One important characteristic is the effect of delays on the behavior of the sector. Because of the transmission delay, the level of pollution may increase for a decade or more after the rate of generation has become constant or even begun to decline. The delay implicit in the assimilation half-life AHL influences the amount of pollution present under steady-state conditions (when generation, appearance, and assimilation are all equal and the level of pollution is constant). When the rate of generation is low and constant, AHL is comparatively short (1.5 years), and the assimilation rate equals the appearance rate at rather low levels of pollution. Ambient pollution will be only about twice the amount of pollution assimilated annually. When the generation rate is high, pollution mounts, and the delay inherent in assimilation increases. Then the ambient pollution must grow to much more than twice the amount assimilated annually before the assimilation rate equals the rate of generation and the pollution level stabilizes.

The delay implicit in the assimilation half-life AHL also causes the assimilation rate to lag behind both the appearance rate and the generation rate. As a result, ambient pollution levels tend to rise whenever the generation rate is increasing. The strength of the relationship between the level of pollution and AHL is also an important determinant of the model's behavior. If AHL is not raised by increasing pollution levels, then the pollution crisis mode becomes much less likely. Because the actual magnitude and the long-term determinants of AHL are not well understood for the total class of global persistent pollutants, obtaining information on AHL would be an important empirical research objective.

The magnitude of the pollution transmission delay PPTD has little effect on the general behavior mode of the sector if growth continues. However, when adaptive pollution control policies are instituted in response to observed pollution damage (the most likely case in the real world), the length of the transmission delay becomes very important. The greater the delays in the response of society to pollution damage, the longer will society be exposed to unacceptably high levels of pollution before abatement becomes effective. Thus longer transmission delays make effective pollution control much more difficult.

Finally, as long as there is exponential growth in the generation of pollution, ameliorative measures ultimately do little to prevent the model from exhibiting unacceptable levels of pollution damage. Growth in the generation of pollution must eventually stop if unacceptable consequences are to be avoided. An ostensibly short delay in acting to curtail growth in the generation of pollution may add disproportionately to the pollution damage that is caused. Pollution stabilization measures enacted in the World3 pollution sector in 2020 left the ultimate ambient pollution levels 4 times as great as when the same policies were enacted in the year 2000.

Although these inclusions are derived from hypothetical exogenous inputs from the other sectors of World3, they will facilitate an understanding of the behavior of the pollution sector once it is immersed in the remainder of World3. Chapter 7 tests the behavior of the entire world model when the dynamic behavior of all variables is endogenously determined over time.

APPENDIX A: PROGRAM LISTING

```
          POLTR
          NOTE
          NOTE   PERSISTENT POLLUTION SECTOR WITH EXOGENOUS INPUTS
          NOTE
137       R      PPGR.KL=(PPGIO.K+PPGAO.K)*(PPGF.K)
138       A      PPGF.K=CLIP(PPGF2.K,PPGF1,TIME.K,PYEAR)
          C      PPGF1=1
          A      PPGF2.K=SWITCH(PPGF21,PPGF22.K,SWAT)
          C      PPGF21=1
139       A      PPGIO.K=PCRUM.K*POP.K*FRPM*IMEF*IMTI
          C      FRPM=.02
          C      IMEF=.1
          C      IMTI=10
140       A      PPGAO.K=AIPH.K*AL.K*FIPM*AMTI
          C      FIPM=.001
          C      AMTI=1
141       R      PPAPR.KL=DELAY3(PPGR.JK,PPTD.K)
          A      PPTD.K=CLIP(PPTD2,PPTD1,TIME.K,PYEAR)
          C      PPTD1=20
          C      PPTD2=20
142       L      PPOL.K=PPOL.J+(DT)(PPAPR.JK-PPASR.JK)
          N      PPOL=PPOLI
          C      PPOLI=2.5E7
143       A      PPOLX.K=PPOL.K/PPOL70
          C      PPOL70=1.36E8
144       R      PPASR.KL=PPOL.K/(AHL.K*1.4)
145       A      AHLM.K=TABHL(AHLMT,PPOLX.K,1,1001,250)
          T      AHLMT=1/11/21/31/41
146       A      AHL.K=AHL70*AHLM.K
          C      AHL70=1.5
          NOTE
          NOTE   EXOGENOUS INPUTS TO THE PERSISTENT POLLUTION SECTOR
          NOTE
          NOTE   TABLE FUNCTIONS FOR CONTINUED MATERIAL GROWTH
          NOTE
          A      PCRUM.K=TABHL(PCRUMT,TIME.K,1900,2100,20)*1E-2
          T      PCRUMT=17/30/52/78/138/280/480/660/700/700/700
          A      POP.K=TABHL(POPT,TIME.K,1900,2100,20)*1E8
          T      POPT=16/19/22/31/42/53/67/86/109/139/176
          A      AIPH.K=TABHL(AIPHT,TIME.K,1900,2100,20)
          T      AIPHT=6.6/11/20/34/57/97/168/290/495/845/1465
          A      AL.K=TABHL(ALT,TIME.K,1900,2100,20)*1E8
          T      ALT=9/10/11/13/16/20/24/26/27/27/27
          NOTE
          NOTE   ADAPTIVE TECHNOLOGICAL CONTROL CARDS
          NOTE
          C      SWAT=0
          A      PPGF22.K=DLINF3(PCTI.K,TDD)
          C      TDD=10
          L      PCTI.K=PCTI.J+(DT)(PCTIR.JK)
          N      PCTI=1
          R      PCTIR.KL=CLIP(PCTI.K*PCTCM.K,0,TIME.K,PYEAR)
          A      PCTCM.K=TABHL(PCTCMT,1-PLMP.K,0,.10,.10)
          T      PCTCMT=0/-.05
          A      PLMP.K=DLINF3(LMP.K,PD)
          C      PD=5
          NOTE
          NOTE   POLLUTION DAMAGE FUNCTIONS
          NOTE
          A      LMP.K=CLIP(LMP2.K,LMP1.K,TIME.K,PYEAR)
          A      LMP1.K=TABHL(LMP1T,PPOLX.K,0,100,10)
```

```
T       LMP1T=1/.99/.97/.95/.90/.85/.75/.65/.55/.40/.20
A       LMP2.K=TABHL(LMP2T,PPOLX.K,0,100,10)
T       LMP2T=1/.99/.97/.95/.90/.85/.75/.65/.55/.40/.20
A       LFDR.K=CLIP(LFDR2.K,LFDR1.K,TIME.K,PYEAR)
A       LFDR1.K=TABHL(LFDR1T,PPOLX.K,0,30,10)
T       LFDR1T=0/.1/.3/.5
A       LFDR2.K=TABHL(LFDR2T,PPOLX.K,0,30,10)
T       LFDR2T=0/.1/.3/.5
NOTE
NOTE    CONTROL CARDS
NOTE
N       TIME=1900
C       PYEAR=1975
SPEC    DT=1/LENGTH=2100/PRTPER=0/PLTPER=5
PLOT    PPGR=G,PPAPR=A,PPASR=S(0,2E9)/PPOLX=X(0,100)/
X       AHL=H(0,40)/LMP=L(0,1)/LFDR=D(0,.5)
RUN     STANDARD
NOTE
NOTE    PARAMETER CHANGES FOR THE POLLUTION SECTOR RUNS
NOTE
NOTE    RUNS SHOWING RESPONSE TO PULSE AND STEP INPUTS
NOTE
NOTE    ** THE FOLLOWING CHANGE MUST BE MADE IN EDIT MODE:
NOTE    ** R PPGR.KL=1E10*CLIP(1,0,TIME.K,1920)*CLIP(0,1,TIME.K,1922)
C       PLTPER=2
C       LENGTH=1980
C       PPOLI=0
PLOT    PPGR=G(0,1E10)/PPAPR=A,PPASR=S(0,1E9)/PPOLX=X(0,24)/
X       AHL=H(0,40)/LMP=L(0,1)/LFDR=D(0,.5)
RUN     FIGURE 6-26: PULSE INPUT
NOTE    ** THE FOLLOWING CHANGE MUST BE MADE IN EDIT MODE:
NOTE    ** R PPGR.KL=STEP(1E9,1920)+STEP(-1E9,2000)
C       PPOLI=0
PLOT    PPGR=G,PPAPR=A,PPASR=S(0,1E9)/PPOLX=X(0,40)/
X       AHL=H(0,40)/LMP=L(0,1)/LFDR=D(0,.5)
RUN     FIGURE 6-27: STEP INPUT
NOTE
NOTE    HISTORICAL RUN
NOTE
C       PLTPER=2
C       LENGTH=1970
PLOT    PCRUM=R(0,1)/POP=P(0,4E9)/AL=L(0,2E9)/
X       AIPH=$(0,50)/PPGR=G(0,2E8)
RUN     FIGURE 6-28: HISTORICAL RUN INPUTS
C       PLTPER=2
C       LENGTH=1970
PLOT    PPGR=G,PPAPR=A,PPASR=S(0,2E8)/PPOLX=X(0,1)/
X       AHL=H(0,2)/LMP=L(0,1)/LFDR=D(0,.5)
RUN     FIGURE 6-29: HISTORICAL RUN
NOTE
NOTE    RUN SIMULATING RESPONSE TO CONTINUED MATERIAL GROWTH
NOTE
PLOT    PCRUM=R(0,8)/POP=P(0,16E9)/AL=L(0,4E9)/
X       AIPH=$(0,1500)/PPGR=G(0,8E9)
RUN     FIGURE 6-30: POLLUTION CRISIS INPUTS
PLOT    PPGR=G,PPAPR=A,PPASR=S(0,2E9)/PPOLX=X(0,100)/
X       AHL=H(0,40)/LMP=L(0,1)/LFDR=D(0,.5)
RUN     FIGURE 6-31: POLLUTION CRISIS
NOTE
NOTE    SENSITIVITY TESTS
NOTE
C       IMTI=1
C       AMTI=.5
C       PPOL70=4.03E7
RUN     FIGURE 6-32: TOXICITY SENSITIVITY
C       PPTD1=40
C       PPTD2=40
C       PPOL70=8.19E7
RUN     FIGURE 6-33: DOUBLE TRANSMISSION DELAY
C       PPTD1=10
C       PPTD2=10
C       PPOL70=1.9E8
RUN     FIGURE 6-34: HALVED TRANSMISSION DELAY
T       AHLMT=1/21/41/61/81
RUN     FIGURE 6-35: HIGHER AHL
T       AHLMT=1/1/1/1/1
RUN     FIGURE 6-36: CONSTANT AHL
NOTE
NOTE    RUNS SIMULATING TECHNOLOGICAL POLICIES
NOTE
```

```
C       PPTD2=40
RUN     FIGURE 6-37: TECHNOLOGICAL INCREASE IN TRANSMISSION DELAY
T       AHLMT=1/6/11/16/21
RUN     FIGURE 6-38: ASSIMILATION TECHNOLOGY
T       LMP2T=1/1/.99/.98/.95/.92/.88/.82/.77/.70/.60
T       LFDR2T=0/.05/.15/.25
RUN     FIGURE 6-39: DAMAGE TECHNOLOGIES
C       PPGF21=.2
RUN     FIGURE 6-40: POLLUTION CONTROL TECHNOLOGY
C       SWAT=1
RUN     FIGURE 6-41: ADAPTIVE TECHNOLOGIES
C       SWAT=1
C       PPTD1=2
C       PPTD2=2
RUN     FIGURE 6-43: ADAPTIVE TECHNOLOGIES, PPTD=2 YEARS
NOTE
NOTE    EQUILIBRIUM RUNS
NOTE
T       PCRUMT=17/30/52/78/138/280/280/280/280/280/280
T       POPT=16/19/22/31/42/53/53/53/53/53/53
T       AIPHT=6.6/11/20/34/51/97/97/97/97/97/97
T       ALT=9/10/11/13/16/20/20/20/20/20/20
RUN     FIGURE 6-44: EQUILIBRIUM IN 2000
T       PCRUMT=17/30/52/78/138/280/480/480/480/480/480
T       POPT=16/19/22/31/42/53/67/67/67/67/67
T       AIPHT=6.6/11/20/34/51/97/168/168/168/168/168
T       ALT=9/10/11/13/16/20/24/24/24/24/24
RUN     FIGURE 6-45: EQUILIBRIUM IN 2020
T       PCRUMT=17/30/52/78/138/280/480/480/480/480/480
T       POPT=16/19/22/31/42/53/67/67/67/67/67
T       AIPHT=6.6/11/20/34/57/97/168/168/168/168/168
T       ALT=9/10/11/13/16/20/24/24/24/24/24
C       SWAT=1
RUN     FIGURE 6-46: ADAPTIVE CONTROL AND EQUILIBRIUM IN 2020
```

APPENDIX B: PARAMETER CHANGES TO RUN DDT AND MERCURY MODELS

Figure 6-15 An illustration of the transmission delays associated with diffusion of DDT through the global environment—the relations between the rate of DDT application over cropland and the level of DDT in marine fish tissue.

To the DDT model reported in Randers (1973), in edit mode:
add A TDDT.K=S.K+A.K+R.K+O.K+F.K
change equation 3 A AR.K=TABHL(ART,TIME.K,1948, 1952,2)*1E4
change equation 3.1 T ART=0/100/0

in rerun mode:
C LENGTH=2000
PLOT AR=A,S=S(0,1E6)/F=F(0,400)/TDDT=T

Figure 6-16 An illustration of the transmission delay associated with the diffusion of mercury through the global environment—the relation between the rate of mercury release to fresh water and the level of mercury in marine fish tissue.

To the mercury model listed in Anderson and Anderson (1973), in edit mode:
add A TM.K=AM.K+AO.K+MM.K+MO.K+SM.K+SO.K+OM.K+OO.K +FM.K+FO.K

change equation 19 A CMOX.K=TABHL(CMOXT,CMM.KC,0,100,50)
change equation 19.1 T CMOXT=0/2.5/5
change equation 20 R BC.KL=MAX(0,(CMOX.K−CMO.K)/DT*(MUD/1E9)

in rerun mode:

```
C AMB =0   C OOB =0
C AOB =0   C FMB =0
C MMB=0    C FOB =0
C MOB =0   C PIT  =4000
C SMB =0   C EN   =0
C SOB =0   T P1T  =0/1E2/0/0/0/0/0/0/0/0/0/0/0/0/0
C OMB =0   PLOT P=P,SO=S,MO=M(0,1Ef)/FO=F(0,1)/TM=T
```

APPENDIX C: SIMPLE TWO-POLLUTION MODEL AND RUN CHANGES

Figure 6-19 Secular shifts in the composition of total pollution in a simple two-pollution model when the half-lives are unequal. The basic model is:

```
       *     SIMPLE MODEL OF POLLUTION ACCUMULATION AND ASSIMILATION
       NOTE
1      L     MO93.K=MO93.J+(DT)(MO93PR.JK-MO93DR.JK)
1.1    N     MO93=MO93I
1.2    C     MO93I=75
2      L     SR90.K=SR90.J+(DT)(SR90PR.JK-SR90DR.JK)
2.1    N     SR90=SR90I
2.2    C     SR90I=25
3      R     MO93DR.KL=MO93.K/(HLMO93*1.4)
3.1    C     HLMO93=2
4      R     SR90DR.KL=SR90.K/(HLSR90*1.4)
4.1    C     HLSR90=25
5      A     TP.K=SR90.K+MO93.K
6      A     FPSR90.K=SR90.K/TP.K
7      R     MO93PR.KL=FPRMO*TPPR.K
7.1    C     FPRMO=.75
8      R     SR90PR.KL=FPRSR*TPPR.K
8.1    C     FPRSR=.25
9      A     TPPR.K=PPRI*EXP(GC*TIME.K)
9.1    C     PPRI=0
9.2    C     GC=.05
       NOTE
       NOTE  CONTROL CARDS
       NOTE
       SPEC  DT=.25/LENGTH=25/PLTPER=1.25/PRTPER=0
       PLOT  MO93=3,SR90=0(0,75)/MO93PR=M,SR90PR=S(0,50)/
       X     FPSR90=F(0,1)
       RUN   FIGURE 6-19A: ZERO POLLUTION INPUTS
       C     MO93I=3
       C     SR90I=1
       C     PPRI=4
       PLOT  MO93=3,SR90=0(0,50)/MO93PR=M,SR90PR=S(0,10)/
       X     FPSR90=F(0,1)
       RUN   FIGURE 6-19B: 5%/YR GROWTH IN POLLUTION INPUTS
```

To obtain Figure 6-19A, in rerun mode:

C GC=0

To obtain Figure 6-19B, in rerun mode:

C MO93I=0
C SR90I=0

REFERENCES

AEC 1971	United States Atomic Energy Commission. *Forecast of Growth of Nuclear Power*. Washington, D.C.: Government Printing Office, 1971.
Anderson 1972	Anderson, J. M. ''System Simulation to Test Environmental Policy: Eutrophication of Lakes.'' *Environmental Letters* 3 (1972), no. 3, pp. 203–228. Also in Meadows and Meadows 1973.
Anderson et al. 1973	Anderson, A. A., et al. ''System Simulation to Identify Environmental Research Needs: Mercury Contamination.'' *Oikos: Acta Oecologica Scandinavica* 24 (1973) no. 2, pp. 231–238. Also in Meadows and Meadows 1973.
Beeton 1970	Beeton, A. M. *Statement on Pollution and Eutrophication of the Great Lakes*. University of Wisconsin, Center for Great Lakes Studies Special Report no. 11. Milwaukee, 1970.
Blalock 1960	Blalock, H. M. *Social Statistics*. New York: McGraw-Hill, 1960.
Brubaker 1972	Brubaker, S. *To Live on Earth*. Baltimore: Johns Hopkins University Press, 1972.
Census 1971	United States. Bureau of the Census. *The American Almanac for 1971*. New York: Grosset & Dunlap, 1971.
Commodity Yearbook 1950–1970	Commodity Research Bureau. *Commodity Yearbook*. Annual. New York, 1950–1970.
Commoner 1971	Commoner, B. *The Closing Circle*. New York: Alfred A. Knopf, 1971.
Commoner 1972	Commoner, B. ''The Environmental Cost of Economic Growth.'' In *Population Resources and the Environment*. edited by R. G. Ridker. Washington, D.C.: Government Printing Office, 1972.
Dubos 1968	Dubos, R. ''Adapting to Pollution.'' *Scientist and Citizen* 10, no. 10 (January–February 1968), pp. 2–8.
Ehrlich and Ehrlich 1972	Ehrlich, P. R., and A. H. Ehrlich. *Population, Resources, Environment*. San Francisco: W. H. Freeman, 1972.
EPA 1972	United States. Environmental Protection Agency. Office of Radiation Programs. *Radiation Data and Reports* 13, no. 11 (November 1972).
Facts 1964	*Disarmament and Nuclear Tests: 1960–63*. New York: Facts on File, Inc., 1964.
Fruton and Simmonds 1958	Fruton, J. S. and S. Simmonds. *General Biochemistry*. New York: John Wiley, 1958.
Harrison et al. 1970	Harrison, H. L., et al. ''Systems Studies of DDT Transport.'' *Science* 170, no. 3957 (October 30, 1970), pp. 503–508.
Jensen 1972	Jensen, S. ''The PCB Story.'' *Ambio* 1, no. 4 (September 1972), pp. 123–131.
Johnels and Westermark 1969	Johnels, A. G., and T. Westermark. ''Mercury Contamination of the Environment in Sweden.'' In *Chemical Fallout*, edited by M. W. Miller and G. G. Berg. Springfield, Ill.: Charles G. Thomas, 1969.
Klein 1972	Klein, D. H. ''Some General and Analytical Aspects of Environmental Mercury Contamination.'' *Journal of Chemical Education* 49, no. 1 (January 1972), pp. 7–10.

Lee 1972	Lee, D. H. K., ed. *Metallic Contaminants and Human Health.* New York: Academic Press, 1972.
Meadows and Meadows 1973	Meadows, D. L., and D. H. Meadows, eds. *Toward Global Equilibrium: Collected Papers.* Cambridge, Mass.: Wright-Allen Press, 1973.
Montague and Montague 1971	Montague, K., and P. Montague. *Mercury.* San Francisco: Sierra Club, 1971.
Moulds 1972	Moulds, D. E. "Lead." In U.S. Bureau of Mines, *Minerals Yearbook* 1. Washington, D.C.: Government Printing Office, 1972.
Murozumi et al. 1969	Murozumi, M., et al. "Chemical Concentrations of Pollutant Lead Aerosols, Terrestrial Dusts, and Sea Salts in Greenland and Antarctic Snow Strata." *Geochimica et Cosmochimica Acta* 33, no. 10 (October 1969), pp. 1247–1294.
Nash and Woolson 1967	Nash, R. G., and E. A. Woolson. "Persistence of Chlorinated Hydrocarbon Insecticides in Soils." *Science* 157, no. 3791 (August 25, 1967), pp. 924–927.
NYT 1973	Lyons, R. D. "Chemical Debris Fouling Vast Areas of Atlantic." *New York Times,* February 12, 1973.
Odum 1971	Odum, P. *Fundamentals of Ecology.* Philadelphia, Pa.: W. B. Saunders, 1971.
Odum and Kuenzler 1963	Odum, E. P., and E. T. Kuenzler. "Experimental Isolation of Food Chains in an Oldfield Ecosystem with Use of Phosphorus-32." In *Radioecology,* edited by V. Schultz and A. W. Klemnet, Jr. New York: Rheinhold, 1963.
Randers 1973	Randers, J. "DDT Movement in the Global Environment." In Meadows and Meadows 1973.
Ridker 1972	Ridker, R. G. "The Economy, Resource Requirements, and Pollution Levels." In *Population, Resources, and the Environment,* edited by R. G. Ridker. Washington, D. C.: Government Printing Office, 1972.
SCEP 1970	*Man's Impact on the Global Environment: Report on the Study of Critical Environmental Problems.* Cambridge, Mass.: The M.I.T. Press, 1970.
Schroeder and Balassa 1961	Schroeder, H. A., and J. J. Balassa. "Abnormal Trace Metals in Man: Lead." *U.S. Journal of Chronic Disease* 14 (October 1961): 408–425.
Snow 1967	Snow, J. A. "Radioactive Waste from Reactors." *Scientist and Citizen* 9, no. 5 (May 1967), pp. 89–95.
Starr 1971	Starr, C. "Energy and Power." *Scientific American* 224, no. 3 (September 1971), pp. 36–49.
Tucker 1972	Tucker, A. *The Toxic Metals.* London: Earth Island, 1972.
U.N. 1969	United Nations. Department of Economic and Social Affairs. *Statistical Yearbook, 1969.* New York, 1970.
Wayland 1966	Wayland, J. H., Jr. "Monitoring Food and People for Pesticide Content." In Natural Resource Council, *Scientific Aspects of Pest Control.* Washington, D. C.: National Academy of Sciences, 1966.
Weiss et al. 1971	Weiss, H. V., et al. "Mercury in a Greenland Ice Sheet: Evidence of Recent Input by Man." *Science* 174, no. 4010 (November 12, 1971), pp. 692–694.

Wood 1972	Communication from Professor John Wood, University of Illinois. Cited in Council on Environmental Quality, *Environmental Quality,* 3rd Annual report. Washington, D.C.: Government Printing Office, 1972.
Woodwell et al. 1967	Woodwell, G. M., et al. "DDT Residues in an East Coast Estuary: A Case of Biological Concentration of a Persistent Insecticide." *Science* 156, no. 3776 (May 12, 1967), pp. 821–824.
Woodwell et al. 1971	Woodwell, G. M., et al. "DDT in the Biosphere: Where Does It Go?" *Science* 174, no. 4014 (December 10, 1971), pp. 1101–1110.
Wright 1970	Wright, J. H. "Power and the Environment." Paper presented at the American Power Conference, Chicago Ill., April 21–23, 1970. Cited in SCEP 1970, p. 299.

7
Simulations of the World Model

Roger F. Naill and William W. Behrens III

7.1 INTRODUCTION

The previous five chapters have described in detail the assumptions and equations that comprise the World3 model. The equations were chosen to represent the major interactions within and among five important sectors of the world system: population, capital, agriculture, nonrenewable resources, and persistent pollution. In this chapter a computer is used to simulate the behavior of the complete model and to test the effects of various possible policies.

Computer simulation ensures that the behavior of the model over time is a direct consequence of the model's assumptions described in the five sector chapters. Therefore, the model's behavior per se should not be disputed. Instead, criticism should be directed at the assumptions that generate the model's behavior. Through the use of computer simulation one can examine the effects of alternative assumptions on the model's behavior.

The simulation runs shown in this chapter are accurate predictions of global development only if (1) no important assumptions were omitted from the model, and (2) all the included assumptions are completely accurate and will continue to be accurate in the future.

Since neither of these conditions can be fully met by any model of a social system, no such model can ever predict the future precisely. Like every other model, World3 is subject to possible errors of omission or misspecification. The relationships assumed in World3 focus primarily on the material aspects of growth and their long-term side effects. It is conceivable that other social, political, or institutional aspects of growth may be as important as the material-related aspects modeled in World3 and we therefore would encourage further research to examine the extent to which the addition of social, political, or institutional factors would alter the model's behavior.

To determine the effects of possible misspecification of relationships, we conducted hundreds of tests to examine the sensitivity of the model to changes in different parameters. This chapter includes only a few of those tests as examples of the model's sensitivity to exact numerical assumptions; other sensitivity tests have been included in the sector chapters.

The thirty simulation runs presented here were chosen to promote an understanding of the dynamic properties of the world model and to demonstrate the effectiveness of alternative policies. Section 7.2 compares the behavior of the principal model variables over the period 1900 to 1970 with the historical development of the world system. The model is then run from 1900 to 2100 in section 7.3 to determine its behavior mode for later reference. Section 7.4 shows that the reference behavior mode is insensitive to significant changes in the underlying parametric assumptions.

Sections 7.5 and 7.6 test the effects of changes in technology and in social values on the reference behavior mode. The final set of simulation runs (see section 7.7) combines technological and social value changes as a means of achieving a sustainable equilibrium behavior mode.

For every simulation except the historical ones we present an output plot of the behavior of the seven most important system variables over time:

Variable	Units
Population POP	Persons
Industrial output per capita IOPC	1968 dollars per person-year
Food per capita FPC	Vegetable-equivalent kilograms per person-year
Index of persistent pollution PPOLX	Dimensionless
Nonrenewable resource fraction remaining NRFR	Dimensionless
Crude birth rate CBR	Births per thousand person-years
Crude death rate CDR	Deaths per thousand person-years

Full descriptions of these variables and their units are included in the five sector chapters and in Appendix B to this volume. Appendix E to this volume describes the format of a DYNAMO output for readers unfamiliar with this type of computer run. To facilitate comparisons between the runs, we maintained the same scales for the variables, where possible, in the successive runs.

Figure 7-1 is a DYNAMO flow diagram of the word model, showing the interconnections between the model variables described in Chapters 2 through 6. The diagram can be roughly divided into five sectors, clockwise from the upper left corner, which describe the structures of the population, nonrenewable resource, persistent pollution, agriculture, and capital sectors. The appendix to this chapter lists all the DYNAMO equations of the world model and summarizes the parametric and structural changes made in the model equations to produce each of the simulation runs discussed in this chapter. Any reader with access to a computer of sufficient capacity and a DYNAMO compiler can refer to the appendix and reproduce all the global simulation runs.

The runs described in this chapter were obtained by simulating the complete world model as shown in Figure 7-1. In these runs, all the sectors interact during the simulations, and none of the variables were assumed to be exogenously determined.

7.2 HISTORICAL RUNS

The utility or relevance of any model is directly dependent on the degree of confidence one has in the model. To increase our confidence in the World3 model, we tried to make certain that each individual model relationship not only was a plausible representation of the real world but also was consistent with the available data. (The preceding five chapters have described the individual model assumptions and compared them with empirical data.) In addition, the total behavior of World3's relationships, acting together, had to reproduce the pattern of world growth over the historical period of the model. The first five simulation runs of this chapter show the behavior of the variables within the five sectors as the complete model is run over the 1900–1970 period. A summary of the observed historical trends precedes the run for each sector so that the two can be compared.

The historical time trends are presented verbally rather than graphically for two reasons. First, in most cases the aggregate world time-series data are of an extremely low quality. Second, the verbal descriptions of the historical trends deemphasize the precise quantitative interpretation of the model output. It should be remembered that we are interested in the overall behavior *modes* of the model. Therefore, the evaluation of the actual values of the variables at any point in time is not a significant test of the model's utility.

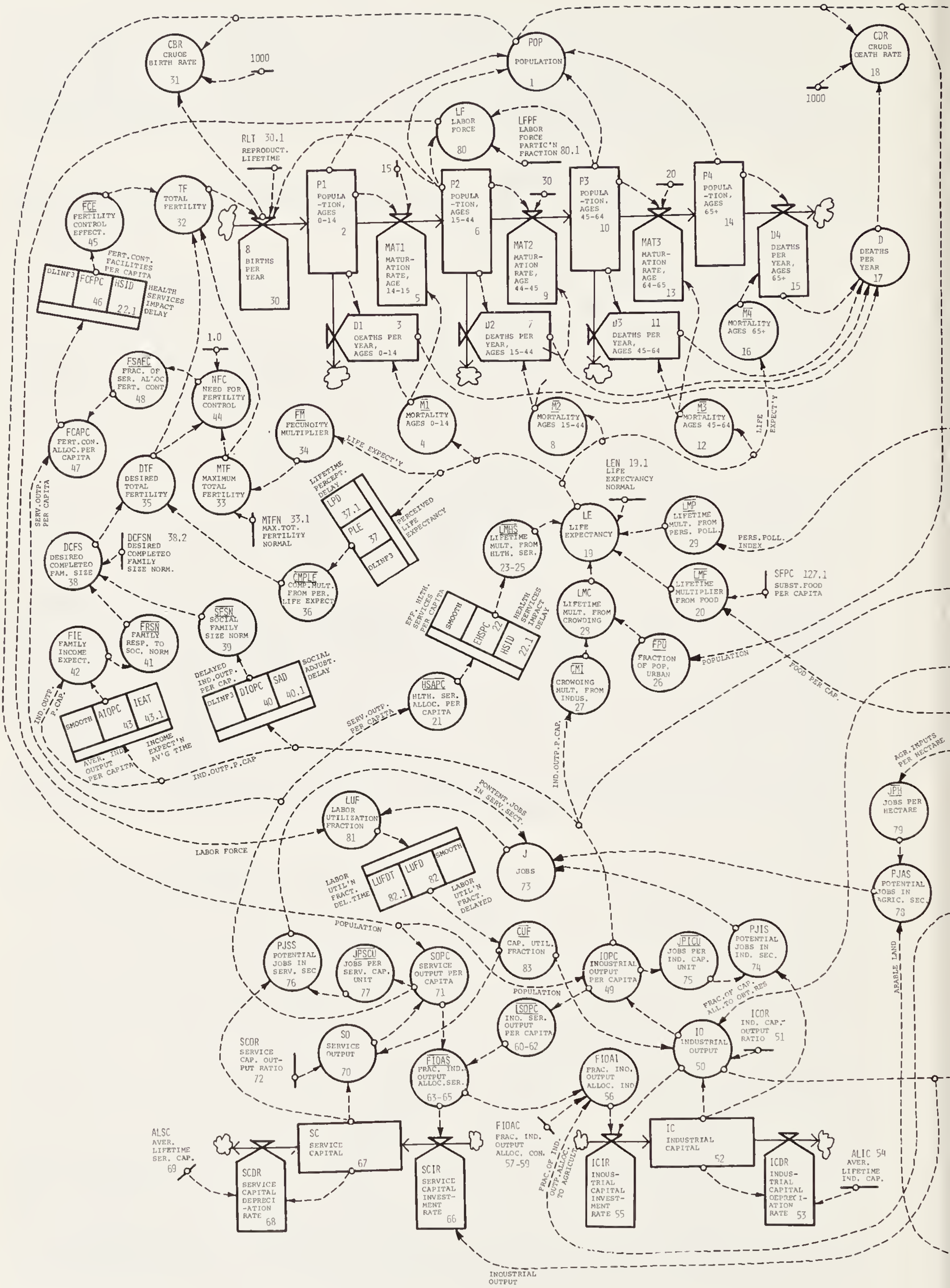
Population Sector Variables The historical behavior modes characteristic of the world population over the years 1900–1970 are:

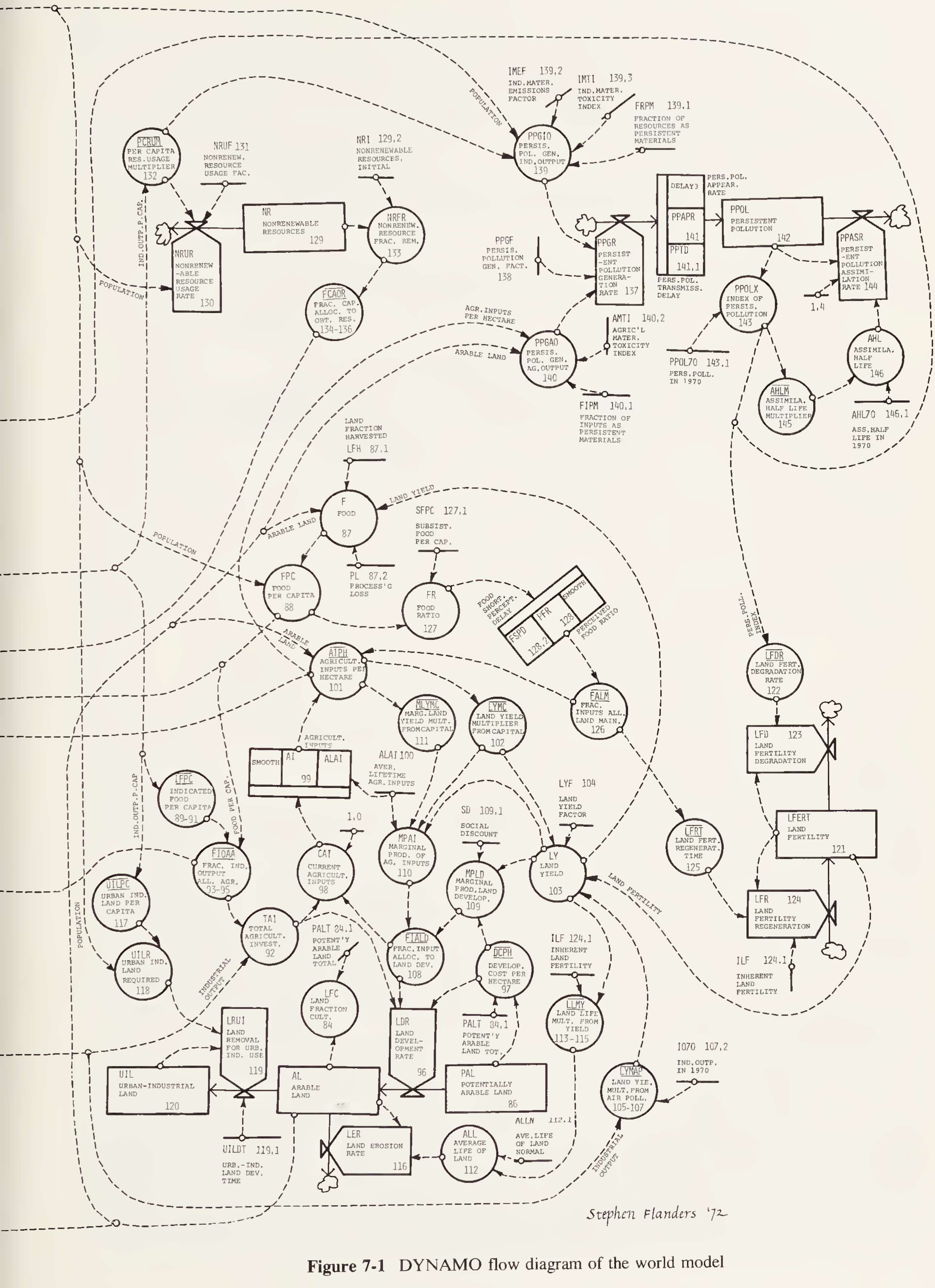
1. Exponential growth of the world population caused by:
   a. Falling mortality.
   b. Intermediate values of fertility.
   c. An inverse correlation of fertility with industrialization.
2. A delayed response of population behavior to changes in external influences due to:
   a. The population age structure.
   b. Inherent delays in adjustment to social change.
3. Falling birth rates lagging behind falling death rates, a characteristic of the demographic transition as industrialization proceeds.

Run 7-1 (Figure 7-2) shows the behavior of important variables in the population sector when the world model is run from 1900 to 1970. In accordance with the major time trend of the world population, population POP exhibits exponential growth over the period. The model population was initialized at 1.6 billion people in 1900 and passes through the historical value of 3.6 billion people in 1970, representing an average population growth rate of 1.2 percent per year for the period. The rate of growth varies over time in the model (as in the real world) and at any given time is equal to the difference between the crude birth rate CBR and the crude death rate CDR.

During the 1900–1970 period, the global population exhibited a trend toward falling mortality (see Figure 2-6). In Run 7-1 the crude death rate CDR also declines over time, principally as a result of improved health services. The world population is also characterized by intermediate values of fertility, as shown in Figure 2-7, where the observed behavior of the crude birth rate CBR is in a range well below the maximum biologically possible rate but above the replacement level of fertility. Run 7-1 shows that the model-generated crude birth rate CBR also operates in this intermediate region. Third, world populations have generally shown an inverse correlation between fertility and industrialization (see Figure 2-8). This correlation is evident in the model runs, for as industrial output per capita IOPC rises through time, as shown in Run 7-2 (Figure 7-3), the crude birth rate CBR falls (Run 7-1).

The rising life expectancy LE in Run 7-1 has been attributed principally to the increase in health services over the past century (see Chapter 2, section 2.5). In the model, the influences on life expectancy from health services, food, pollution, and crowding are represented by the lifetime multiplier from health services LMHS, the lifetime multiplier from food LMF, the lifetime multiplier from pollution LMP, and


CBR CRUDE BIRTH RATE 31
1000
POP POPULATION 1
CDR CRUDE DEATH RATE 18
1000
LF LABOR FORCE 80
LFPF LABOR FORCE PARTIC'N FRACTION 80.1
RLT 30.1 REPRODUCT. LIFETIME
15
30
20
TF TOTAL FERTILITY 32
FCE FERTILITY CONTROL EFFECT. 45
P1 POPULA-TION, AGES 0-14 2
P2 POPULA-TION, AGES 15-44 6
P3 POPULA-TION, AGES 45-64 10
P4 POPULA-TION, AGES 65+ 14
B BIRTHS PER YEAR 30
MAT1 MATUR-ATION RATE, AGE 14-15 5
MAT2 MATUR-ATION RATE, AGE 44-45 9
MAT3 MATUR-ATION RATE, AGE 64-65 13
D4 DEATHS PER YEAR, AGES 65+ 15
D DEATHS PER YEAR 17
FERT.CONT. FACILITIES PER CAPITA
DLINF3 FCFPC 46 HSID 22.1
HEALTH SERVICES IMPACT DELAY
D1 3 DEATHS PER YEAR, AGES 0-14
D2 7 DEATHS PER YEAR, AGES 15-44
D3 11 DEATHS PER YEAR, AGES 45-64
M4 MORTALITY AGES 65+ 16
1.0
FSAFC FRAC. OF SER. ALLOC FERT. CONT 48
NFC NEED FOR FERTILITY CONTROL 44
M1 MORTALITY AGES 0-14 4
M2 MORTALITY AGES 15-44 8
M3 MORTALITY AGES 45-64 12
LIFE EXPECT'Y
FCAPC FERT.CON. ALLOC.PER CAPITA 47
FM FECUNDITY MULTIPLIER 34
LIFE EXPECT'Y
DTF DESIRED TOTAL FERTILITY 35
MTF MAXIMUM TOTAL FERTILITY 33
LIFETIME PERCEPT. DELAY
LPD 37.1 PLE 37 DLINF3
PERCEIVED LIFE EXPECTANCY
LEN 19.1 LIFE EXPECTANCY NORMAL
SERV.OUTP. PER CAPITA
MTFN 33.1 MAX.TOT. FERTILITY NORMAL
LE LIFE EXPECTANCY 19
LMP LIFETIME MULT. FROM PERS. POLL. 29
PERS.POLL. INDEX
LMHS LIFETIME MULT. FROM HLTH. SER. 23-25
DCFS DESIRED COMPLETED FAM. SIZE 38
DCFSN 38.2 DESIRED COMPLETED FAMILY SIZE NORM.
CMPLE COMP.MULT. FROM PER. LIFE EXPECT 36
SFPC 127.1 SUBST.FOOD PER CAPITA
LMF LIFETIME MULTIPLIER FROM FOOD 20
LMC LIFETIME MULT. FROM CROWDING 28
EFF. HLTH. SERVICES PER CAPITA
SMOOTH EHSPC 22 HSID 22.1
HEALTH SERVICES IMPACT DELAY
SFSN SOCIAL FAMILY SIZE NORM 39
FRSN FAMILY RESP. TO SOC. NORM 41
FIE FAMILY INCOME EXPECT. 42
FPU FRACTION OF POP. URBAN 26
POPULATION
CMI CROWDING MULT. FROM INDUS. 27
FOOD PER CAP.
DELAYED IND.OUTP. PER CAP.
DLINF3 DIOPC 40 SAD 40.1
SOCIAL ADJUST. DELAY
HSAPC HLTH. SER. ALLOC. PER CAPITA 21
IND.OUTP. P.CAP.
SMOOTH AIOPC 43 IEAT 43.1
AVER. IND. OUTPUT PER CAPITA
INCOME EXPECT'N AV'G TIME
SERV.OUTP. PER CAPITA
IND.OUTP.P.CAP
IND.OUTP.P.CAP.
AGR.INPUTS PER HECTARE
JPH JOBS PER HECTARE 79
LUF LABOR UTILIZATION FRACTION 81
PONTENT.JOBS IN SERV.SECT.
LABOR FORCE
LUFDT 82.1 LUFD 82 SMOOTH
LABOR UTIL'N FRACT. DEL.TIME
LABOR UTIL'N FRACT. DELAYED
J JOBS 73
PJAS POTENTIAL JOBS IN AGRIC. SEC. 78
POPULATION
PJSS POTENTIAL JOBS IN SERV. SEC 76
JPSCU JOBS PER SERV. CAP. UNIT 77
SOPC SERVICE OUTPUT PER CAPITA 71
CUF CAP. UTIL. FRACTION 83
IOPC INDUSTRIAL OUTPUT PER CAPITA 49
JPICU JOBS PER IND. CAP. UNIT 75
PJIS POTENTIAL JOBS IN IND. SEC. 74
POPULATION
ISOPC IND. SER. OUTPUT PER CAPITA 60-62
FRAC.OF CAP. ALL.TO OBT.RES
ARABLE LAND
SCOR SERVICE CAP. OUT-PUT RATIO 72
SO SERVICE OUTPUT 70
FIOAS FRAC. IND. OUTPUT ALLOC.SER. 63-65
FIOAI FRAC. IND. OUTPUT ALLOC. IND 56
IO INDUSTRIAL OUTPUT 50
ICOR IND. CAP. OUTPUT RATIO 51
ALSC AVER. LIFETIME SER. CAP. 69
SC SERVICE CAPITAL 67
FIOAC FRAC. IND. OUTPUT ALLOC. CON. 57-59
IC INDUSTRIAL CAPITAL 52
SCDR SERVICE CAPITAL DEPRECI-ATION RATE 68
SCIR SERVICE CAPITAL INVEST-MENT RATE 66
FRAC.OF IND. OUTP.ALLOC. TO AGRICULT.
ICIR INDUS-TRIAL CAPITAL INVEST-MENT RATE 55
ICDR INDUS-TRIAL CAPITAL DEPRECI-ATION RATE 53
ALIC 54 AVER. LIFETIME IND. CAP.
INDUSTRIAL OUTPUT



Stephen Flanders '72

Figure 7-1 DYNAMO flow diagram of the world model

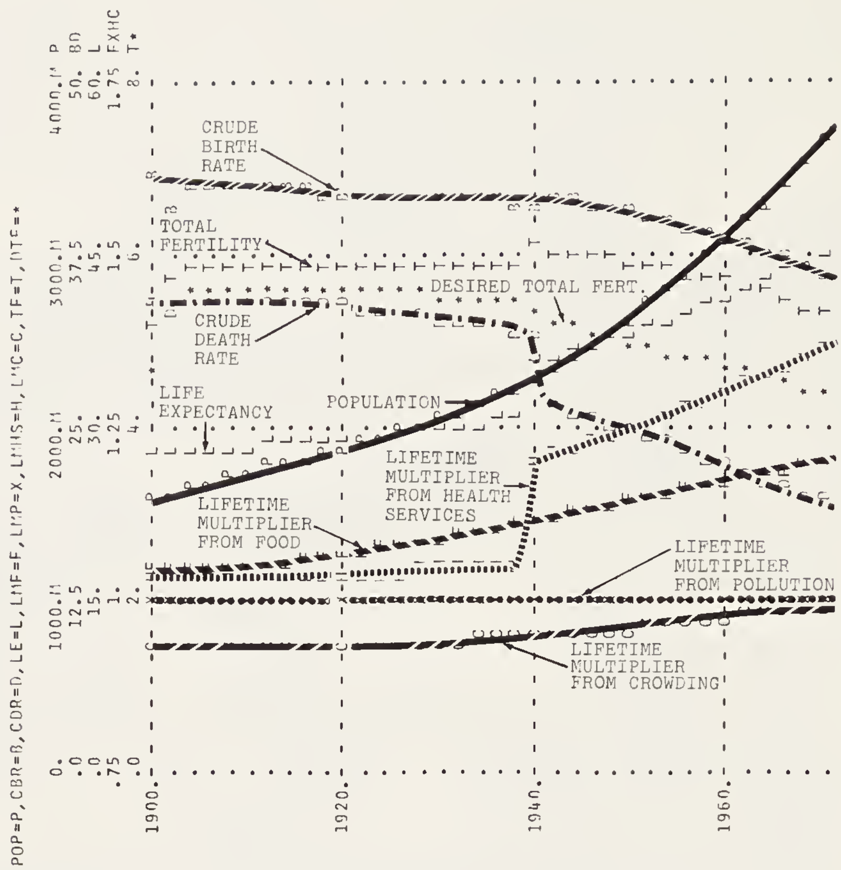


Figure 7-2 Run 7-1: population sector behavior, 1900–1970

Population POP increases over time at an average growth rate of 1.2 percent per year. Both the birth rate CBR and the death rate CDR decrease over the period, the former largely because of a lower desired total fertility DTF, and the latter primarily as a result of increased health services LMHS. Both trends occur as a result of industrialization.

the lifetime multiplier from crowding LMC. It can be seen in Run 7-1 that the increase in LMHS from 1940 to 1970 is greater than the combined changes in the other three lifetime multipliers, although LMF also has a significant positive influence.

An important determinant of the birth rate CBR in the model is the total fertility TF, or total number of children borne per woman. In Run 7-1 the slight decrease in TF from 1900 to 1970 is primarily due to the decline in desired total fertility DTF. The main cause of the decrease in DTF over this period is the increasing industrial output per capita IOPC, for it is hypothesized that the desired family size decreases as industrialization changes social norms about families and childbearing.

In the model, the relationship between desired total fertility DTF and industrial output per capita IOPC is one example of the delayed response of population behavior to external influences. The rise in IOPC affects DTF only after a delay of 20 years, representing the time a society takes to adjust its norms regarding family size. Similar delaying effects attributable to the population age structure are not directly evident from Run 7-1, for the relatively small changes in birth and death rates from 1900 to 1970 do not alter the age structure significantly. A detailed description of the age structure equations and their effects on the model's behavior is given in Chapter 2.

The final time trend evident in Run 7-1 is the shift of birth and death rates that is characteristic of the demographic transition. As the economy of a population undergoes industrialization, the behavior of the birth and death rates of that population usually follows four successive stages:

1. High birth and death rates, slow rate of population growth.
2. Rapidly declining death rate, slowly declining birth rate, increasing rate of population growth.
3. Slowly declining death rate, rapidly declining birth rate, decreasing rate of population growth.
4. Low birth and death rates, slow to moderate rate of population growth.

In Run 7-1 the population POP advances through roughly the first two stages of the demographic transition. The crude birth rate CBR and the crude death rate CDR are at relatively high values in 1900, and the low value of industrial output per capita IOPC indicates that the world system is only in the beginning stages of industrialization. As industrialization proceeds, however, the model moves into the second stage of the demographic transition; around 1940, CDR declines fairly rapidly and CBR declines more slowly. Consequently, the rate of population growth increases in the model during the next thirty years, as happened in the real world. The pattern of development evidenced by the model after 1970 will determine whether or not the model's population proceeds through the final two stages of the demographic transition.

Capital Sector Variables The following list briefly summarizes the historical time trends characteristic of the world economy (see Chapter 3 for a detailed description of these trends):

1. Exponential growth in total capital and in per capita service and industrial output.
2. Shifts in the composition of total output as the level of development (measured by industrial output per capita) increases, as follows:
   a. A decrease in the fraction of total output in agriculture.
   b. A slight increase in the fraction of total output in services (which should remain near 50 percent of total output).
   c. An increase in the fraction of total output in industry.

Run 7-2 (Figure 7-3) illustrates the behavior of the major variables in the capital sector during the 1900–1970 period. Both industrial capital IC and industrial output IO exhibit exponential growth. Industrial output IO grows at an average rate of 3.6 percent per year, which is the same as the historical growth rate of real-world industrial output. Because this rate of growth is greater than the rate of population growth in the model (1.2 percent per year), industrial output per capita IOPC also grows exponentially at a rate of 2.4 percent per year in the model, passing through its 1970 value of 220 dollars per person-year. The growth in IOPC causes increased

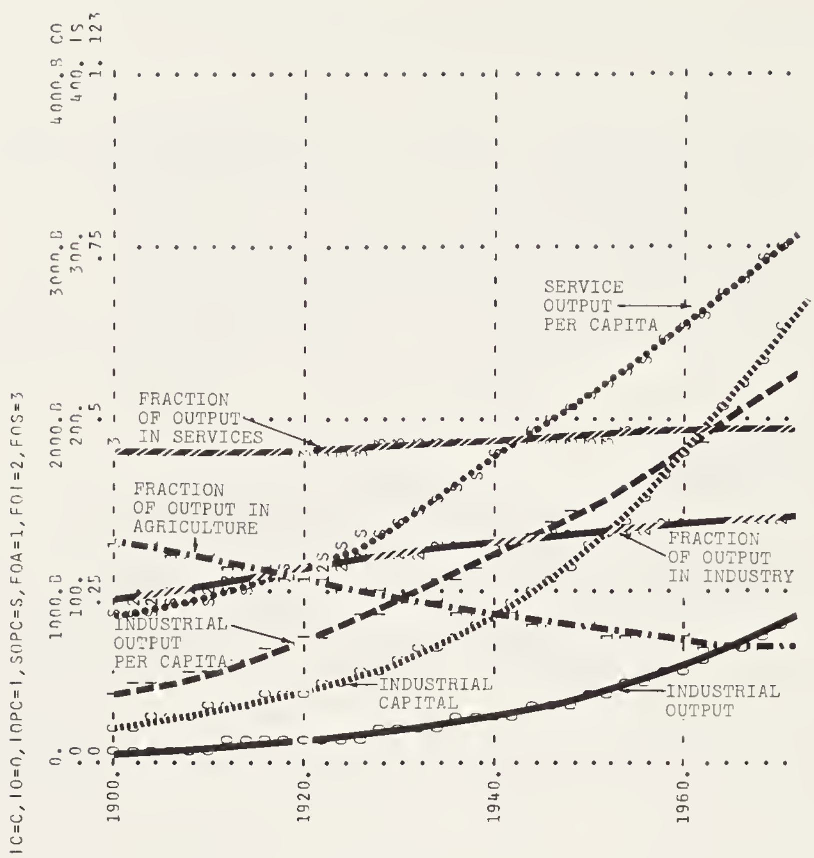


Figure 7-3 Run 7-2: capital sector behavior, 1900–1970

Industrial capital IC grows exponentially, causing industrial output IO to grow. Since their growth rate is greater than that of population, industrial output per capita IOPC also grows over the period, as do service output per capita SOPC and food per capita (not graphed). As development proceeds, (1) the fraction of output in agriculture FOA declines, (2) FOA is largely replaced by the increasing fraction of output in industry FOI, and (3) the fraction of output in services FOS remains relatively constant, near 50 percent of total output.

investment and thus growth in both the service and the agriculture sectors. Run 7-2 shows that the growth in service output per capita SOPC is proportionate to industrial output per capita in the model, reaching almost 300 dollars per person-year in 1970. This value of SOPC is slightly below that indicated by world development patterns (330 dollars per person-year) because of the slight delay involved in effecting an increase in service output. The behavior of industrial output per capita IOPC is also a prime determinant of the behavior of food per capita FPC, which is shown later as a part of the behavior of the agriculture sector in Run 7-3 (Figure 7-4).

As the world economy grows, the composition of total world output should change significantly in accordance with the historical development patterns outlined by Chenery and Taylor (1968). The nature of these development patterns are discussed in section 3.2 of Chapter 3. Briefly, a developing economy tends to replace agricultural output with industrial output as the development process proceeds. To illustrate the model-generated development patterns more clearly, Run 7-2 shows the behavior of the fraction of total output in agriculture FOA, the fraction of total output in services FOS, and the fraction of total output in industry FOI over time. These fractions were approximated by attributing a dollar value to food per capita FPC. The conversion factor for food output of 0.22 dollars per vegetable-equivalent kilogram was obtained by dividing the 1968 dollar value of food per capita (110 dollars per person-year from Chapter 3) by the 1968 value of food per capita in vegetable-equivalent kilograms (500 vegetable-equivalent kilograms per person-year from Chapter 4). Run 7-2 shows that the model-generated and historical development patterns are very similar: as development proceeds, the decrease in FOA is largely offset by the increase in FOI between 1900 and 1970. As a result, the fraction of total output in services FOS increases very slightly, from 45 percent to 48 percent of total output.

In the model, investment is divided between agricultural, service, and industrial capital according to the difference between desired and actual output in each sector. The desired output per capita in each sector changes as development proceeds, reflecting a form of social value change that is built into the model's structure. We chose to include the historical pattern of social value changes reflected in the development pattern described by Chenery and Taylor (1968): as development proceeds, individuals satisfy their food and service needs first, then shift their preferences to industrial output as their incomes rise (see Chapter 3 for a full description of this mechanism). The effects of possible future divergences from this historical pattern of changing values are tested in section 7.6 of this chapter.

Agriculture Sector Variables The historical time trends of the agriculture sector may be summarized from Chapter 4 as an exponential increase in total food output and food per capita over time, due to:

1. Increases in the cultivated land area.
2. Increases in the average land yield. Land yield increases have resulted primarily from increases in the use of modern agricultural inputs such as fertilizers, pesticides, new seeds, and farm machinery.

Run 7-3 (Figure 7-4) shows the behavior of the World3 agriculture sector between 1900 and 1970, when both total food F and food per capita FPC grow exponentially. Total food F grows at an average of 1.8 percent per year in the model during the 70-year period, and at about 2.4 percent per year during the last 20 years. Food per capita FPC grows at an average rate of about 0.6 percent per year in the model from 1900 to 1970 and at about 0.8 percent per year from 1950 to 1970. The historical growth rates, derived from Figure 4-1, are 2.9 percent per year for total food production and 0.8 percent per year for food per capita FPC for the 1950–1970 period.

The increase in total food production F results from the rise in both arable land AL cultivated and land yield LY. Arable land AL increases in the model from 0.9 billion hectares in 1900 to 1.4 billion hectares in 1970. These values correspond well with the historical values referenced in Chapter 4. Land yield LY increases at an average rate of about 1.5 percent per year over the 70-year period.

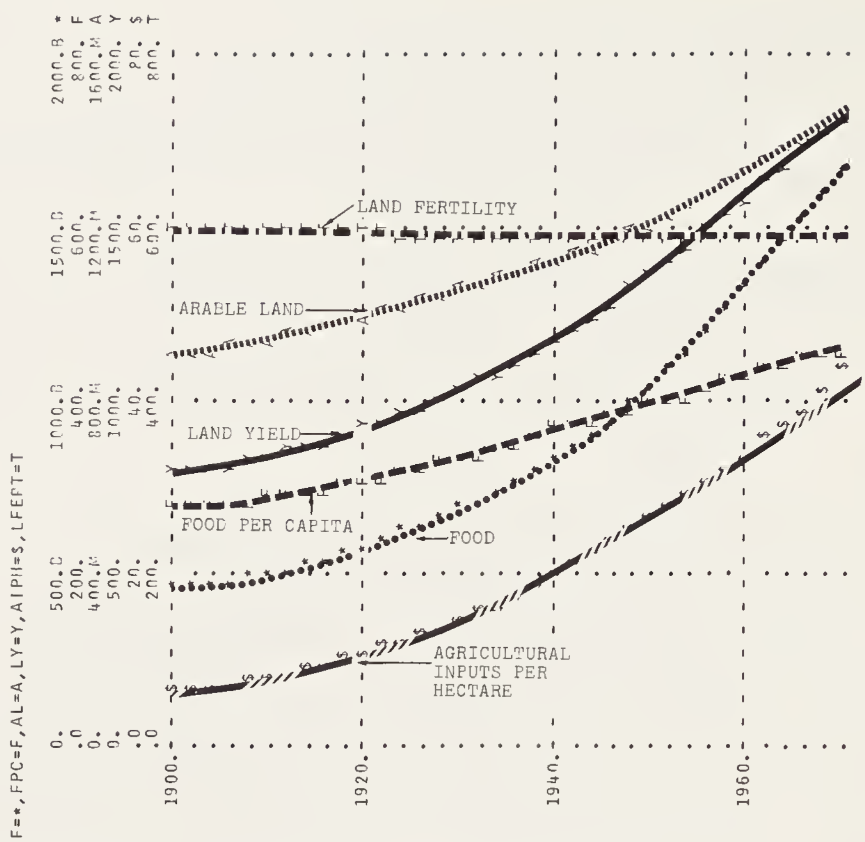


Figure 7-4 Run 7-3: agriculture sector behavior, 1900–1970

Increases in arable land AL and land yields LY cause a rise in food production over the historical period. The increase in land yields is primarily attributable to greater agricultural inputs per hectare AIPH (fertilizers, pesticides), for the land fertility LFERT remains nearly constant. Food per capita FPC also grows during the 70-year period but at a much slower rate than total food F, since the population is also increasing.

In the model, land yield LY is assumed to be a function of both the agricultural inputs per hectare AIPH applied to the land and the land fertility LFERT, defined as the ability of the soil to produce crops without the use of modern agricultural inputs. The increase in LY shown in Run 7-3 can be attributed to the increasing AIPH, for LFERT has actually decreased slightly over the 70-year period. This behavior seems to be consistent with available data, for Figures 4-4 and 4-5 indicate high rates of growth of agricultural inputs, and Chapter 4 gives some evidence (such as Figure 4-7) that land fertility may indeed be decreasing.

Nonrenewable Resource Sector Variables The historical time trends of the nonrenewable resource sector can be summarized as follows:

1. Exponential growth in the consumption of resources, caused by:
    a. Increasing population.
    b. Increasing per capita resource usage.
2. The fraction of capital allocated to obtaining resources FCAOR remains constant over time. This behavior actually reflects two trends: a tendency toward

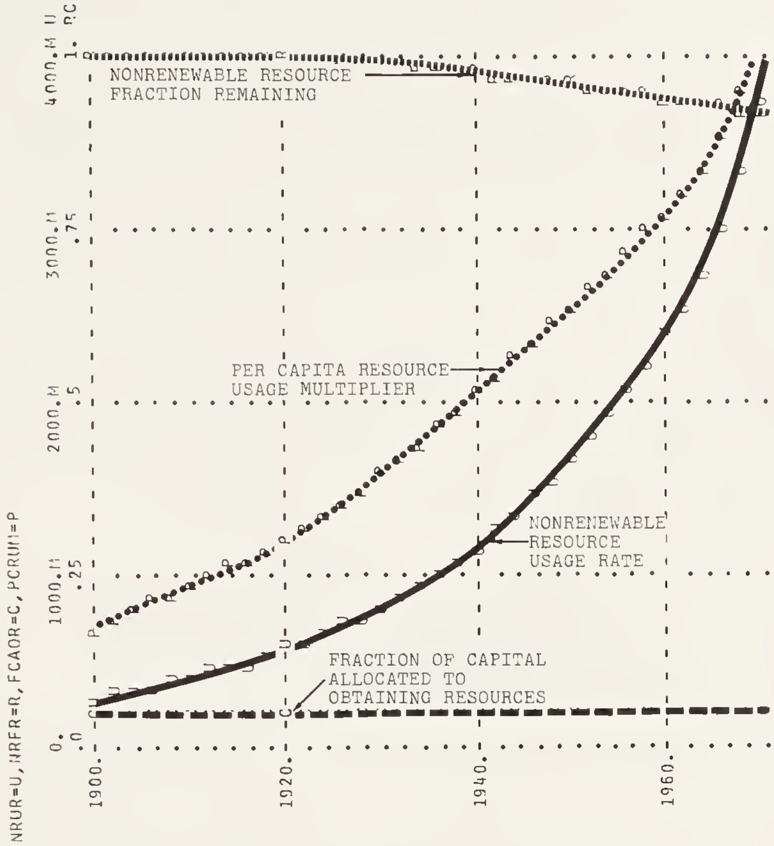


Figure 7-5 Run 7-4: nonrenewable resource sector behavior, 1900–1970

The rate of usage of nonrenewable resources NRUR grows exponentially at 4 percent per year over the historical period. This continuous increase is caused by the growth in both population POP and resource usage per capita PCRUM. Per capita resource usage rises as a result of industrial development. The increase in resource usage occurs at no additional increase in unit costs (see FCAOR in graph), in accordance with historical trends. In 1970, over 90 percent of the initial supply of nonrenewable resources remains to be used.

increases in resource costs over time due to depletion effects, and advances in cost-reducing resource technologies that tend to offset these depletion effects.

Run 7-4 (Figure 7-5) shows the behavior of the nonrenewable resource sector variables over the 70-year historical period of the simulation. In this figure, the nonrenewable resource usage rate NRUR grows exponentially at an average of 4 percent per year over the period. According to data collected by the National Commission on Materials Policy, the production of world resources grew historically at a rate of 4.1 percent per year between 1950 and 1970 (NCMP 1972). The growth in the nonrenewable resource usage rate NRUR can be divided into two components: growth in population POP and growth in the per capita resource usage multiplier PCRUM. In the model, population grows at an average rate of 1.2 percent per year, which is the historical average growth rate for the 70-year period. Per capita resource usage grows at 2.8 percent per year in the model, compared with the historical world average growth rate of 2.6 percent per year from 1950 to 1970 (U.N. 1969, NCMP 1972). This increase in per capita resource usage is caused by industrial development in the model: as industrialization proceeds, per capita resource usage tends to increase.

Run 7-4 shows that the fraction of capital allocated to obtaining resources FCAOR remains constant during the period of the run. This constant fraction reflects the fact that, in the past, the tendency toward rising resource capital costs has been continually offset by advances in technology.Although resource capital costs historically have remained constant or have decreased, it is assumed in the model that this trend can continue only as long as resources are relatively abundant—that resource costs (FCAOR) will begin to rise after resources are depleted to half their initial value. Note that in Run 7-4 over 90 percent of the initial amount of nonrenewable resources remains unexploited in 1970 (nonrenewable resource fraction remaining NRFR equals 0.9 in 1970). Different assumptions about the eventual rise in resource costs will be tested later in this chapter.

Persistent Pollution Sector Variables As described in Chapter 6, the historical time trends characteristic of global persistent pollutants are:

1. Exponential growth in the global concentration of pollutants.
2. Significant delays between the generation of pollutants and their appearance.

Run 7-5 (Figure 7-6) shows the historical behavior of the persistent pollution sector. The persistent pollution generation rate PPGR increases exponentially as a result of growth in both the persistent pollutants generated from industrial output PPGIO and the persistent pollutants generated from agricultural output PPGAO. The total amount of persistent pollutants present in 1970 is used as a normalizing constant to determine the index of persistent pollutants PPOLX relative to 1970 levels. As shown in this run, PPOLX also grows through time, passing through its normalized value of 1.0 in 1970.

Run 7-5 also illustrates the effect of the delay between the generation of pollutants and their appearance as persistent pollutants. The rate of appearance of persistent pollutants PPAPR also rises exponentially in Run 7-5, but the increase in the appearance of pollutants lags behind the generation of pollutants by 20 years.

Several additional variables of interest in the pollution sector are plotted in Run 7-5. The pollution assimilation half-life AHL remains constant at a value of 1.5 years during the 70-year period, reflecting the assumption that the index of pollution PPOLX has not risen high enough to interfere with the assimilation process. The lifetime multiplier from pollution LMP also remains constant over the initial 70 years of the run, indicating that persistent pollution has had no significant effect on the life expectancy of the population.

Runs 7-1 through 7-5 were intended to illustrate the model's behavior over the period for which historical data are available for comparison, 1900–1970. As expected, some small discrepancies occur between the output of the model and the historical time-series data. These discrepancies arise from two factors. First, discrete events such as

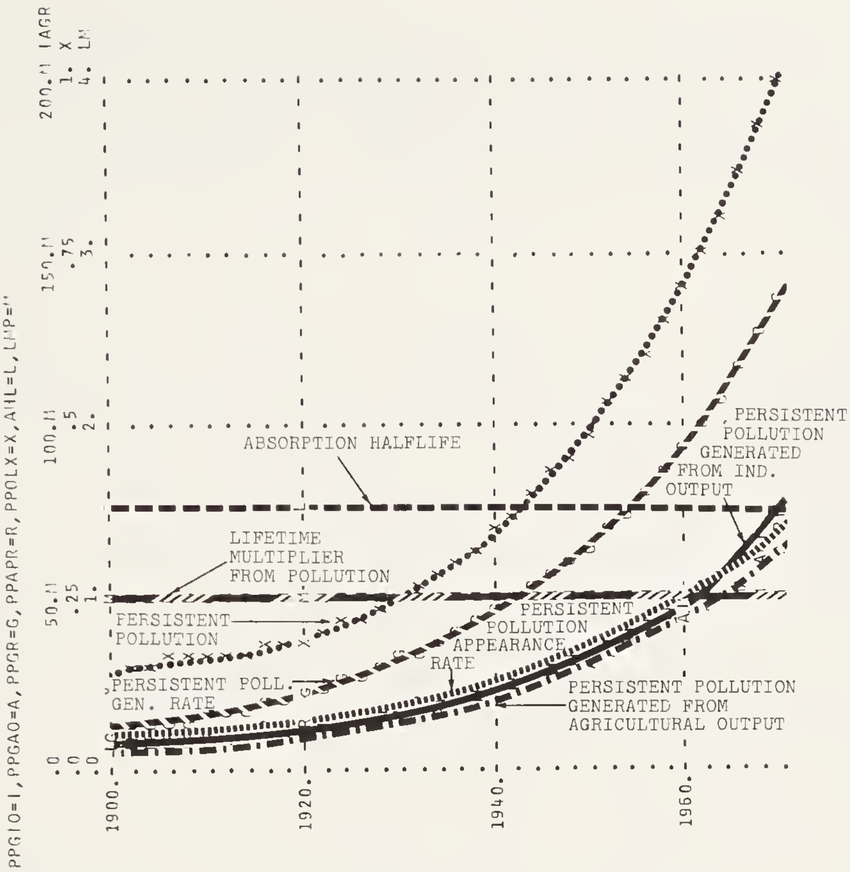


Figure 7-6 Run 7-5: persistent pollution sector behavior, 1900–1970

The rate of generation of persistent pollutants PPGR increases exponentially as its two components, persistent pollutants generated from industrial output PPGIO and persistent pollutants generated from agricultural output PPGAO, rise over the 70-year period. After a 20-year delay, the persistent pollutant appearance rate PPAPR also rises, causing the index of persistent pollutants PPOLX to rise and eventually pass through its normalized value of 1.0 in 1970.

wars and depressions that have short-term effects on world historical data are excluded from the model. Second, instead of choosing numerical parameters that would fit model-generated data to historical time-series data, the parameters were chosen individually and independently to represent each causal relationship. A comparison of the behavior of the model with that of the historical system therefore becomes a second criterion for model utility, independent of the defense of individual parameters. As mentioned earlier, the model must reproduce historical behavior modes, not replicate exact time-series data, and the model does meet that criterion.

7.3 REFERENCE BEHAVIOR OF THE WORLD3 MODEL

The historical runs of the previous section have plotted the behavior of the major sector variables for comparison with world historical behavior as the model was run from 1900 to 1970. The following global reference run, Run 7-6A (Figure 7-7), illustrates the behavior mode of the model as the simulation is continued to the year 2100. The succeeding sensitivity tests and policy runs are presented in the same format to facilitate their comparison with the reference run. Two plots of additional variables from the reference run are given in Runs 7-6B and 7-6C (Figures 7-8 and 7-9, respectively) to provide a more thorough understanding of the mechanisms responsible for the observed behavior.

World3 Reference Run Run 7-6A (Figure 7-7) depicts the behavior of the seven major model variables as the world model is run from 1900 to 2100. This run assumes that the general values and policies that guided the world system from 1900 to 1970 will continue into the future. The global population, after reaching the 1970 level of 3.6 billion people, continues to grow to a level of 6 billion in the year 2000 and peaks at about 7 billion in the year 2030. After that time, the crude death rate CDR exceeds the crude birth rate CBR, so the population POP declines. Food per capita FPC rises steadily throughout the twentieth century to more than 500 vegetable-equivalent kilograms per person-year, but it declines sharply after 2015. Industrial output per capita IOPC reaches a maximum value of 375 dollars per person-year in 2015. The index of persistent pollution PPOLX reaches a peak of 11 times the 1970 level of pollution in the year 2035.

The behavior mode exhibited by the reference run shown in Figure 7-7 is overshoot and decline. Population and capital grow past their sustainable physical limits and then return to a preindustrial level of development. Growth is halted in this run through the effects of nonrenewable resource depletion.

Additional Variables from the Reference Run The reference run can be better understood by examining the behavior of several additional model variables from the same computer run, shown in Run 7-6B (Figure 7-8) and Run 7-6C (Figure 7-9). As the nonrenewable resource fraction remaining NRFR drops below 0.5 in the year 2015, the fraction of capital that must be allocated to obtaining those resources FCAOR begins to rise above its minimum level of 0.05 (Run 7-6B). Thus industrial capital must be diverted from the production of industrial output toward obtaining the resources necessary to sustain that output. When investment in industrial capital no longer exceeds depreciation, the industrial capital base declines, reducing industrial output IO and industrial output per capita IOPC.

As industrial output IO declines, the total agricultural investment TAI is also forced to decrease (Run 7-6B), even though the agriculture sector tries to compensate for the reduction in food per capita FPC by increasing the fraction of industrial output allocated to agriculture FIOAA after the year 2025.* The decrease in total agricultural investment TAI causes the agricultural inputs per hectare AIPH to decline after a short delay. Because the model's agricultural sector is highly capital intensive at this stage of its development, a decrease in agricultural inputs per hectare AIPH

*FIOAA declines again after 2040, however, as the decline in industrial output per capita IOPC causes a decline in the indicated food per capita IFPC.

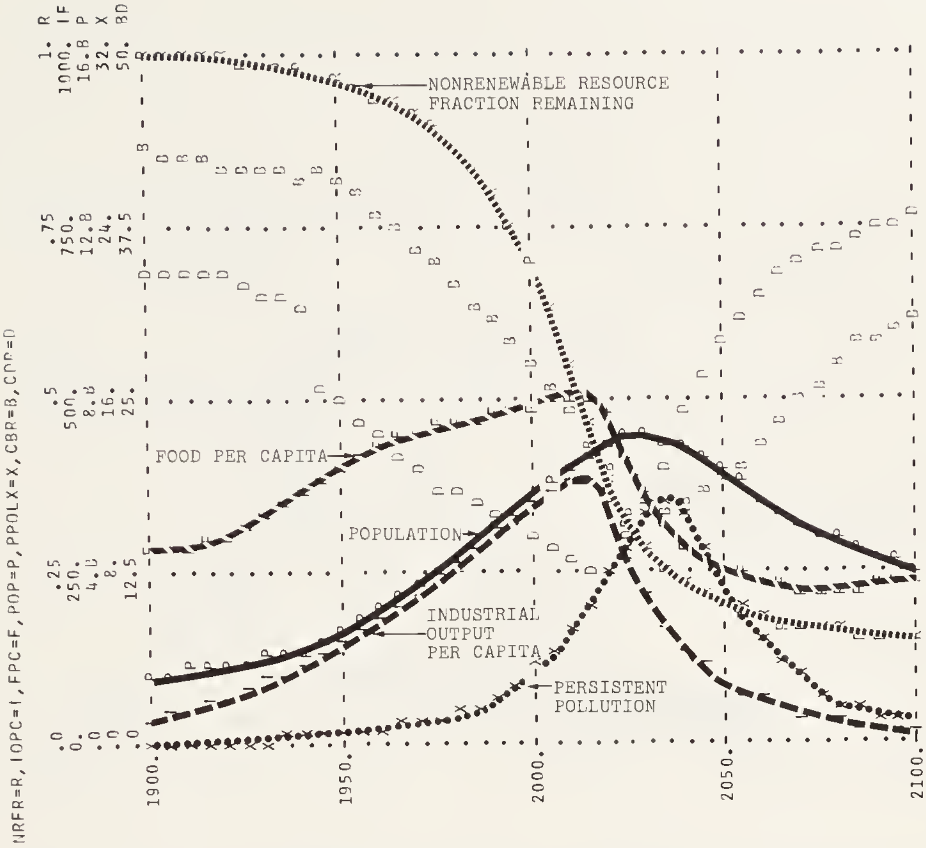


Figure 7-7 Run 7-6A: World3 reference run

This is the World3 reference run, to be compared with the sensitivity and policy tests that follow. Both population POP and industrial output per capita IOPC grow beyond sustainable levels and subsequently decline. The cause of their decline is traceable to the depletion of nonrenewable resources. Runs 7-6B and 7-6C illustrate the mechanisms that force population POP and industrial output per capita IOPC to decline.

immediately depresses land yield LY, that is, the amount of food per hectare harvested from the arable land AL under cultivation (Run 7-6C). The decline in yields causes food per capita FPC to decrease sharply after 2015, and as FPC nears the level of subsistence the lifetime multiplier from food LMF begins to decline. This chain of causal interactions eventually forces the population POP to decline after the year 2030.

It should be emphasized that the reference run (Figure 7-7) is not a prediction of the precise values of any of the model variables in the future, nor does it necessarily represent the most likely behavior mode of the real world. It is termed the reference run only because the output is obtained from the reference model structure and parameters; it is unchanged by any new policies, technologies, or values. The strongest statement of certainty we can make about this run is that it represents the most likely behavior mode of the system if the process of industrialization in the future proceeds in a way very similar to its progress in the past, and if the technologies and value

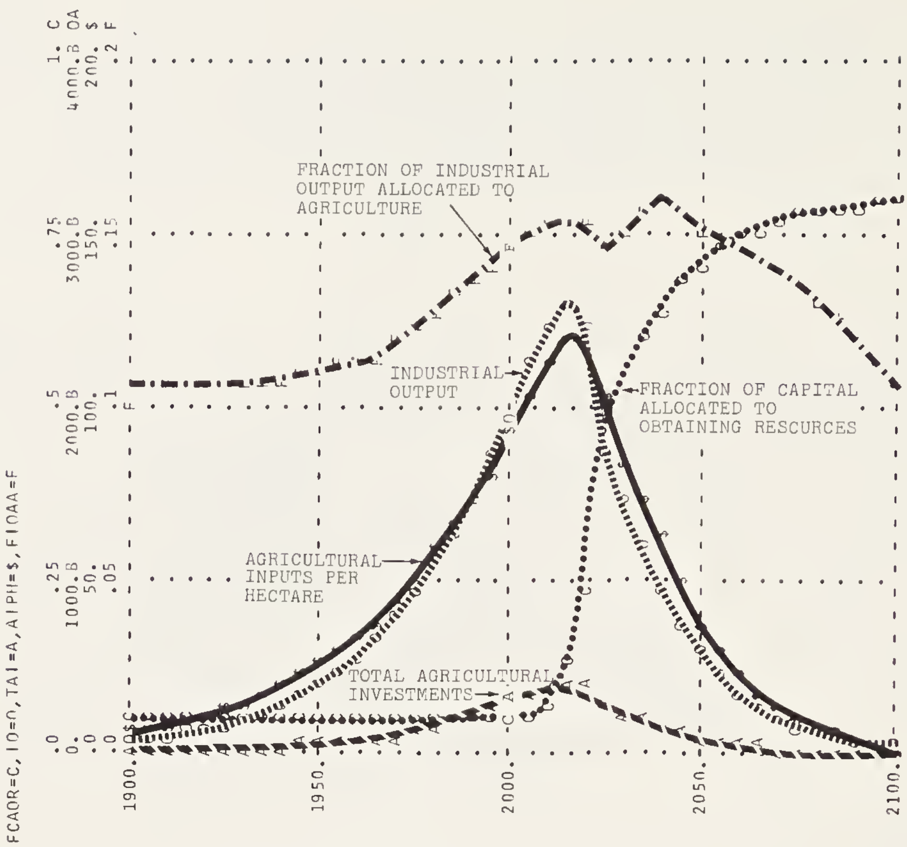


Figure 7-8 Run 7-6B: capital sector variables from the reference run

This and the following run depict the mechanisms that forced population POP and industrial output per capita IOPC to decline in the preceding reference run (Figure 7-7). As resources are depleted, a larger fraction of capital must be allocated to obtaining resources FCAOR after the year 2000. FCAOR rises quite steeply because of the high rate of growth of the nonrenewable resource usage rate. The increase in FCAOR reduces the amount of capital allocated to producing industrial output so that both industrial output IO and industrial output per capita IOPC decrease after the year 2015. The lower industrial output IO causes a reduction in total agricultural investment TAI and therefore in the amount of agricultural inputs per hectare AIPH allocated to producing food.

changes that have already been institutionalized continue to evolve. The reference run is most useful as a basis for comparison as we go on to test the sensitivity of the model to possible errors in parameter values and to possible changes in technologies and values.

7.4 SENSITIVITY TESTS

In the derivation of all the model relationships we employed existing information to establish a priori the direction and magnitude of causal influences. For several relationships, however, the available information regarding the magnitude of influence is relatively scarce, so we tried to approximate reasonable estimates of those parameters. Because it is entirely possible that the parameter values we chose contain significant errors, it was necessary to test the sensitivity of the model's behavior to changes in these uncertain parameters. This section presents sensitivity tests of four

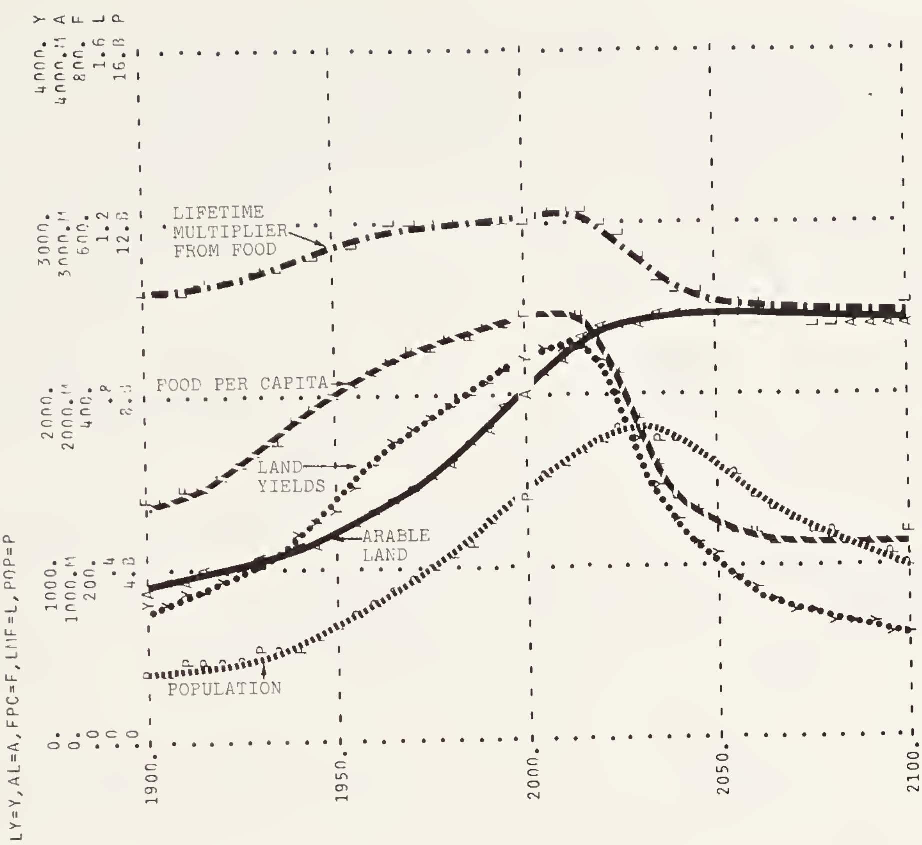


Figure 7-9 Run 7-6C: agriculture sector variables from the reference run

As the level of agricultural inputs per hectare AIPH decreases after the year 2015 (Run 7-6B), land yield LY begins to fall. The resulting drop in food production causes food per capita FPC to decline after 2015. The lower food per capita FPC in turn reduces the lifetime multiplier from food LMF, which eventually raises the death rate and stops population growth.

system parameters in the global model: nonrenewable resources initial NRI, the fraction of industrial output allocated to agriculture FIOAA, the average lifetime of industrial capital ALIC, and the industrial capital output ratio ICOR.

These sensitivity tests are not meant to represent a thorough sensitivity analysis of World3, for the model includes many more uncertain parameters than the four listed here. These tests represent only a few of the many simulation runs that could be made to test the sensitivity of the basic behavior mode to errors in the estimation of parameters. These runs are presented merely as examples of the model's behavior under different numerical assumptions. Other sensitivity tests have been described in the individual sector chapters. It is important to remember here that we are testing the sensitivity of the model's behavior, not the influence of parameter changes on the numerical values of variables at certain points in time. A parameter is therefore judged to be insensitive if, after being varied within its limits of uncertainty, the behavior mode of overshoot and collapse is still evident in the model.

Nonrenewable Resources Initial NRI—*Double* NRI The initial value given to the stock of nonrenewable resources NR was described in Chapter 5 as yielding a 1970 static index for aggregated world resources of 250 years. Although this value was chosen as a reasonable estimate, it is highly uncertain, so it was important to examine the effects of errors in this estimate on the behavior of the system. Run 7-7 (Figure 7-10) illustrates the model's behavior when the estimate of nonrenewable resources initial NRI is doubled. Note that Run 7-7 plots the nonrenewable resource fraction remaining NRFR rather than the absolute level of nonrenewable resources. The overall behavior of the system is quite similar to that of the reference run except in three areas: industrial output per capita IOPC continues to grow 15 years longer than in Figure 7-7, or until the year 2030. Population POP also continues to grow for an additional 15 years, reaching a level of over 8 billion in the year 2045. Pollution increases to 32 times its 1970 value in the year 2070, compared with the level of 11 times its 1970 value reached in 2035 in the reference run. Thus, after a 15-year postponement, growth is again halted by the effects of a decline in available resources—through a mechanism similar to that described for the reference run (Figure 7-7). Increasing our estimate of NRI by 100%, that is, assuming a static resource index of over 500 years instead of 250 years in 1970, has no significant influence on the basic behavior mode, and very little effect on the timing of the overshoot.

Nonrenewable Resources Initial NRI—*Ten Times* NRI In Chapter 5 it was stated that the most likely range of the 1970 static resource index was 50 to 500 years. Run 7-7 depicted the behavior of the model when the initial value of nonrenewable resources was increased to its maximum likely value. Run 7-8 (Figure 7-11) examines the sensitivity of the model's behavior to an order-of-magnitude increase in the initial value of nonrenewable resources NRI.

Run 7-8 shows that an extremely high estimate of nonrenewable resources eliminates resources as a constraint to growth within the time horizon of the model. With initial resources raised by a factor of 10, population POP and industrial output per capita IOPC continue to grow until constrained by other, more immediate limits—in this run, the high level of persistent pollutants. Even with the effective removal of one limit to growth, the basic behavior mode of the system remains one of overshoot and decline. The limiting factor is changed, changing the order in which the variables decline, but the behavior mode remains unstable.

Fraction of Industrial Output Allocated to Agriculture FIOAA In Chapter 4 the fraction of industrial output allocated to agriculture FIOAA was defined as the relationship governing the redirection of industrial output IO into or out of agricultural investment. The magnitude of this factor depends on the discrepancy between actual food per capita FPC and the desired or indicated food per capita IFPC. The fraction of industrial output allocated to services FIOAS performs an analogous function in the service sector.

As described in Chapter 4, a steeper slope for the FIOAA relationship represents a faster and stronger response to food shortages or surpluses. To test the sensitivity of the model's behavior to stronger economic responses to food shortages, the slope of the FIOAA relationship was increased as shown in Figure 7-12.

The effect of this change on the behavior of the reference run (Figure 7-7) is shown in Run 7-9 (Figure 7-13). A comparison of Run 7-9 with the reference run indi-

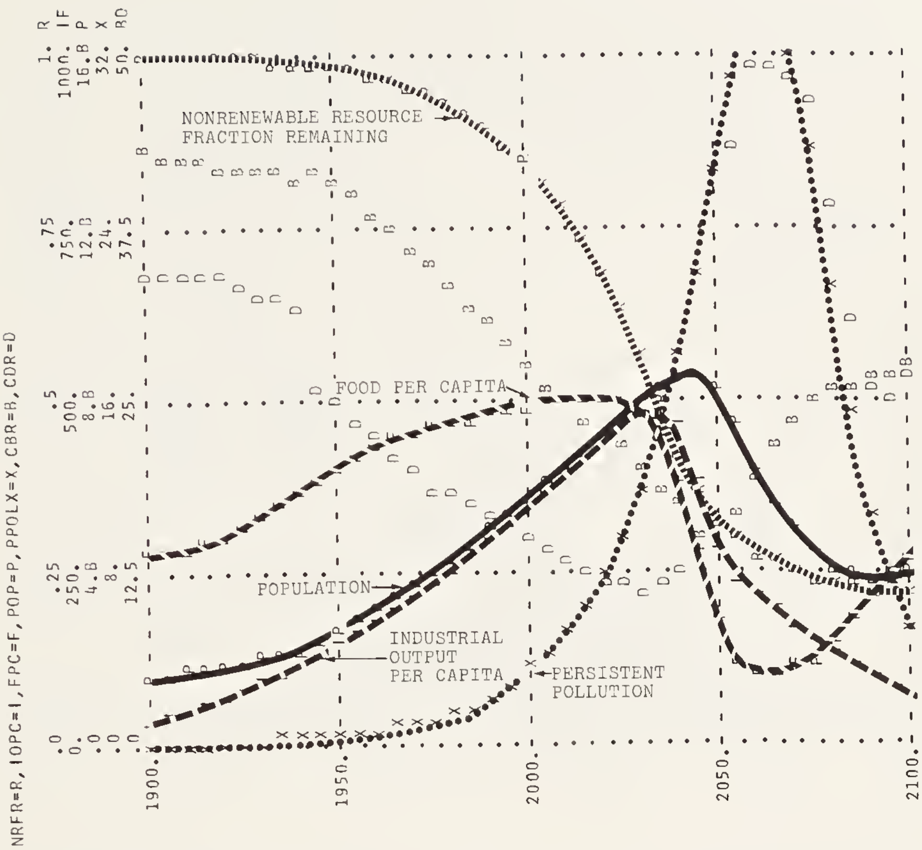


Figure 7-10 Run 7-7: sensitivity of the initial value of nonrenewable resources to a doubling of NRI

To test the sensitivity of the reference run (Figure 7-7) to an error in the estimate of initial nonrenewable resources, NRI is doubled. As a result, industrialization continues for an additional 15 years until growth is again halted by the effects of resource depletion.

cates that a change in the slope of this relationship will not alter the basic behavior mode of the model. Changes in the fraction of industrial output allocated to agriculture FIOAA have little effect on the model's behavior because this relationship governs only the short-term efficiency of the allocation of available industrial output. The purpose of this variable is to equilibrate actual food per capita FPC with indicated food per capita IFPC. The slope of the FIOAA curve determines the time necessary for the equilibration to take place, and this time is always very short compared with the more significant delays in other parts of the model. Thus the exact numbers that express the FIOAA relationship are important only in minor, short-term adjustments of the agriculture sector and have almost no effect on the long-term development of the total system.

Average Lifetime of Industrial capital ALIC The average lifetimes of service and industrial capital ALSC and ALIC were derived from international data on capital depreciation, as described in Chapter 3. These derivations are at best approximations because the international statistics are not uniformly accurate and because changes in the mix of capital items will change the average lifetime of capital. It was useful, therefore, to test the sensitivity of the model to changes in these parameters. As an

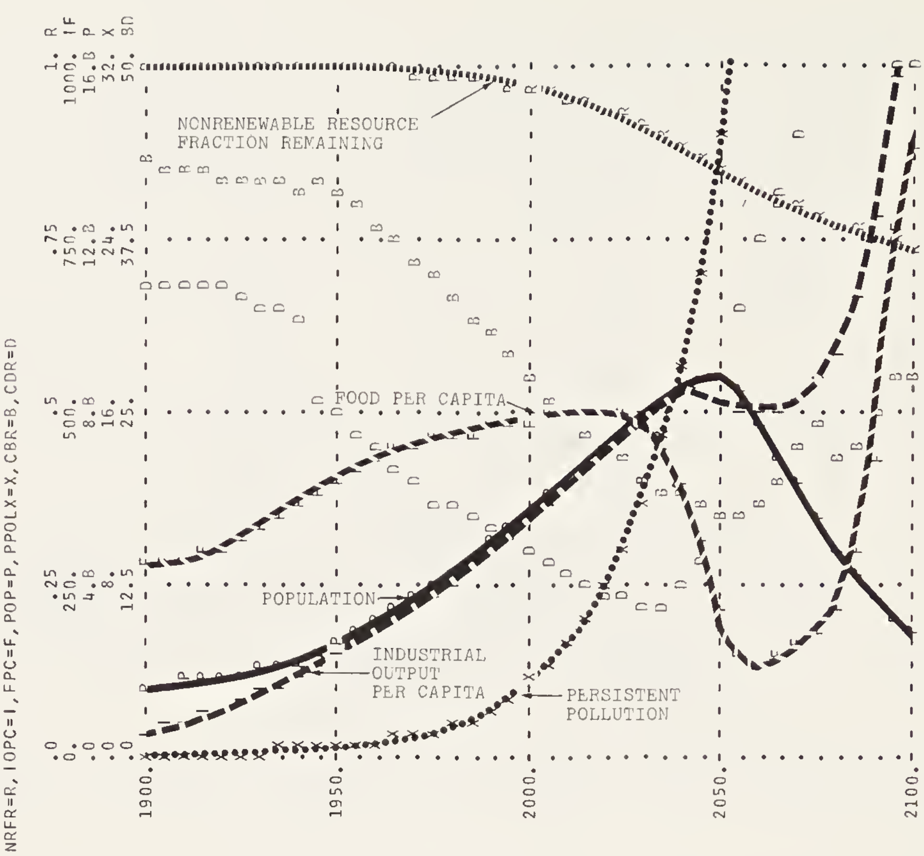


Figure 7-11 Run 7-8: sensitivity of the initial value of nonrenewable resources to a tenfold increase in NRI

The initial value of nonrenewable resources NRI is increased by a factor of 10, to a value well outside its most likely range. Under this optimistic assumption, the effects of nonrenewable resource depletion are no longer a constraint to growth. Note that there is no dynamic difference in this run between setting resources at 10 times their reference value or assuming an infinite value of resources. However, population and capital continue to grow until constrained by the rising level of pollution.

example, we show here the effects of varying the value of the average lifetime of industrial capital ALIC.

We might expect that an increase in ALIC would cause industrial capital IC and thus industrial output IO to grow faster, since the depreciation of industrial capital each year would be smaller. Run 7-10 (Figure 7-14) simulates the behavior of the model when ALIC equals 21 years, an increase of 50 percent over its value in Figure 7-7, the reference run. The result is as we had expected. Initially, both industrial output per capita IOPC and service output per capita SOPC grow faster than in the reference run, but the overall behavior mode of the system is the same.

The variables, however, no longer pass through their historical 1970 values. The reason for this discrepancy is that the gain around the positive feedback loop governing capital growth has been altered by this change in ALIC. In Chapter 3 it was shown that this gain is a complex function of the average lifetime of service capital ALSC, the average lifetime of industrial capital ALIC, the industrial capital-output

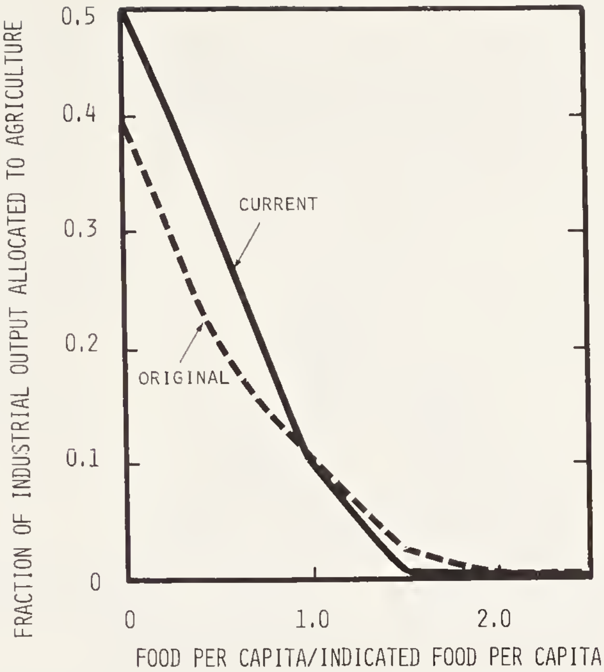


Figure 7-12 Increase in the slope of the fraction of industrial output allocated to agriculture relationship for sensitivity test

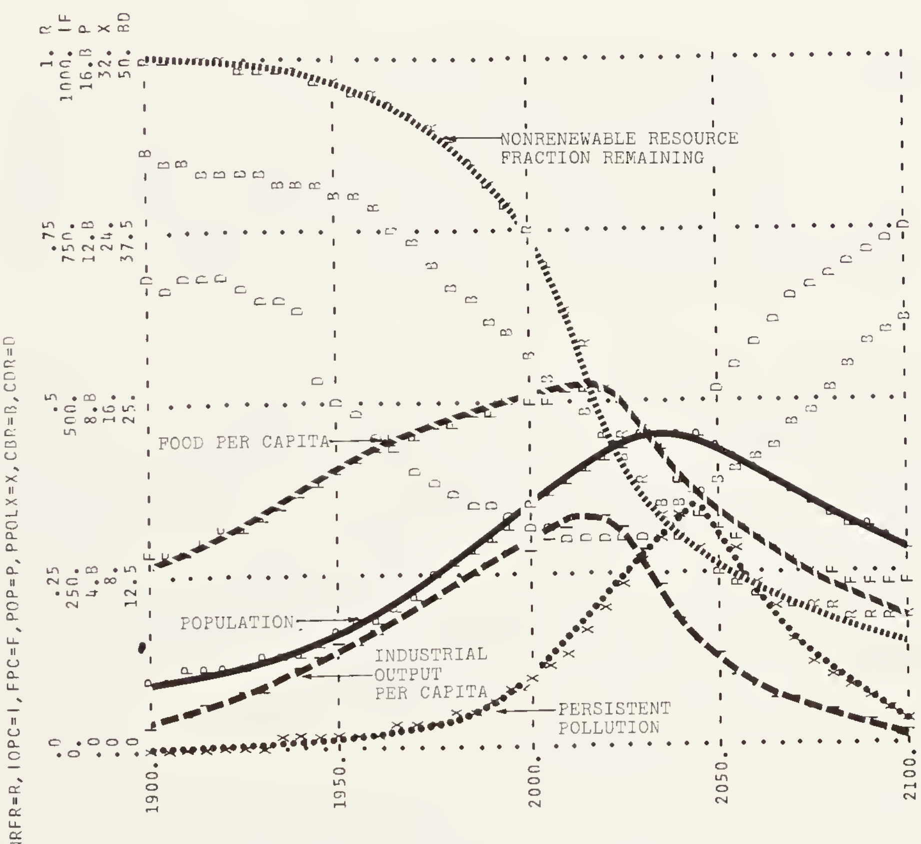


Figure 7-13 Run 7-9: sensitivity of the fraction of industrial output allocated to agriculture

The slope of the fraction of industrial output allocated to agriculture FIOAA relationship is increased, reducing the time needed to redirect industrial output into or out of agricultural investment. This change has very little effect on the overall behavior of the model.

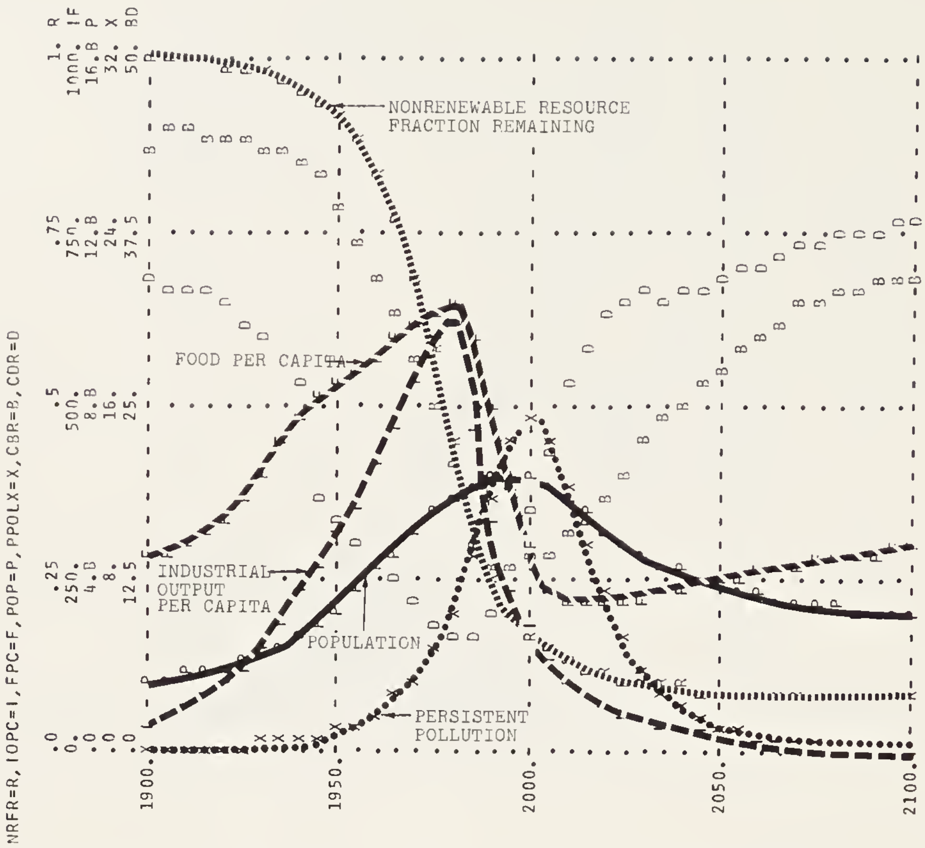


Figure 7-14 Run 7-10: sensitivity of the average lifetime of industrial capital
The average lifetime of industrial capital ALIC is increased 50 percent over its value in the reference run (from 14 years to 21 years), causing capital to grow faster than in the reference run. Although the behavior mode of the model is unchanged, the model variables do not pass through their 1970 historical values. This parameter, as well as the other parameters in the capital growth loop, is an important factor in determining the growth rate of capital.

ratio ICOR, and several other factors. In the growth phase of the reference run, this gain is nearly constant at about 3.6 percent per year, which compares well with historical data. When ALIC is increased to 21 years, however, the gain around the industrial capital growth loop is increased to 5.4 percent per year. To make this sensitivity test consistent with the historical data, a change in the gain caused by a higher ALIC must be offset by changing an additional parameter in the capital sector. When two such offsetting changes are made, the model is again consistent with historical behavior, which is a minimum criterion for any test of the model. An example of a sensitivity test where two such offsetting changes are made in the capital sector is shown in the following run.

Average Lifetime of Industrial Capital ALIC *and Industrial Capital-Output Ratio* ICOR Run 7-10 illustrated the sensitivity of the model's behavior to changes in the average lifetime of industrial capital ALIC. Although the increase in ALIC from 14 to 21 years did not change the model's behavior mode, the change did cause the industrial capital level to grow significantly faster than the historical growth of in-

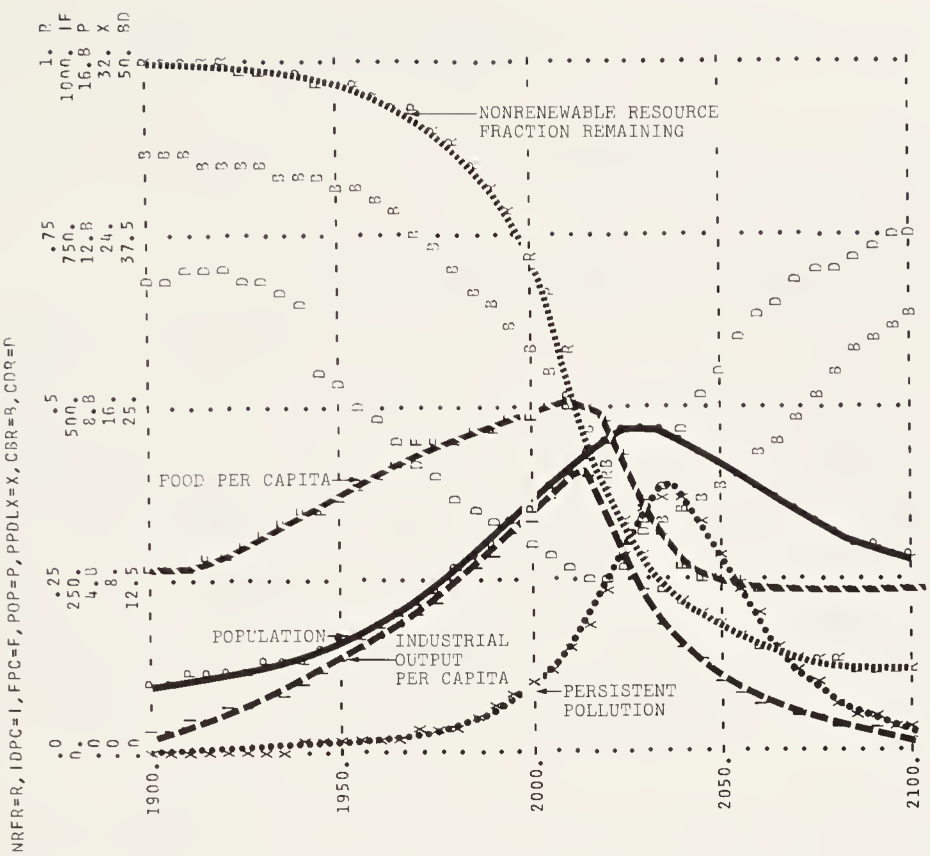


Figure 7-15 Run 7-11: sensitivity of the average lifetime of industrial capital and the industrial capital-output ratio

As in the previous run, the average lifetime of industrial capital ALIC is increased from 14 to 21 years. To ensure that the model duplicates historical behavior, the industrial capital-output ratio ICOR is also increased (from 3 to 3.75). The resulting behavior is very similar to that of the reference run. Changes in the elements affecting capital growth, when constrained to produce behavior consistent with historical behavior, do not significantly affect the behavior of the model.

dustrial capital. To ensure that the resulting model behavior is consistent with historical data, the change in the average lifetime of industrial capital ALIC from 14 to 21 years was accompanied in Run 7-11 (Figure 7-15) by an increase in the industrial capital-output ratio ICOR. That increase (from 3.0 to 3.75) is just enough to slow down the growth in industrial capital to the historical growth rate of 3.6 percent per year. When the additional criterion of reproducing historical behavior is added to the sensitivity test, the resulting run behaves more like the reference run; again, the behavior mode of the reference run is unchanged by these alterations in parameter values.

Runs 7-7 through 7-11 have been presented as examples of the sensitivity of the world model's reference behavior mode to possible errors in parameter estimates. Through this series of runs and many others not reported in this volume, we reached the conclusion that the behavior mode of overshoot and decline exhibited by the model is remarkably insensitive to variations in the estimates of most of the model's parameters.

This insensitivity becomes more understandable when the basic dynamic properties that lead to the unstable overshoot mode are considered. These basic properties are:

1. *Relatively rapid physical growth.*
2. *Physical limits to that growth.*
3. *Possible erosion of those limits by overuse or misuse.*
4. *Delays in the feedback signals that limit growth.*

Physical growth is generated in the model by the balance between the positive and negative feedback loops that control population and industrial capital. Physical limits are represented in the three other sectors: the stocks of nonrenewable resources and arable land, the maximum value of land yield, and the pollution assimilation half-life. Erosion of those physical limits can occur through the mechanisms of nonrenewable resource depletion, land loss from urban-industrial use and erosion, land yield decrease from air pollution or loss of soil fertility, or a decrease in the effectiveness of the pollution absorption process from the accumulation of pollution itself. Delays in feedback loops occur throughout the model. Every level, or state variable, represents an implicit delay in a feedback process. Other delays are explicitly represented, for example, the pollution appearance delay, the social adjustment delay, and the delay inherent in the population age structure.

The combination of these four basic properties causes the World3 system to grow beyond its sustainable carrying capacity and to erode that carrying capacity before the delayed feedback mechanisms that stop growth can take effect. It follows that small numerical changes (such as the change in the fraction of industrial output allocated to agriculture FIOAA) that do not alter any of the four basic properties will not affect the model's overshoot behavior mode. Numerical changes that do alter the exact specification of these properties (the change in initial nonrenewable resources NRI that moves one limit upward, or the change in the average lifetime of industrial capital ALIC that increases the rate of physical growth) will not affect the general behavior mode, since the basic properties still exist even though the timing or strength of their effects may be altered.

These sensitivity tests are helpful in designing effective policies: any policy designed to avoid the overshoot mode of behavior will be effective only if it influences one or more of the four basic properties of the model. The rest of this chapter is devoted to tests of technological and social policies designed to affect these basic properties.

7.5 TECHNOLOGICAL POLICIES

In the preceding simulations we have demonstrated that the parameters and relationships of World3 produce a global behavior similar to that of the real world for the period 1900–1970. When projected into the future they exhibit a fundamental behavior mode of overshoot and decline. Of the three possible behavior modes of the world system—continued growth, a smooth transition to equilibrium, or overshoot and decline—overshoot and decline appears to be by far the least desirable. This section presents a number of simulations to illustrate the response of the model to technological policy changes designed to avoid this behavior by raising the physical limits to growth. Since all the technological policies tested in this section assume advances beyond those that can be reasonably expected as further developments of present trends, they were modeled as modifications of the parameters and structures employed in the reference run.

In the first part of this section, discrete technological advances are assumed to be implemented within one year, 1975, and at no cost. This is an unrealistic approximation that was relaxed in later technological runs, for, in reality, any global technological change will take place gradually over a number of years in response to a perceived need for the technology and at a cost dependent on the nature of the technology. Furthermore, such discrete changes, if actually implemented in the real world, would undoubtedly cause a certain amount of political and social disruption not represented in the model. It is shown that discrete improvements in technology do not alleviate the model's instability in the long run but simply move the limiting factor that stops growth from sector to sector.

The second part of this section tests the sensitivity of the model to exponentially increasing improvements in technology, again ignoring the delays and costs that would be an inherent part of real-world policy changes. The third part consists of a group of technological runs simulating the effects of adaptive technological policies on the behavior of the model. An adaptive policy is one that is formulated in response to a perceived system need, such as the development of pollution abatement technologies in response to a perceived discrepancy between the existing level of pollution and the desired level of pollution. The improvements resulting from these technologies were modeled as exponentially increasing functions whose rate of growth, measured in percentage improvements per year, is variable but limited by a postulated upper bound. Additional simulations illustrate the effects of delays and costs of technological development and implementation on system behavior. The conclusion drawn from the series of simulations of technological policies presented here is that, when realistic assumptions concerning the nature of technological development are included in the model, technological policies *alone* are not sufficient to avoid the standard model behavior mode of overshoot and decline.

Discrete Changes in Technologies

As a first approximation, all technological changes in this series are assumed to be implemented within one year, 1975, and at no cost. Each successive run represents the effects of an additional policy that is designed to relieve the limitation to growth evidenced in the previous run. These simulations illustrate the fact that discrete technological changes designed to relieve the negative pressures limiting growth are successful only in moving those pressures to a different sector of the model.

Increase in Resource Exploration and Extraction Technologies Run 7-12 (Figure 7-16) analyzes the behavior of the model in response to an advance in resource exploration and extraction technologies implemented in 1975. The technological improvements affect the fraction of capital that must be allocated to obtaining resources FCAOR as shown in Figure 7-17. It was postulated in Chapter 5 that the fraction of capital allocated to obtaining resources FCAOR is a function of the fraction of nonrenewable resources remaining NRFR. Run 7-12 (Figure 7-16) assumes that advances in exploration and extraction technologies beyond those expected in the reference run will tend to offset rising resource costs for a large fraction of the lifetime of resources. Thus FCAOR will remain at its minimum value of 0.05 until very low values of NRFR are reached (Figure 7-17).

A comparison of Run 7-12 with the reference run (Figure 7-7) indicates that this policy is successful only in the short run. Industrial output per capita IOPC rises until the year 2025, just 10 years longer than in the reference run. Population POP is allowed to grow only an additional 10 years, to a level of 8 billion people in 2035. The policy's effectiveness is short-lived because of the continued growth of population and per capita resource usage. In the reference run, growth is halted when the nonrenewable resource fraction remaining NRFR reaches 0.5; in Run 7-12 growth continues until NRFR equals 0.2. Because of the continued growth in the nonrenewable resource usage rate NRUR, the additional amount of resources made available at lower resource costs by improved technology is consumed in only 10 years.

In the long run, a policy of increased investment in resource exploration and extraction technologies is ineffective and even counterproductive if not combined with other resource-conserving policies. Although the decline in industrial output IO is postponed for a few years in Run 7-12, the eventual rise in the fraction of capital allocated to obtaining resources FCAOR precipitates a more rapid decline in industrial output per capita IOPC than that exhibited in the reference run (Figure 7-7). This behavior is attributable to our assumption that advances in exploration and extraction technologies reduce resource costs in the short run, which encourages resource depletion. In the long run, the effects of resource depletion cause FCAOR to rise more rapidly (Figure 7-17), and the system has little time to adjust. As a result, industrial output per capita IOPC falls sharply after the year 2025 in Run 7-12.

Recycling Technologies Run 7-13 (Figure 7-18) illustrates the behavior of the model when the technological advances in resource exploration and extraction of Run 7-12 are supplemented by improved recycling techniques in 1975, allowing the annual usage of nonrenewable resources to be reduced by a factor of 8.0. Improvements in the efficiency of resource use may be represented in World3 in two ways—through changes in the table of per capita resource consumption PCRUMT or through changes in the nonrenewable resource usage factor NRUF. When the former is reduced, the magnitude of persistent pollution generation PPGR will also be reduced. When the latter is reduced, per capita resource consumption is decreased with no effect on the generation of persistent materials.

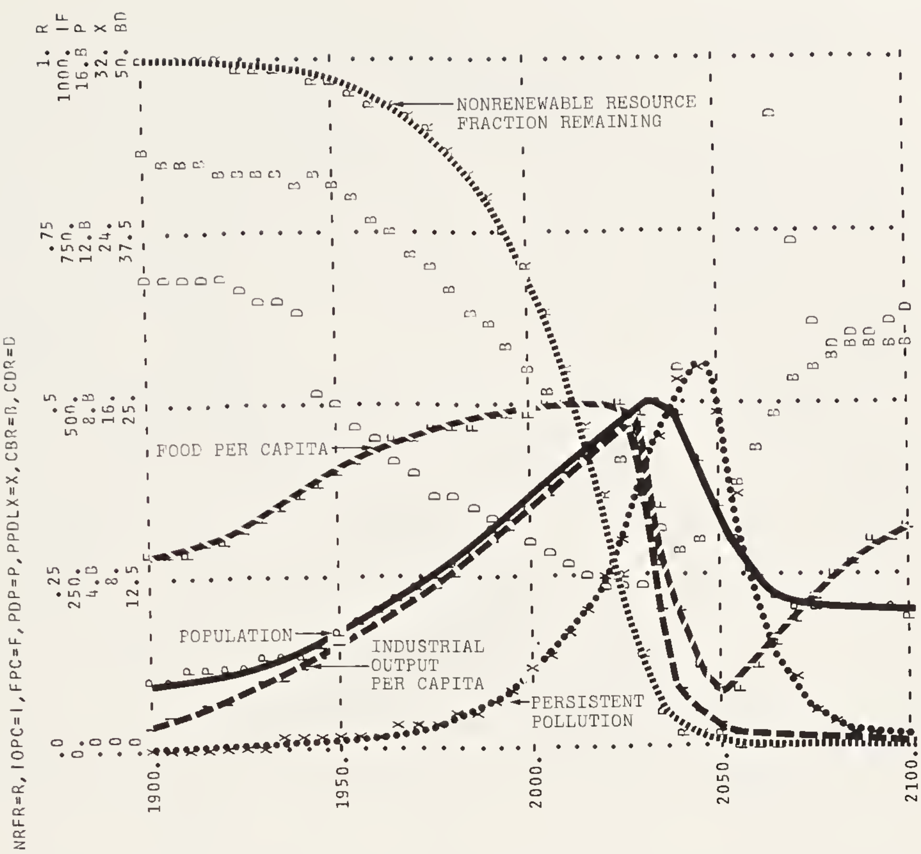


Figure 7-16 Run 7-12: improved resource exploration and extraction technologies

The implementation of improved resource exploration and extraction technologies in 1975 is modeled by lowering the capital cost of obtaining resources for industrial production. This policy allows industrial production to continue growing for a few more years than in the reference run, but it is ineffective in avoiding the effects of resource depletion.

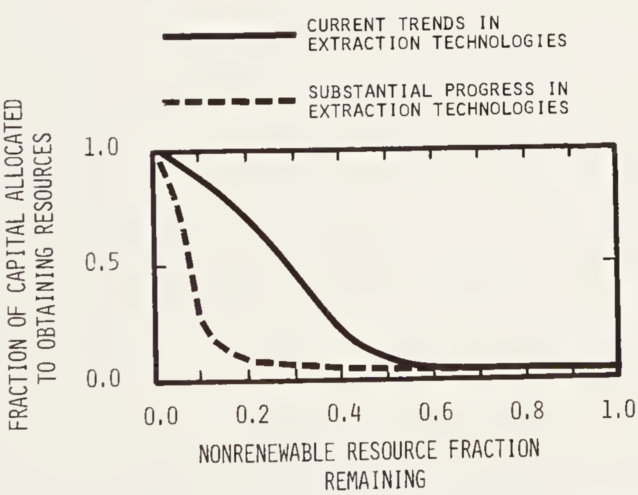


Figure 7-17 The effects of resource exploration and extraction technologies on the fraction of capital allocated to obtaining resources

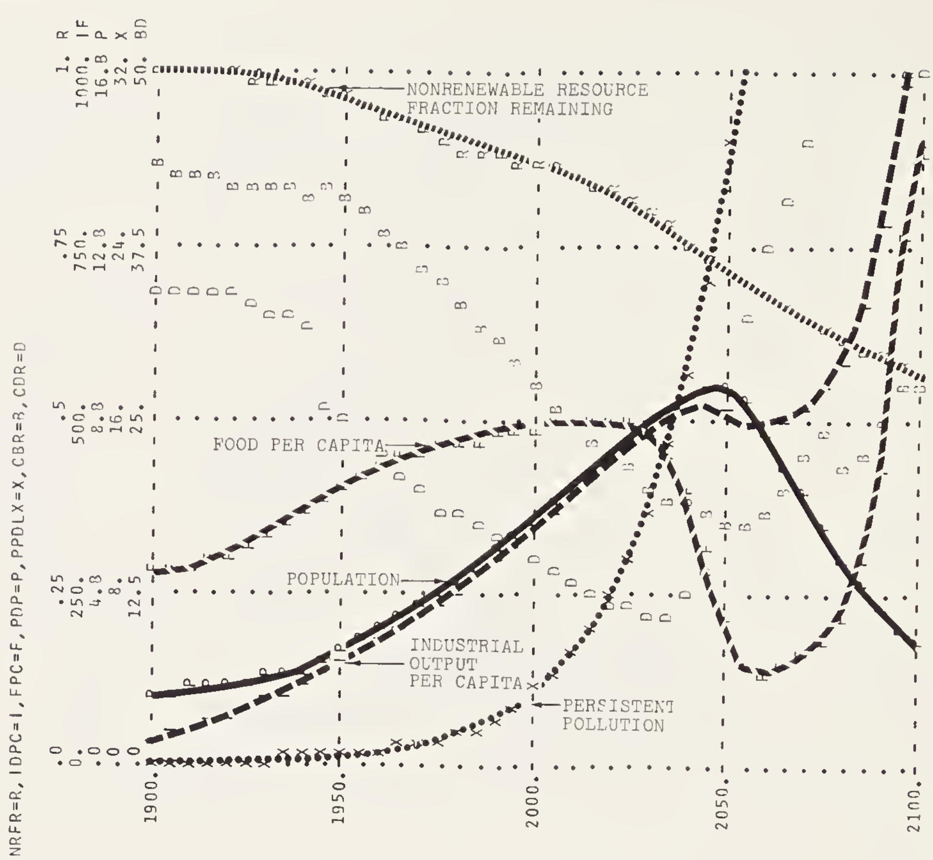


Figure 7-18 Run 7-13: recycling technologies

The advances in resource exploration and extraction technologies of Run 7-12 are supplemented by an improvement in recycling technologies that reduces per capita resource usage by a factor of eight in 1975. That policy removes the constraining effects of resource depletion and allows population and capital growth to continue until checked by persistent pollution.

We chose to model the implementation of recycling technologies as a change in NRUF because increased recycling does not necessarily change the amount of materials in use at any time for each person. Recycling merely changes the source of the materials, reducing the rate of decline of virgin nonrenewable resources. Because we hypothesized a causal link between per capita material usage and per capita pollution, increased recycling does not necessarily mean that less pollution will be generated. A reduction in the PCRUMT values, on the other hand, would represent the effects of a policy change that would reduce both resource usage and pollution generation. An example of a change that would be represented by shifting the PCRUMT table would be a significant increase in the use of smaller cars that consume less gasoline (a nonrenewable resource) and thus release less lead into the environment (a persistent pollutant).

One might expect the policies implemented in Run 7-13 to extend the period of continued growth in the model by effectively eliminating resource depletion as a limitation to growth. The resulting behavior shown in Run 7-13 does show that resource depletion no longer suppresses growth as in Run 7-12, but the basic overshoot and decline mode of behavior is still evident. The removal of the resource constraint allows the system to continue its growth until the level of persistent pollution becomes the limiting constraint.

In Run 7-13 industrial output IO and industrial output per capita IOPC continue to grow beyond the levels reached in Run 7-12. These higher levels of output generate enough persistent pollution to interfere significantly with the persistent pollution absorption process. As a result, the positive loop relating the level of persistent pollutants PPOL, the pollution assimilation half-life AHL, and the persistent pollution assimilation rate PPASR becomes active. The higher the level of persistent pollutants, the longer the assimilation half-life of those pollutants and the lower the assimilation rate. The decrease in the persistent pollution assimilation rate tends to increase the level of persistent pollutants still further. Run 7-13 shows that persistent pollutants accumulate quite rapidly once the positive loop becomes active, exceeding by 32 times the 1970 level of pollution in the year 2050. The high level of persistent pollutants generates side effects that eventually force both population POP and industrial output per capita IOPC to decline after the year 2050.

As the level of persistent pollution rises above its 1970 level, the rate of degradation of land fertility increases, causing land yields to decrease after 2030. The increase in industrial output adds to air pollution, which also decreases land yields, so that food per capita FPC decreases sharply after 2030. The increasing index of persistent pollutants PPOLX also tends to decrease the life expectancy of the population through the lifetime multiplier from persistent pollution. The combined effects of decreases in the lifetime multipliers from food and from pollution force the population POP to decline steadily after 2050 in Run 7-13.

As food per capita FPC declines after 2030, the agriculture sector demands more of the available industrial output to achieve an increase in land yields. The increasing allocation of industrial output away from the industrial sector and into the agriculture sector decreases the reinvestment of industrial output in industrial capital and forces the growth of industrial output to halt after 2050. Note that the last decades before the year 2100 show a startling recovery in the indicators of material well-being (industrial output per capita IOPC and food per capita FPC), although the pollution level remains extremely high. The recovery occurs through the following mechanism: as the decline in population gains momentum after the year 2000, the population begins to decrease faster than the total output of food and industrial goods. As a result, per capita food and industrial output again start to rise. The higher food availability per person indicates that smaller allocations of industrial output to agriculture are necessary, and the surplus is used to fuel growth in industrial production. Industrial output again begins to grow, making even more resources available for the production of food and goods.

The decline and recovery are accentuated by the seemingly unimportant assumption that allocations to the maintenance of land fertility are reduced when food is extremely scarce, as embodied in the relationship describing the fraction of agricultural inputs allocated to land maintenance FALM. The link between total food production F, food per capita FPC, the fraction allocated to land maintenance FALM, and land fertility LFERT constitutes a positive feedback loop in the normal operating range of World3 (that is, for food per capita FPC less than about 600 vegetable-equivalent kilograms per person-year). In this range, better maintenance of land results in higher land fertility, more food, higher food per capita, and finally even larger allocations to land maintenance. When food per capita declines, shortsighted attempts to increase current food production by neglecting long-term conservation leads to the destruction of land fertility and even less food in the longer run. The land maintenance loop (loop 6 in the agriculture sector, section 4.5) operates in Run 7-13 (and several of the following runs) to make the decline sharper and the recovery more spectacular during a crisis caused by shortages of a renewable resource. Even if one were to assume a continuation of land maintenance activities throughout a food crisis, as was explored in supplementary runs, the behavior mode described here stays the same but is less severe.

Resource and Air Pollution Technologies In the previous run, additional advances in resource technologies eliminated resources as a constraint to growth, but continued industrial expansion causes pollution to rise to intolerable levels. Run 7-14 (Figure 7-19) shows the behavior of the model if the technological policies of Run 7-13 are augmented by an increase in air pollution control technologies in 1975. These technologies decrease the adverse effects of air pollution on land yield, modeled as the land yield multiplier from air pollution LYMAP. Run 7-14 shows that this policy has practically no effect on the model's behavior. Although air pollution is the most visible form of pollution created by industrial output, the implementation of air pollution control technologies has solved only a small part of the pollution problem, the rise in the index of persistent pollutants PPOLX being the primary cause of the decline in food per capita FPC.

Persistent pollutants decrease food per capita FPC through the land fertility degradation process. As the index of persistent pollutants PPOLX increases above its normalized 1970 value of 1.0 (Run 7-14), the land fertility degradation rate increases. As the rate of fertility degradation rises above the fertility regeneration rate, land fertility is decreased. In the model, the exponential increase in persistent pollution from 1900 to 2060 causes land fertility to decrease exponentially until the year 2060. This decline in land fertility does not lower the amount of available food until 2025, for it is offset by the effects of increased agricultural inputs (fertilizers, pesticides) throughout this period. After 2025, however, increased agricultural inputs are no longer sufficient to offset the declining land fertility, and food per capita FPC begins to decline.

The combined effects of the decline in food per capita FPC and a decrease in life expectancy due to rising persistent pollution cause the population to decline quite rapidly after 2050. As in Run 7-13, industrial output begins to decline after the year 2045 because of the increased need to invest industrial output in the agriculture sector (thus decreasing the reinvestment of industrial output in industrial capital stock). Although industrial output declines after 2050, industrial output per capita IOPC begins to increase after 2065 because of the rapid decline in population POP.

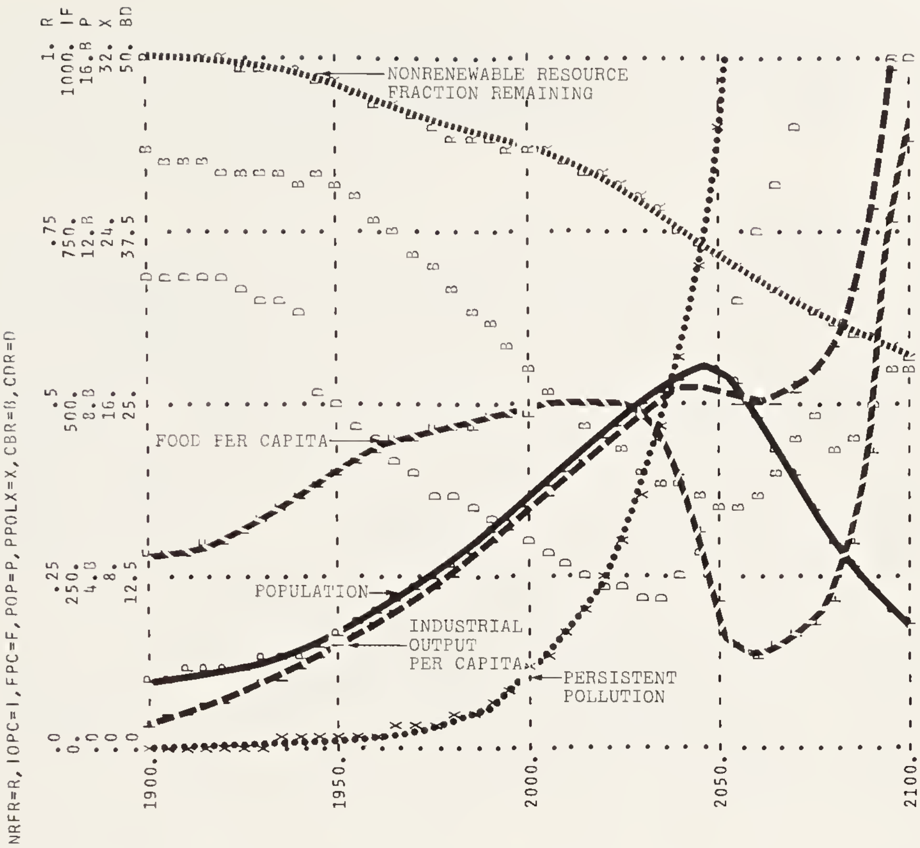


Figure 7-19 Run 7-14: resource and air pollution control technologies

As resource technologies eliminate the resource constraint to growth, industrial output continues to grow until it generates intolerable levels of pollution. To decrease the constraining effects of pollution on the system, Run 7-14 assumes that new air pollution control technologies are implemented in 1975. These additional technologies substantially reduce the adverse effects of air pollution on land yield. However, land yield and food per capita still decline, for the high index of persistent pollution PPOLX decreases the land fertility. The improvement in air pollution control technologies has solved only a small part of the pollution problem, for the rise in persistent pollutants ends growth in the other sectors of the model.

Resource and Pollution Technologies Run 7-15 (Figure 7-20) shows the behavior of the model if the resource and air pollution control technologies of Run 7-14 are supplemented by a technological policy that reduces the level of persistent pollution generated by each unit of industrial or agricultural output by a factor of 10 in 1975. As in all the technological policies tested so far, the real costs and delays of such a policy would undoubtedly be large, but in the model it is assumed that this policy is implemented at no additional cost and with no development and implementation delays.

The increase in pollution generation control technologies implemented in Run 7-15 reduces the index of persistent pollution PPOLX to a level that no longer interferes with agricultural production or growth in the population during the model run. As a result, both population POP and industrial output per capita IOPC continue to grow for 30 more years than in Run 7-14. Population POP reaches a level of 11 billion people in the year 2075 and subsequently declines. Industrial output per capita

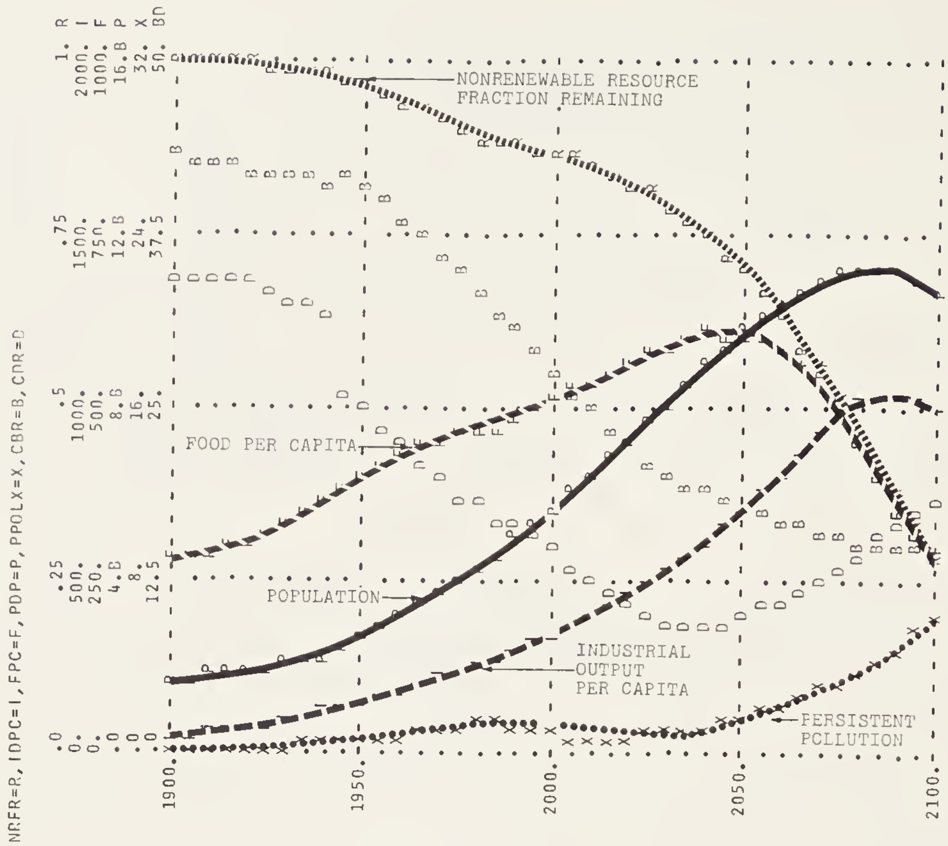


Figure 7-20 Run 7-15: resource and pollution technologies

Note: The scale for IOPC has been increased from 1,000 to 2,000 dollars per person-year

The resource and air pollution control technologies of the previous run are augmented in 1975 by a technological policy that reduces by a factor of 10 the index of persistent pollution PPOLX generated by each unit of agricultural and industrial output. The lower level of pollution allows population and industrial output to continue to grow until the amount of available food becomes the constraining factor. The decline in food per capita FPC eventually causes a reduction in both population POP and industrial output per capita IOPC.

IOPC reaches a level of 1,000 dollars per person-year in the year 2080 and then declines. (Note that the scale for IOPC has been changed in this run). The removal of the resource and pollution constraints to growth has allowed the system to continue to grow until limited by the third constraint in the system—the limits to food production assumed in the agriculture sector. In Run 7-15, growth is halted by the decline in food per capita FPC after the year 2040.

The decline in FPC stops the growth in population POP through the effect of the lifetime multiplier from food on the life expectancy of the population. As food per capita FPC declines toward the assumed subsistence food per capita of 230 vegetable-equivalent kilograms per person-year, the life expectancy of the population begins to decrease. The crude death rate CDR rises after 2050, and after 2075 exceeds the crude birth rate CBR, causing the population to decrease. The decline in food per capita also causes more industrial output to be allocated to the agriculture sector, for the discrepancy between the indicated food per capita (a function of industrial output per capita IOPC) and actual food per capita FPC rises after 2050. This reallocation of industrial output eventually forces the level of industrial capital (and thus industrial output) to decline after the year 2080 because less output is reinvested in the industrial capital stock.

Resource, Pollution, and Land Yield Technologies In Run 7-15, developments in resource and pollution control technologies succeeded in eliminating these two factors as limitations to growth, but continued growth was eventually halted by a decline in food per capita FPC. The amount of available food in the model was assumed to be equal to the product of the amount of arable land under cultivation and the average yield per hectare of that land. To increase the level of food, Run 7-16 (Figure 7-21) assumes that the resource and pollution technologies of the previous run are combined with technological advances in the agriculture sector that double the effectiveness of all agricultural inputs employed to increase land yield after 1975.

Run 7-16 shows that the rise in land yield in 1975 increases the available food and thus food per capita FPC in the short run (1975–2030). In the long run, however, the intensive use of the cultivated land results in faster land erosion, which decreases the amount of arable land available for food production. Although land yields are high, food per capita begins to decrease after the year 2030, for the amount of arable land cultivated begins to decline. The policy of increasing land yields is effective in the short run but could be counterproductive in the long run if not combined with other policies to avoid land deterioration. After the year 2050 the land erosion rate is so high that food per capita FPC is actually lower than in the previous run, even though land yields are considerably higher.

The long-term behavior mode resulting from new land yield technologies is actually quite similar to the behavior shown in the previous run, where land yields increased gradually because of increased agricultural inputs per hectare. The growth in population POP and industrial output per capita IOPC is again halted by a decline in food per capita FPC. However, the doubling of land yields in 1975 reduces the negative pressures from the agriculture sector that hinder growth after 1975. Thus both population POP and industrial output per capita IOPC grow faster from 1975 to 2050 in Run 7-16 than in the previous run; population POP reaches a level of 10.5 billion people by 2050; and industrial output per capita IOPC reaches a level of almost 1,500 dollars per person-year by the year 2065 (note the change in scale for IOPC). Both population POP and industrial output per capita IOPC decline earlier than in the previous run, for the decline in food per capita FPC is more severe in Run 7-16 than in Run 7-15, where no additional land yield technologies were assumed.

Resource, Pollution, and Agricultural Technologies Runs 7-12 through 7-15 show that discrete increases in resource and pollution control technologies implemented in 1975 tend to move the limitation to growth to the agricultural sector. An increase in land yields in Run 7-16 increases food in the short run but causes excessive erosion in the long run, which again reduces food production. Run 7-17 (Figure 7-22) shows the behavior of the model if additional land maintenance tech-

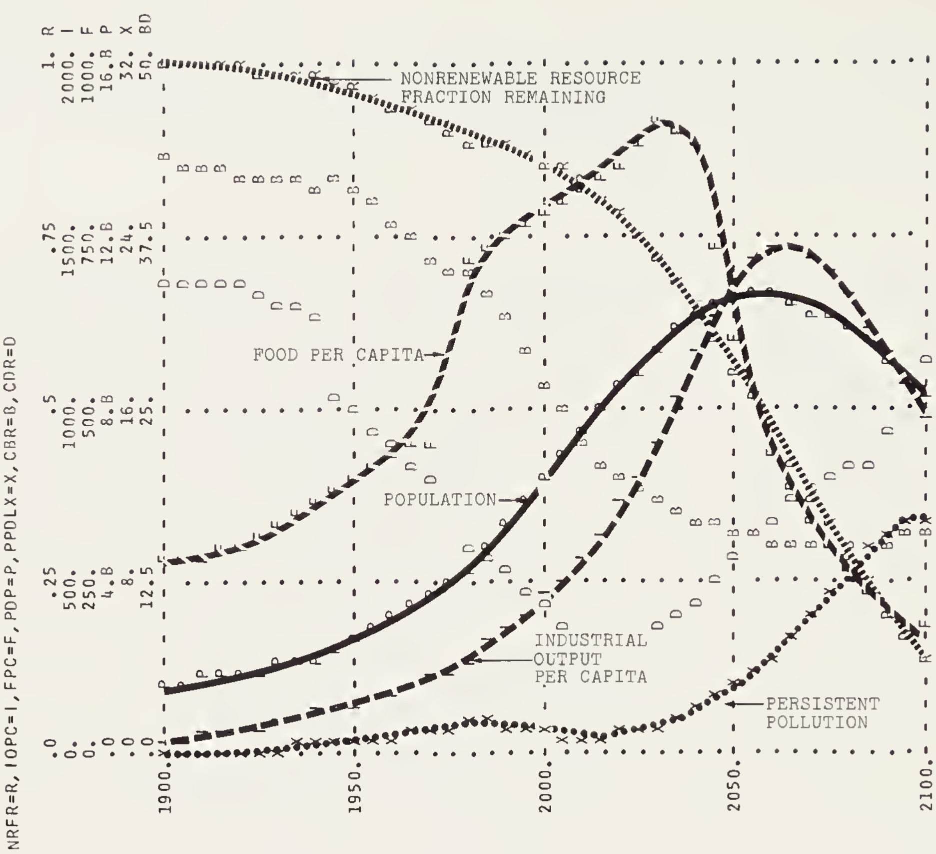


Figure 7-21 Run 7-16: resource, pollution, and land yield technologies
Note: The scale of IOPC has been increased from 1,000 to 2,000 dollars per person-year.

To increase food production, new agricultural technologies are implemented, augmenting the resource and pollution technologies of the previous run; they increase the land yield LY by a factor of 2 in 1975. This policy successfully raises the level of food in the short run, but in the long run the high yields cause increased land erosion, which later decreases the available food. After the year 2050 the higher rate of erosion depresses yields (and thus food per capita FPC) below the values observed in the previous run. As a result, population POP and industrial output per capita IOPC decline earlier than in Run 7-15, which assumed no new land yield technologies.

nologies are implemented in 1975, which reduce the amount of erosion caused by intensive land cultivation. One might expect that the combined effects of increased resource, pollution, and agricultural technologies would ensure that population POP and industrial output per capita IOPC could continue to grow for the duration of the run. However, Run 7-17 shows that growth is halted in the year 2080, only 20 years later than in the previous run.

In Run 7-17 the reduction of the growth-limiting pressures from the resource, pollution, and agriculture sectors allows population POP to grow to over 12 billion people and industrial output per capita IOPC to reach almost 5,000 dollars per person-year by the year 2080 (note that the scale for industrial output per capita IOPC has been changed). Per capita resource usage levels off at 7 times the 1970 level of per capita usage as industrial output per capita exceeds 1,400 dollars per

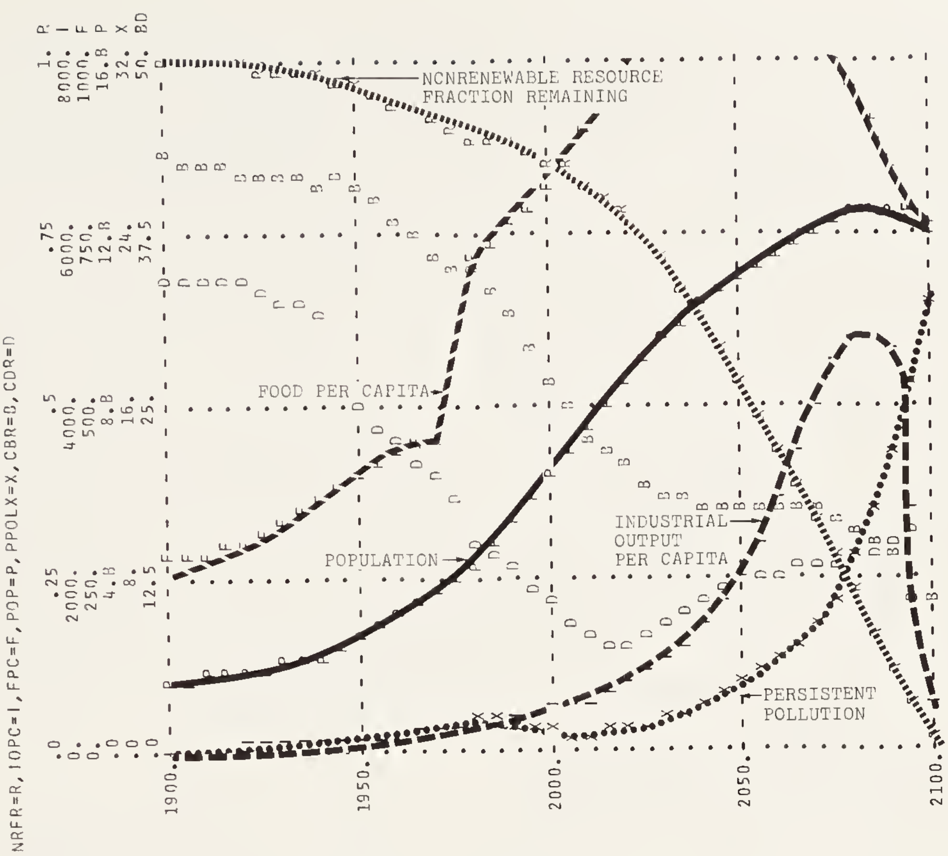


Figure 7-22 Run 7-17: resource, pollution, and agricultural technologies

Note: The scale of IOPC has been increased from 1,000 to 8,000 dollars per person-year.

The resource, pollution, and land yield technologies of the previous run are supplemented in 1975 by an improvement in land maintenance technologies. These new technologies ensure that higher land yields do not lead to any significant increase in land erosion. The reduced constraints in the resource, pollution, and agriculture sectors allow population POP and industrial output per capita IOPC to continue to grow until the effects of resource depletion are again evident, as in the reference run. Both population POP and industrial output per capita IOPC decline after the year 2080.

person-year. However, the increases in population and in affluence cause the resource usage rate to grow to over 23 times its 1970 value by the year 2080. Even though the policies tested in this run include a reduction of per capita resource usage by a factor of 8 in 1975, resources have been depleted by the year 2080 to the point where the fraction of capital allocated to obtaining resources begins to rise. This rise in resource costs forces a decline in industrial output per capita IOPC similar to that exhibited by the reference run (Figure 7-7).

Runs 7-12 through 7-17 illustrate that discrete technological advances designed to remove the pressures limiting growth in the system are ineffective in avoiding the overshoot and decline behavior mode. Unless accompanied by social policies, technological improvements tend to be short-term solutions that only postpone an ultimate *decline by moving the limiting factor from one sector to another sector. As each new technology is implemented, growth is allowed to continue until growth-limiting pressures arise elsewhere. Eventually in Run 7-17 growth is again halted by the effects of resource depletion, the same mechanism that was active in the reference run (Figure 7-7). The combined effects of large advances in resource, pollution, and agricultural technologies manage to postpone the eventual decline by less than 100 years.*

Perhaps of more significance than the timing of the eventual decline exhibited in this series of runs is the fact that a technological response to approaching growth limits does not lead to a smooth accommodation with those limits. A technological response does not normally reduce the delays in the response of the world system to growth, nor does it weaken the positive feedback mechanisms causing growth. The physical limits are effectively raised, but not raised indefinitely; thus all the properties that lead to the unstable overshoot mode are still present in the system. To remove the property of physical limits completely, the process of developing technological solutions to expand the ultimate limits must be exponential; in fact, their growth rates must be faster than the exponential growth rates of population and capital. The next section presents a simulation run to illustrate this point.

Exponential Changes in Technology

The preceding set of technological runs showed that discrete changes in technology only tend to postpone overshoot and decline in the world model. Run 7-18 (Figure 7-23) shows the behavior of the model if one assumes that all the ceilings to growth in the model are lifted exponentially at 4 percent per year beginning in 1975, and at no cost. Under these conditions, the model no longer exhibits the overshoot and decline mode of behavior. Industrial output per capita IOPC continues to grow exponentially throughout the model run, and in fact could keep on growing forever. Food per capita FPC grows very quickly after 1975 and eventually stabilizes near the maximum indicated level of food per capita. Although the crude birth rate CBR declines continually throughout the 200-year period, it remains slightly higher than the crude death rate CDR throughout the run. Therefore, population POP continues to grow throughout the model run, reaching 14 billion people in the year 2100. The index of persistent pollution PPOLX remains at very low levels, and resources are being depleted very slowly by the year 2100. What changes had to be made to obtain such a different behavior mode from the same model?

Because the output of this technological run is so different from that of the reference run and the preceding technological runs, it is important to examine the policy changes implicit in this run in detail. First, it is assumed that advances in recycling and other resource-conserving technologies tend to decrease per capita resource usage at 4 percent per year. This implies that, if population and industrial output per capita remain constant, resource usage will be halved in approximately 17 years, divided by four after 34 years, and so on. Even though the growth in industrial output per capita tends to increase per capita resource usage, the exponential increase in recycling technologies assumed in the run implies that by the year 2100 each person will be consuming less than one-twentieth of the resources he used in 1970, all

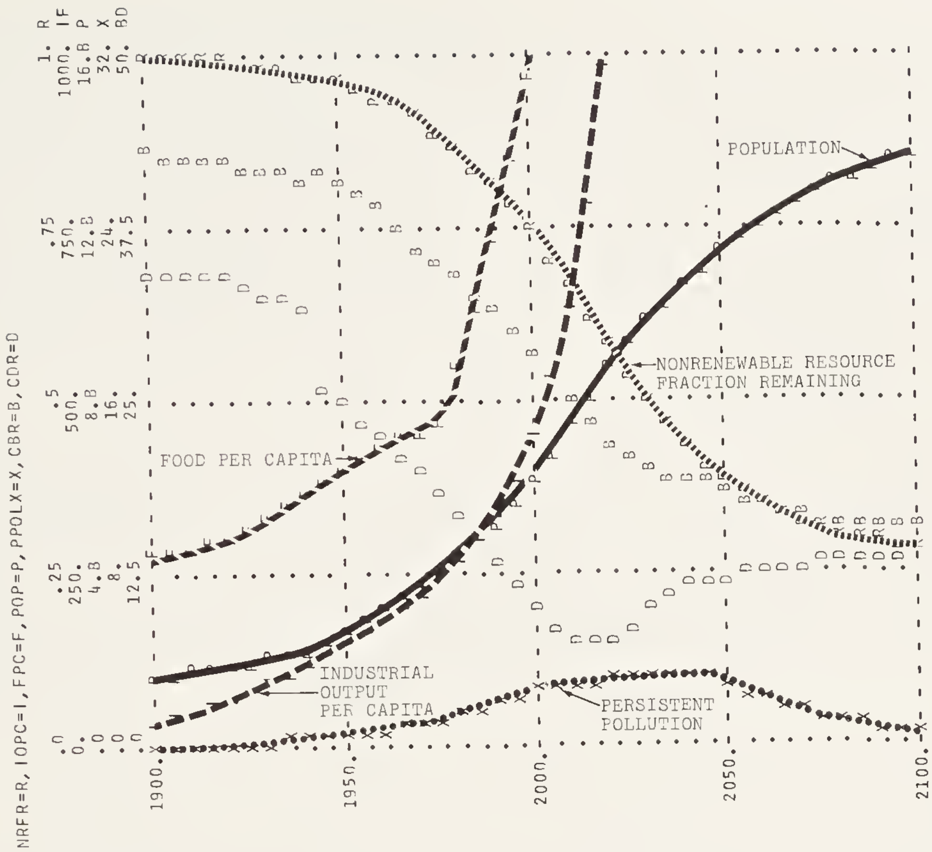


Figure 7-23 Run 7-18: exponential changes in technology

Here it is assumed that exponentially increasing technologies are able to postpone indefinitely the effects of the constraints to growth, as modeled in World3, at no cost and with no delays in development and implementation. The improved technologies tend to reduce per capita resource usage and pollution generation per unit of agricultural and industrial output at 4 percent per year after 1975. At the same time, land yields tend to increase at 4 percent per year, with no upper limit and with practically no adverse side effects such as land erosion. Although industrialization grows exponentially, the rate of removal of land for urban-industrial use decreases to zero by the year 2000. Finally, air pollution is assumed to have no adverse effects on land yield. Under these assumptions, population reaches 14 billion people in the year 2100 and continues to grow (though at a slow rate of 0.6 percent per year). Food is in abundance throughout the run, resource usage declines to zero as fewer resources are needed to sustain output, and industrial output per capita IOPC continues to grow indefinitely.

at no additional costs of energy, land, or any other physical factor. Under these assumptions, although the industrial capital stock has skyrocketed by 2100, the overall annual rate of nonrenewable resource usage *decreases* to less than one-fourth of its 1970 value by that year. Presumably this capital stock is primarily composed of renewable resources, as are the goods it manufactures, and presumably there are no limits to the rate of use of these renewable resources.

Similar assumptions were made in the agriculture and pollution sectors. Run 7-18 assumes that advances in land yield technologies increase land yields exponentially at 4 percent per year with no cost and no upper limit, and that virtually no erosion will occur as a result of such intensive land use. Under these assumptions, land yield increases are easily able to stay ahead of the growth in both population and indicated food per capita. Land yields grow to over 20 times their 1970 value by the year 2100, even though physical agricultural inputs *decrease* during that period. Either genetic changes have vastly increased the efficiency of the conversion of sun energy by green plants or, perhaps, an increase in sun energy has been engineered. Furthermore, although industrialization is expanding exponentially and population continues to increase, the rate of removal of land for urban-industrial use declines to zero after the year 2000 due to technological advances in the efficiency of land utilization (perhaps all new cities are built over the ocean).

In the pollution sector, pollution generation per unit of industrial and agricultural output declines exponentially at 4 percent per year during the model run. By the year 2100 each unit of industrial output generates less than one one-hundredth of the amount of pollution that a similar unit of output generated in 1970. Even though population and industrial output continue to increase exponentially through the year 2100, the index of persistent pollution PPOLX is declining in the year 2100. Run 7-18 also assumes that air pollution control technologies increase fast enough to offset the adverse effects of air pollution on land yield during the model run. Finally, the run assumes that technological advances in methods of production ensure that the growth in industrial output will never be curtailed by a labor shortage.

When the assumptions behind Run 7-18 are made explicit, the reason for the radical change in the behavior of the model becomes obvious. The assumption of continuous exponential advance in technology at 4 percent per year and at no cost eliminates all the assumed limits in the model. Resource usage declines essentially to zero by the year 2100, which implies the building and maintenance of an immense capital stock with no net physical consumption of any resource, including land. Exponential land yield increases assume that the energy or caloric conversion per hectare of land has no limit—even though this energy is supplied at a finite rate from the sun. Exponentially decreasing pollution levels imply that practically no materials are involved in the industrial process by 2100, or that pollution control is nearly perfect and cost-free. Because the social and political limits to growth that may be associated with increasing population densities were not included in the model, there are no reasons for growth to stop.

Although we believe that new technologies are certainly capable of extending some of the natural limits modeled in World3, we do not believe that these new technologies can eliminate the effects of those limits altogether, as depicted in Run 7-18. Successful advances in technology are by no means an automatic, continuous exponential process. They are subject to decreasing returns and increasing costs and to physical laws (for example, the second law of thermodynamics, which implies that recycling cannot be 100 percent effective or cost-free). Technological development is a delayed and costly process that occurs only in response to perceived social needs. The next set of runs tests the behavior of the system if this more realistic representation of technological advance is explicitly modeled.

Adaptive Changes in Technology

The first set of technological policies tested in this chapter assumed that new technologies tend to be implemented in discrete increments, with no costs and no development or implementation delays. Next, a run was presented in which the effectiveness of new technologies was assumed to increase exponentially, again with no costs and no delays in development or implementation. These representations of technology appear to be unrealistic. Technological improvements seem to arise only in response to a perceived need for the improvements and as a result of a costly and time-consuming period of scientific development and social implementation, not through some automatic process that causes improvements to increase regularly each year.

We have labeled this model of technological development an adaptive process because the technological improvements tend to move the system toward a desired set of goals in response to a perceived need for such technological developments. The following set of policy runs tests the effects of this adaptive process of technological development on the behavior of the model as shown in the reference run (Figure 7-7). The parameter changes and structural additions for each adaptive policy run may be found in the appendix to this chapter.

Adaptive Technological Policies—No Delays, No Costs Run 7-19 (Figure 7-24) shows the behavior of the model under the assumption that technological advances in reducing resource usage, reducing pollution generation, and increasing land yields all occur in response to a perceived need for the technologies. In this run it is still assumed that these advances in technology are achieved with no delays in development and implementation, and at no cost. Figure 7-25 illustrates the structural additions in the resource, pollution, and agriculture sectors inserted for this run. In the resource sector, technological advances in recycling reduce the nonrenewable resource usage factor NRUF as annual resource usage rises above a desired rate, set at the 1970 rate of usage. In the pollution sector, technological advances in pollution control are developed as the level of pollution rises above a desired pollution level, here assumed to be 3 times the level of pollution in 1970. Pollution control technologies then reduce the pollution generation factor, representing a decrease in the pollution generated per unit of industrial and agricultural output. In the agriculture sector, technological advances raise the land yield as the food per capita drops below the desired level, which is assumed to be 3 times the subsistence level. In each case, the maximum rate of technological change is assumed to be 5 percent per year.

In addition to the three adaptive technological policies shown in Figure 7-25, discrete increases in resource exploration and extraction technologies, land maintenance technologies, and air pollution technologies are assumed to occur in 1975. Note that these technological advances could have been modeled as adaptive policies, but they are modeled here as step increases to simplify the presentation in this section. These three additional technologies are included in each succeeding adaptive policy, Runs 7-19 through 7-23.

The behavior mode exhibited by Run 7-19 is similar to that of 7-18, where

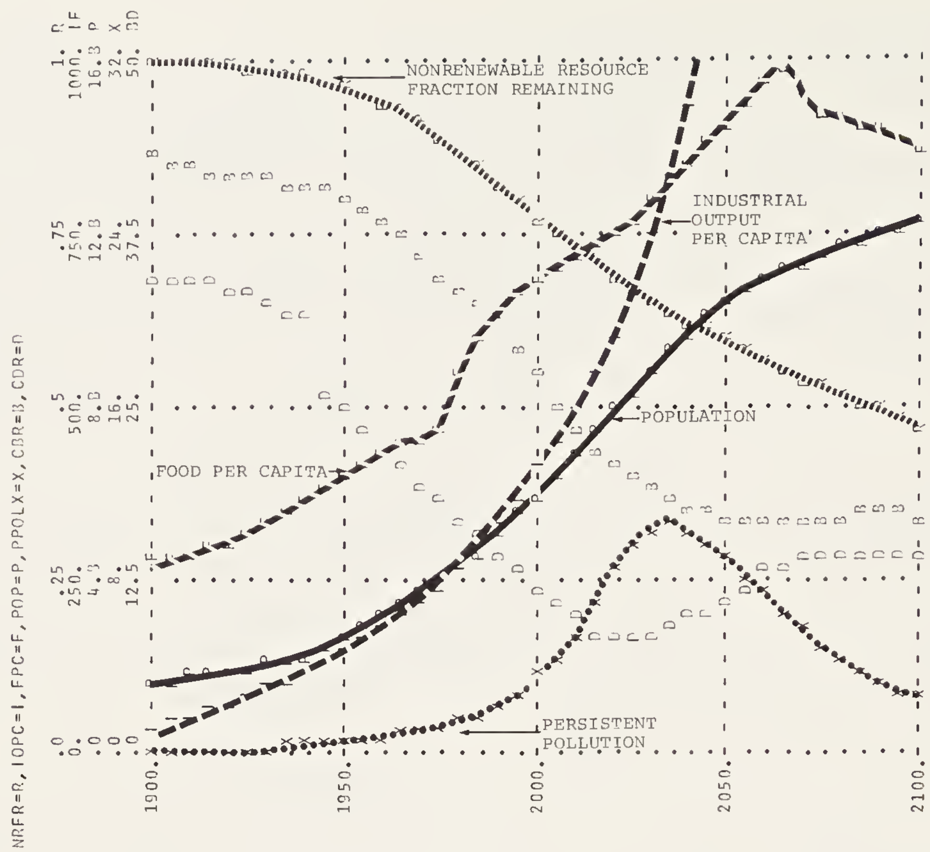


Figure 7-24 Run 7-19: adaptive technological policies—no delays, no costs

Technological advances in reducing per capita resource usage, diminishing pollution, and increasing land yield are assumed to occur in response to a perceived need for the technologies. The maximum rate of change for each technology is assumed to be 5 percent per year. In addition, discrete advances in exploration and extraction technologies, land maintenance technologies, and air pollution technologies are assumed to be implemented in 1975. This run is similar in behavior to Run 7-18, in which technological improvements rise continuously at 4 percent per year. Growth is maintained through the year 2100 because of the absence of significant delays and costs in the development of new technologies.

exponential advances in technology increased continuously after 1975. In Run 7-19, industrial output per capita IOPC increases continuously to nearly 6,000 dollars per person-year in the year 2100. The increase in industrial development causes an overall decrease in the birth and death rates over the 200-year period. By the year 2100, the population has grown to over 12 billion and, as a result of the increase in industrial development, is increasing at only 0.3 percent per year. Technological advances in resource recycling allow population POP and industrial output per capita IOPC to continue to increase without causing an increase in the usage rate of nonrenewable resources. Improvements in land yield technologies cause food per capita FPC to increase to a level of 700 vegetable-equivalent kilograms per person-year by the year 2000.

The similarity in the behavior of Run 7-18 and Run 7-19 stems from the fact that in both runs technology is capable of postponing the ultimate limits modeled in

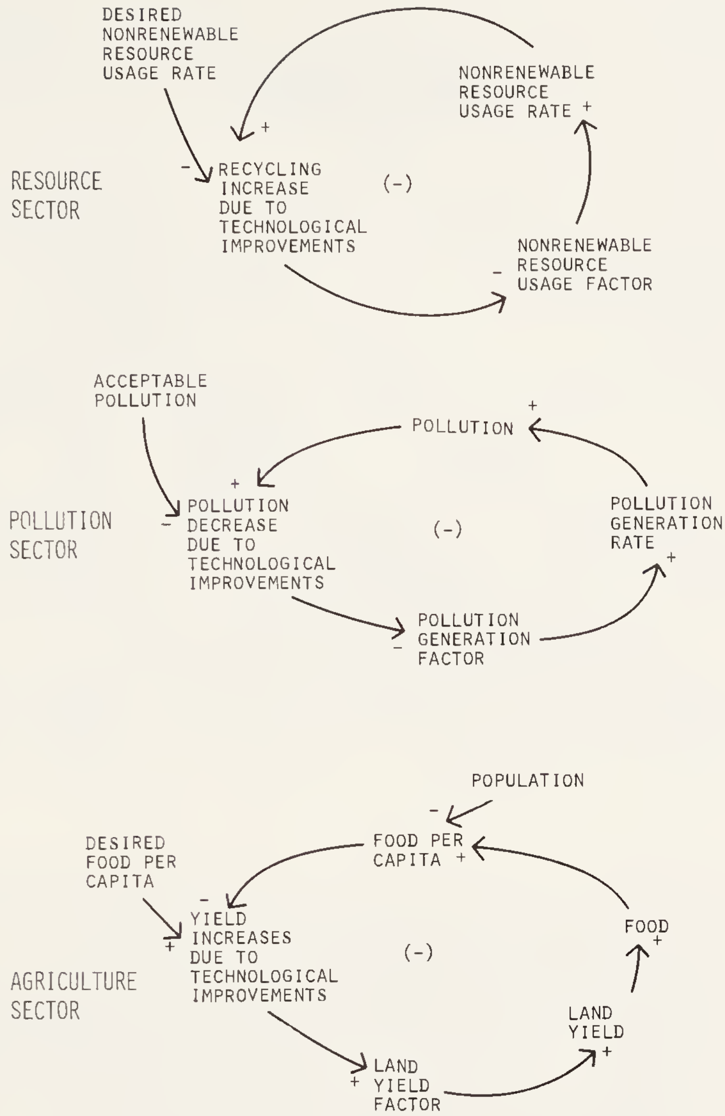


Figure 7-25 Structural additions for adaptive technological policies (with no delays or costs of development and implementation)

World3 at an exponential rate, with no delays in the development or the implementation of these new technologies and with no negative long-term side effects. In Run 7-19, however, these advances in technology occur only in response to a perceived need for the new technologies. Because the automatic exponential advances in technology anticipate the perceived needs for such technologies, the development process depicted in Run 7-18 occurs at a faster rate than in Run 7-19.

Adaptive Technological Policies—The Effects of Limitations to Technological Capabilities Run 7-20 (Figure 7-26) assumes adaptive technological policies identical to those tested in Run 7-19, except that the maximum rate of technological change is assumed to be 2 percent rather than 5 percent per year. This run therefore represents the behavior of the world system when there are significant limitations to the rate at which technology is able to reduce the negative side effects of growth.

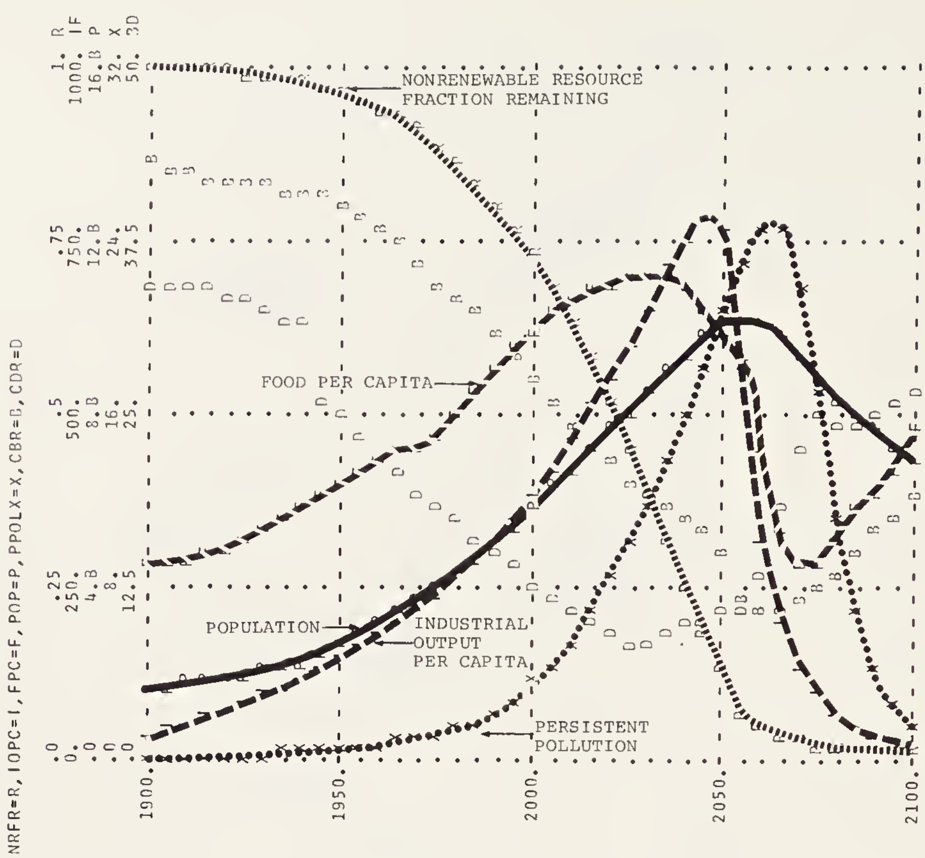


Figure 7-26 Run 7-20: adaptive technological policies—the effects of limitations to technological capabilities

The adaptive technological policies assumed in this run are identical to those in Run 7-19 except that the maximum rate of technological change is assumed to be 2 percent instead of 5 percent per year. Technology is unable to avoid the effects of the constraints to growth because industrial output per capita IOPC and population POP grow faster than the maximum rate of technological change. In this run, resource depletion again halts growth in population and industrial output.

Run 7-20 shows that the adaptive technological policies allow growth to continue for 75 years after 1975. Industrial output per capita IOPC, food per capita FPC, and population POP all continue to grow until the year 2050. But because industrial output per capita IOPC and population POP grow faster than the maximum rate of technological development, technology is unable to avoid the negative pressures that occur when the model's limits are approached. In this case, nonrenewable resource depletion is the first limit reached, for resource usage tends to increase by 4 percent per year due to population growth and industrial development, while recycling technologies tend to reduce per capita resource usage by only 2 percent per year. Growth in industrial output per capita IOPC is halted after the year 2050 as resources near depletion, forcing the fraction of capital that must be allocated to obtaining resources FCAOR to rise. The decrease in industrial output per capita IOPC causes growth in other sectors to stop in a behavior mode similar to that of the reference run (Figure 7-7).

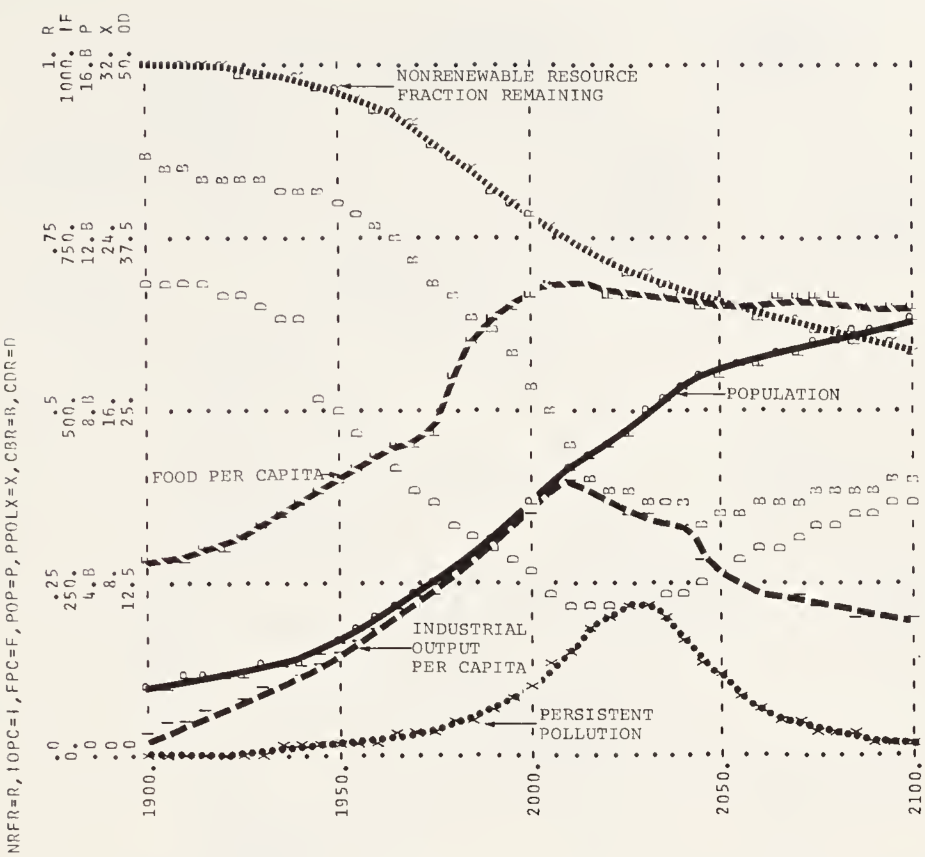


Figure 7-27 Run 7-21: adaptive technological policies—the effects of technological development and implementation costs

Here it is assumed that more effective recycling, pollution control, and land yield advances can be obtained only at increasing costs. These higher costs are represented in the model by a rise in the industrial capital-output ratio ICOR. A trade-off now occurs between the benefits of continued growth and the costs of the technologies that make further growth possible. The rising costs of the new technologies cause industrial output per capita IOPC to decline after the year 2010.

Adaptive Technological Policies—The Effects of Costs of Technological Development and Implementation In Run 7-19 it was shown that continued growth in population and industrial capital is a possible mode of behavior if new technological solutions can be developed at an exponential rate with no side effects and no delays in their development and implementation. Run 7-21 (Figure 7-27) tests the effects of the assumption that the advances in technology modeled in Run 7-19 can be obtained only at some real cost. Figure 7-28 shows the structural additions assumed for this run. As in Run 7-19, technological improvements in resource recycling, pollution control, and land yield capabilities are developed as needed. However, the development and implementation of these new technologies add to the cost of the production process. In this formulation, increases in technological development and implementation costs are modeled as a rise in the industrial capital-output ratio. This simplified representation of costs assumes that the development and

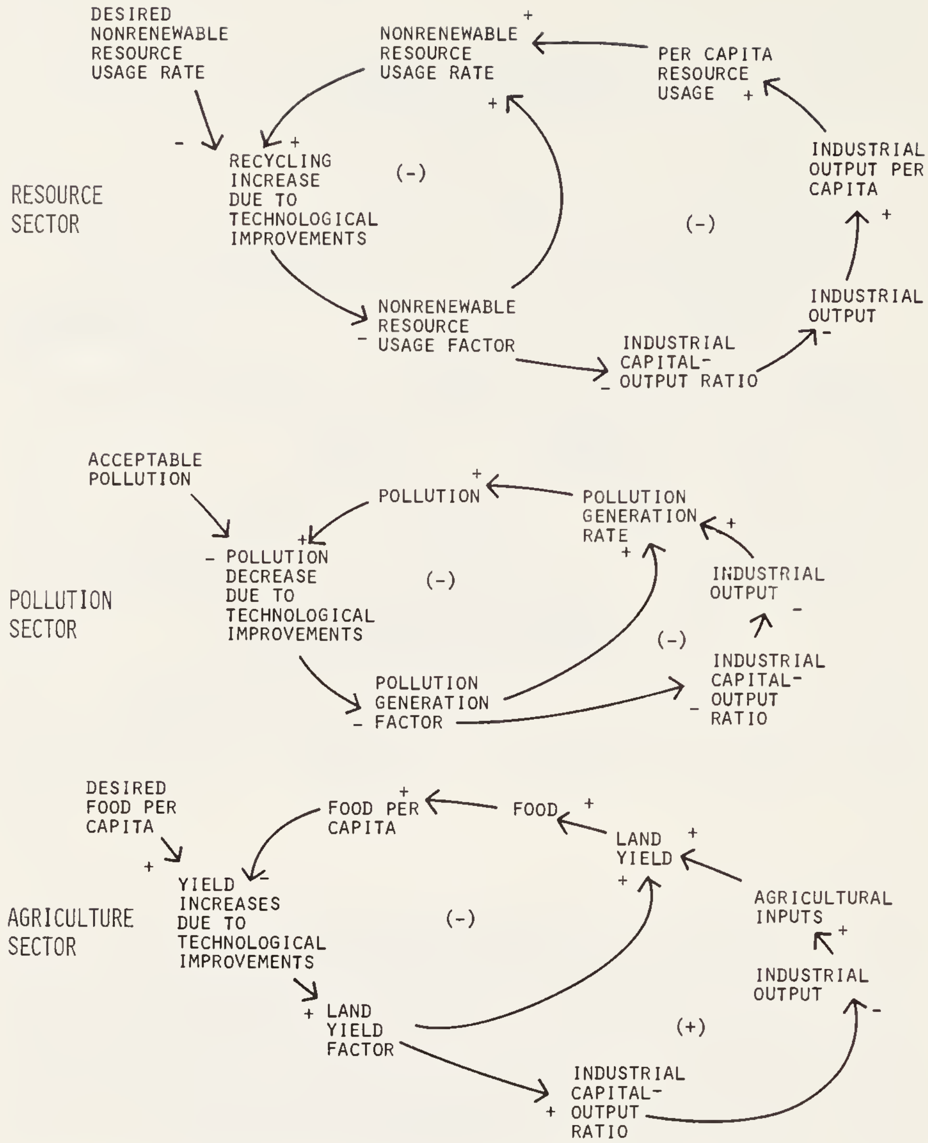


Figure 7-28 Structural additions for adaptive technological policies with development and implementation costs

implementation of the new technologies involved in reducing resource usage, reducing pollution, or increasing land yields all require additional capital; thus more capital is required to produce each unit of industrial output. The additional capital required might be termed ''protective'' capital, for it serves the purpose of offsetting the negative effects of increased industrial production. It should be noted that a more thorough treatment of these costs should detail each factor of production (such as capital, resources, energy, or land) that must be diverted from the other sectors of the model and into the development and implementation of these new technologies.

Figure 7-29 shows the assumed relationships between the effectiveness of the technologies developed and the costs of those technologies. When the nonrenewable resource usage factor NRUF equals 1.0, no new resource recycling technologies are developed, so the industrial capital-output ratio ICOR remains at its normal value of 3.0. As recycling technologies are developed, the nonrenewable resource usage factor

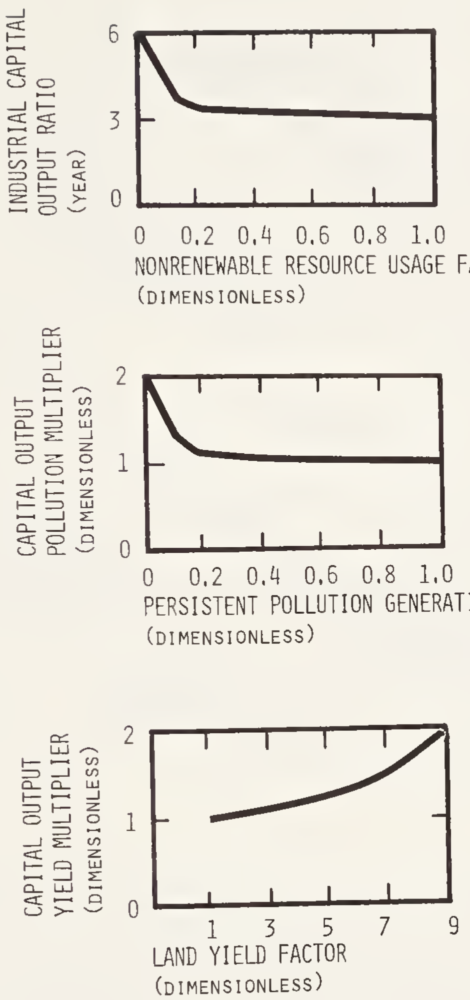


Figure 7-29 Assumed costs of technological development and implementation for adaptive technological policies

NRUF is reduced, and the cost is reflected as a rise in the industrial capital-output ratio ICOR. Similarly, in the pollution sector, the industrial capital-output ratio rises as a result of a decrease in the persistent pollution generation factor PPGF, or level of pollution per unit of industrial and agricultural output. In the agriculture sector, the industrial capital-output ratio rises as new technologies increase the land yield factor LYF. The assumed increases in costs are quite modest—for example, a 50 percent reduction in resource usage due to increased recycling technologies is assumed to require less than 3 percent of the total capital stock.

The assumption of increasing costs of technological development and implementation implies that there is a trade-off between continued growth in population and in industrial output and the control of resource depletion, pollution generation, and land yields. Run 7-21 shows the effects of this assumption on the behavior of the model. As in Run 7-20, technological advances in recycling, pollution generation control, and land yields allow population POP and industrial output per capita IOPC to grow for a longer time than in the reference run (Figure 7-7). As population POP and industrial out-

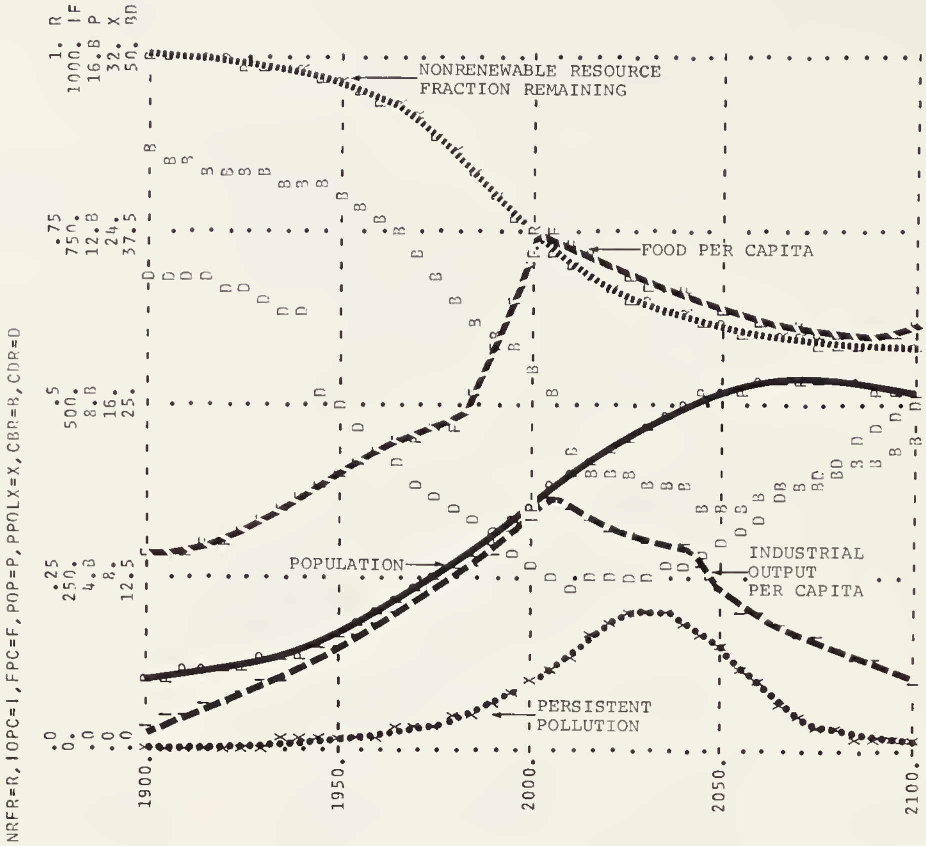


Figure 7-30 Run 7-22: adaptive technological policies—the effects of delays and costs of technological development and implementation

Advances in recycling, pollution control, and land yield technologies are again assumed to be obtainable only at a finite cost. In addition, it is assumed that the benefits of these technologies will not be realized until 10 years after their initiation. As in Run 7-21, the rising costs, modeled as a rise in the industrial capital-output ratio ICOR, cause industrial output per capita IOPC to decline. The added costs incurred by the continued implementation of new technologies even after IOPC has peaked force IOPC to fall more precipitously than in Run 7-21.

put per capita IOPC continue to grow, however, the technological improvements necessary to offset the side effects of this growth must also increase. The increasing technological developments demand more and more protective capital, which raises the capital-output ratio. As the capital-output ratio rises, industrial output per capita IOPC decreases after the year 2010. Food per capita FPC stabilizes near the desired level of 700 vegetable-equivalent kilograms per person-year in the year 2020. Resource usage and the level of pollution both decrease to their desired levels after the year 2000. Population POP stabilizes at 8 billion people in the year 2050, although both birth and death rates CBR and CDR are rising because of the decline in industrial output per capita IOPC.

Run 7-21 shows a behavior quite different from that of Run 7-19 (Figure 7-24), where the development and implementation of new technologies were achieved at no additional costs. In Run 7-21, continued growth in population POP and industrial

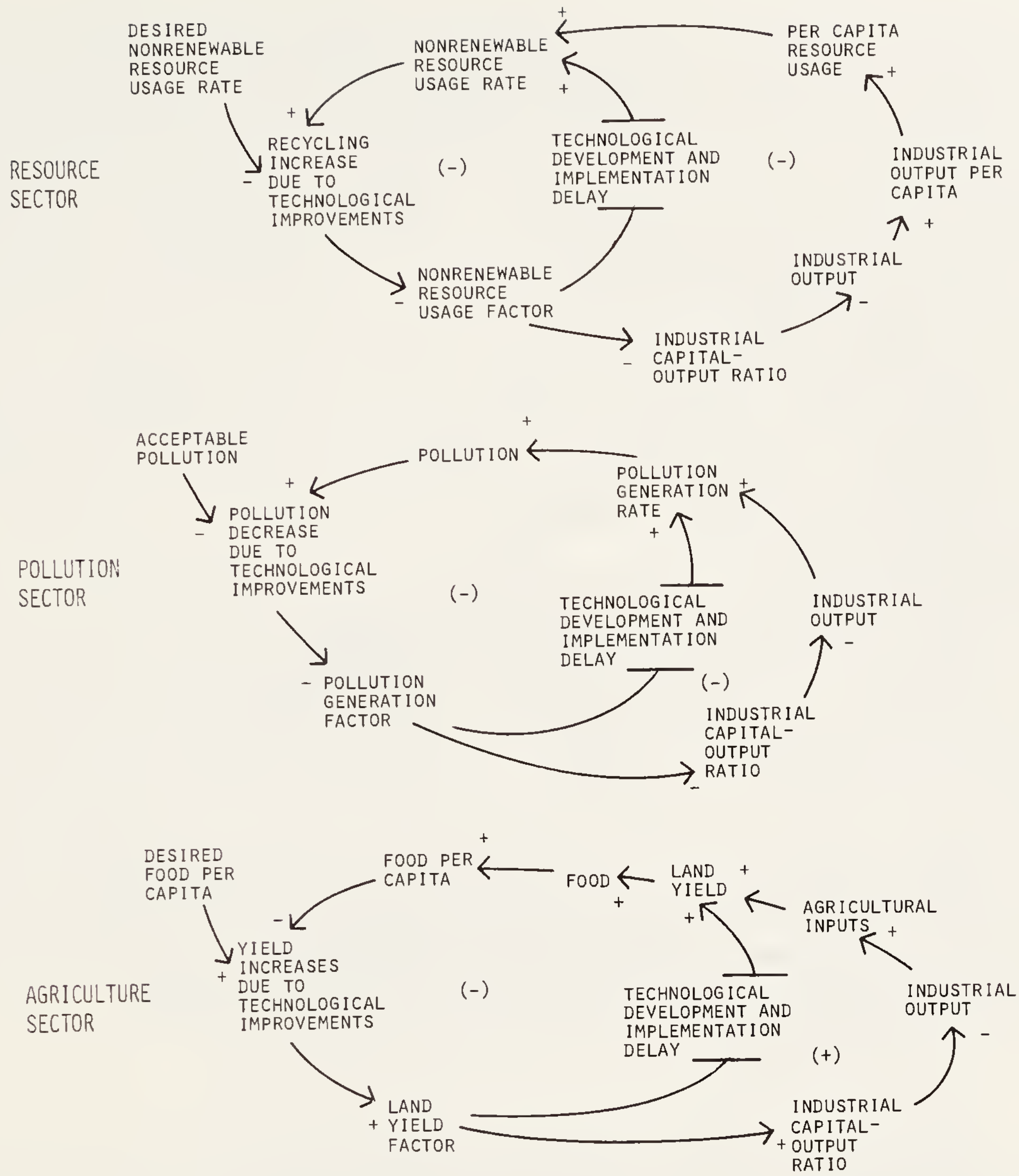


Figure 7-31 Structural additions for adaptive technological policies with delays and costs of technological development and implementation

output per capita IOPC cannot be continuously supported by advances in technology, for these advances become more costly as their magnitude increases. Eventually, this rise in costs causes industrial output per capita IOPC to decrease.

Adaptive Technological Policies—The Effects of Delays and Costs of Technological Development and Implementation Run 7-22 (Figure 7-30) shows the behavior of the model if technological advances are obtained at some cost and only after a 10-year development and implementation delay. Figure 7-31 shows the structural additions assumed in this run. Increases in technology raise the industrial capital-output ratio as in the previous run, but they affect resource usage, pollution generation, and land yields only after a 10-year delay. Run 7-22 shows the effects of these development and implementation delays on the model's behavior.

The delays between the initial decision to develop new technologies and their final implementation cause technological improvements to continue to increase even after industrial output begins to decrease, making the decline in industrial output per capita IOPC more severe than in Run 7-21. However, the additional technological developments in resource recycling lead to a higher nonrenewable resource fraction remaining NRFR in the year 2100 in Run 7-22 than in Run 7-21. Although the insertion of a 10-year technological delay makes the behavior of food per capita FPC unstable, food per capita FPC is higher in Run 7-22 over the long run because of higher land yields. The index of persistent pollution PPOLX declines to a lower value in Run 7-22 than in Run 7-21. Like the other delays in the model, delays in technological development and implementation increase the tendency of the system toward an unstable behavior mode of overshoot and decline. Because of these delays, the decline in industrial output per capita IOPC in Run 7-22 is more precipitous than that observed in Run 7-21.

Both runs show that the adaptive technological policies are successful in achieving their goals: nonrenewable resource usage, pollution generation, and food per capita are all kept near their desired levels through the development of new technologies. However, the assumed value system of the modeled society causes it to maintain its standards for food, pollution, and resource use even at the sacrifice of some industrial output. Eventually, the costs of developing and implementing the new technologies required to maintain these standards force industrial output per capita to decline. The next run tests the behavior of the model under the assumption that a decline in industrial output per capita is too high a price for society to pay for the implementation of new technologies. Technological policies will be initiated only if they do not interfere with the growth in industrial output per capita.

Adaptive Technological Policies—The Effects of Delays and Costs, with a Bias for Continued Growth in Industrial Output per Capita IOPC The previous run assumed that advances in recycling, pollution control, and land yield technologies can be obtained with increasing capital costs, and only after a 10-year technological development and implementation delay. Run 7-23 (Figure 7-32) shows the behavior of the model if these assumptions are augmented with an assumption of a bias toward continued growth in industrial output per capita IOPC. This additional assumption implies that new policies of technological development will be initiated only as long as they do not hamper the growth in industrial output per capita IOPC, as perceived by a year-to-year growth index.

Figure 7-33 shows the structural additions assumed for this run. As in the previous run, improvements in technology decrease nonrenewable resource usage, decrease pollution, and increase land yields after a delay. These technological improvements also raise the industrial capital-output ratio, which tends to decrease industrial output per capita IOPC. In this run, however, if the growth rate of IOPC

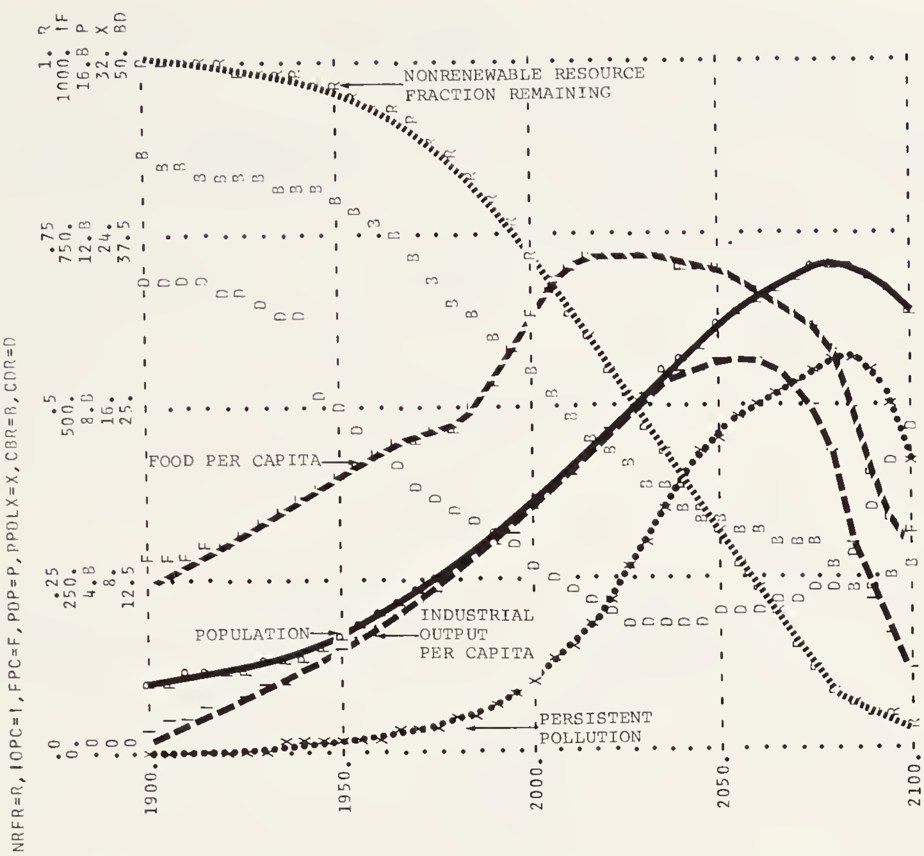


Figure 7-32 Run 7-23: adaptive technological policies—the effects of delays and costs, with a bias for continued growth in industrial output per capita

The previous run assumed that new recycling, pollution control, and land yield technologies are developed in response to a perceived need for them. Because of the time involved in technological development and implementation, however, these new technologies were effective only after a delay. Moreover, their development and implementation required additional capital, which increased the industrial capital-output ratio. In this run, the assumptions of Run 7-22 are augmented with a societal bias toward continued growth in industrial output per capita IOPC. Technological policies are implemented only as long as they do not hamper continued growth in IOPC. This policy is effective in continuing growth in the short run but counterproductive in the long run: the failure to implement the new technologies causes a significant depletion of resources and growth is ultimately terminated.

decreases, the initiation of new technologies is also decreased. If the growth in IOPC declines to zero, no new technological improvements are initiated.

Run 7-23 shows that the adaptive technological policies are successful in keeping resource usage, pollution, and food per capita near their desired levels until the year 2000, when they begin to interfere with the growth in industrial output per capita IOPC. To maintain continued growth in industrial output per capita, fewer new technologies are initiated after the year 2000, for society is not willing to pay their costs in terms of an increase in the capital-output ratio. The decrease in new land yield technologies causes the growth in food per capita to stop shortly after the year 2000. The index of persistent pollution PPOLX remains higher in Run 7-23 than in

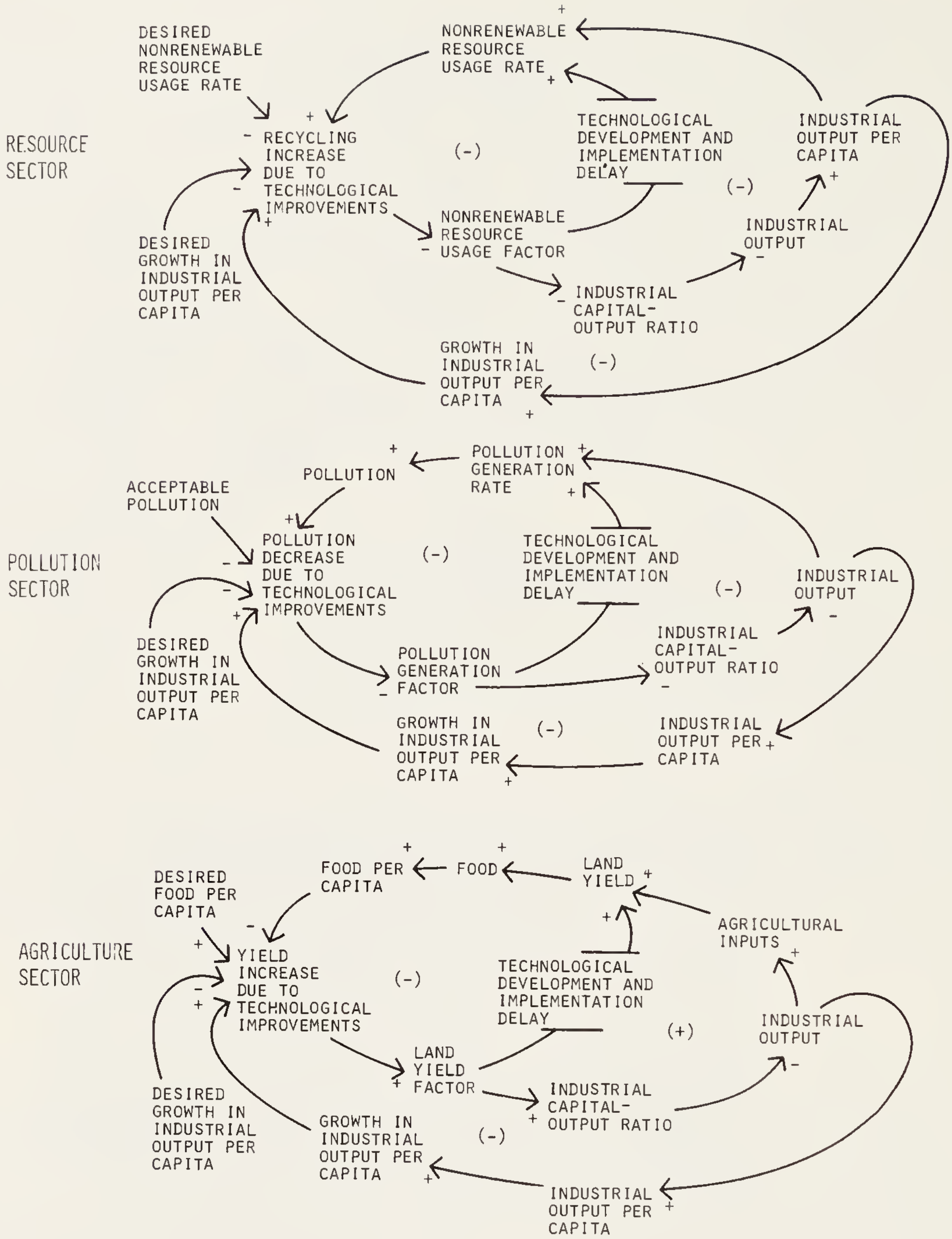


Figure 7-33 Structural additions for adaptive technological policies with a bias toward growth in industrial output per capita

Run 7-22 after the year 2000. Because few new resource recycling technologies are implemented after the year 2000 in Run 7-23, resource usage begins to grow with the rising population POP and industrial output per capita IOPC. As the nonrenewable resource fraction remaining NRFR declines below 0.2 in the year 2070, the fraction of capital that must be allocated to obtaining resources FCAOR rises sharply. Since more capital must be allocated to obtaining resources, industrial output per capita IOPC declines after the year 2070.

When the technological advances necessary to offset the negative effects of growth involve substantial costs, one might expect a reluctance to incur those costs, especially if the costs of the protective technologies interfere with industrial growth. Run 7-23 shows that, if the goal of the policy maker is continued growth, a policy of sacrificing the development of protective technologies in favor of continued growth is successful only in the short run. Industrial output per capita IOPC grows 50 more years in Run 7-23 than in Run 7-22, where protective technologies were continually developed despite their costs. In the long run, however, the choice not to develop these protective technologies in favor of continued growth leads to overshoot and decline as a result of the negative effects of growth. The overall behavior of Run 7-23 is similar to that of reference run (Figure 7-7). Rising resource costs due to resource depletion cause industrial output per capita IOPC to decline in 2070, which eventually limits the growth in population POP after the year 2090.

The technological policies represented here have all been directed at two of the four basic dynamic properties of the world system. Their goal was to raise the physical limits to growth and reduce the mechanisms that might erode those limits (such as pollution or resource depletion). If one is willing to assume that technologies can be developed to accomplish those goals with no delays and no physical costs anywhere in the system, then technological policies are an acceptable way to overcome the instability represented in the overshoot behavior mode (see, for example, Run 7-18 or Run 7-19). If one believes that improved technologies can be achieved only with real physical costs and implementation delays, then the overshoot mode of behavior still prevails (Runs 7-21, 7-22, and 7-23). Physical growth has not been checked, system delays still exist (and in fact new ones have been introduced), and physical limits to growth remain. However, a new dimension was added to these physical limits. In the last three technological runs growth may be stopped either by the natural physical limits included in the model or by devoting so much output to avoiding those limits that intolerable costs are incurred in the economic sector. In either case, the delays in the system and the positive forces favoring physical growth bring about the overshoot of sustainable physical levels of output and subsequent decline.

7.6 SOCIAL POLICIES

In the preceding section we presented the effects of policies that would require major new technological changes before they could be implemented. In this section we test a number of policies that would require major changes in the social value structure of the world system. The majority of the technological policies were directed at relieving the negative pressures that limit growth, but these social policies are aimed primarily at reducing the positive pressures that promote continued growth. For these policies, basic value changes would presumably have to be supplemented by technological changes, but we believe the initiation of these "social policies" comes from significant changes in social value structures. The following runs test the effects of value changes on the model's behavior as shown in the reference run (Figure 7-7).

Reduction of the Desired Completed Family Size DCFS One of the more commonly recommended social policy changes designed to decrease the pressures of population growth is a reduction in the average family size to 2 children. As discussed in Chapter 2, the model's desired completed family size DCFS is a nonlinear function of income expectations and social norms. Run 7-24 (Figure 7-34) shows the behavior of the model if this assumed dependency is interrupted and the desired completed family size is reduced to 2 children in 1975, regardless of economic changes. This policy still assumes that parents will compensate for high perceived mortality by bearing more than 2 children, if necessary, but that their ultimate goal is 2 surviving children. As a result of this policy, population POP gradually reaches a level of about 5 billion people in the year 2040. Population responds slowly to a change in desired completed family size because of the delays inherent in its age structure and in adjustments to perceived lower mortality.

A comparison of Run 7-24 with the reference run (Figure 7-7) illustrates the effective trade-off between population POP and both industrial output per capita IOPC and food per capita FPC. In Run 7-24, both IOPC and FPC grow to a higher level than in the reference run because the population POP grows more slowly. In both runs, however, growth is eventually halted by rising resource costs.

In the absence of any additional technological policies, Run 7-24 shows that even the lower population POP of 5 billion cannot be sustained past the year 2040 in the model because of the long-term effects of the decline in nonrenewable resources. We conclude that this population policy in itself does not appear to be sufficient to create the conditions for a sustainable level of population, for it is thwarted by continued material growth. However, it does relieve some of the pressures causing resource depletion, higher food needs, and greater amounts of pollution. The reduction of the desired completed family size can thus be a powerful influence on the model's behavior when combined with other social and technological policies, as will be demonstrated later in this chapter.

Increase of Industrial and Service Capital Lifetimes ALIC *and* ALSC Another possible policy for reducing the positive pressures of growth is to increase the average lifetime of the capital plant in the economy, thereby decreasing the depreciation rate of capital and the discarding of used resources. We classify this as a social change primarily because an extension of capital lifetimes will require a new social emphasis on durability rather than newness, more attention to repair, or higher quality standards for capital to stimulate the necessary technological changes. In Run 7-25 (Figure 7-35) we increased the average life of industrial capital ALIC to 21 years and the average life of service capital ALSC to 30 years, both representing a 50 percent increase. Run 7-25 indicates that this policy alone is counterproductive to the goal of reducing positive growth pressures. The extension of the productive lifetimes of capital reduces the rate of capital depreciation in the model. Since capital investment rates are not changed, the capital stock and thus output grow more rapidly and resources are depleted more quickly than in the reference run (Figure 7-7). The rapid depletion of resources leads to an earlier decline of industrial output per capita IOPC in Run 7-25 than in the reference run.

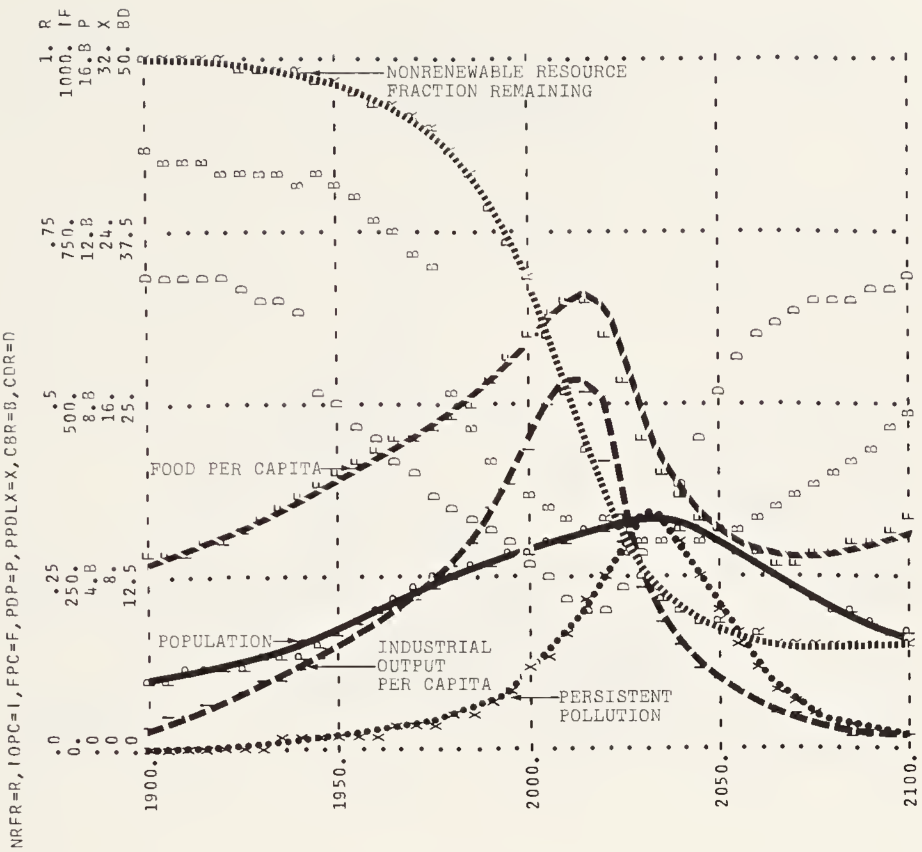


Figure 7-34 Run 7-24: reduction of the desired completed family size

To reduce the pressures of population growth in the reference run, the desired completed family size is reduced to 2 children per family in 1975. Population POP continues to grow gradually for 70 years because of the delays inherent in the age structure. However, the effects of resource depletion again force the population to decline after 2040, as in the reference run. Since population growth is reduced, industrial output per capita IOPC and food per capita FPC rise more rapidly between 1975 and 2020 than in the reference run.

In the world model the process of producing industrial output is primarily responsible for the depletion of nonrenewable resources and the generation of persistent pollutants. The extension of product lifetimes is therefore counterproductive if the uses of output remain the same, for reducing the depreciation of industrial capital without reducing capital investment leads to higher industrial capital growth rates and faster resource depletion. The next run illustrates the behavior of the model if the investment in industrial capital is reduced by a higher preference for food and service outputs.

Shift in the Choice of Output Forms The development patterns described in Chapter 3 are based on the historical choices made by societies among agricultural, service, and industrial goods as their economies developed. It is conceivable, however, that a shift in this choice among output forms might occur through a major change in social values. For example, less emphasis might be placed on industrial output and more emphasis placed on food and service output. Run 7-26 (Figure 7-36)

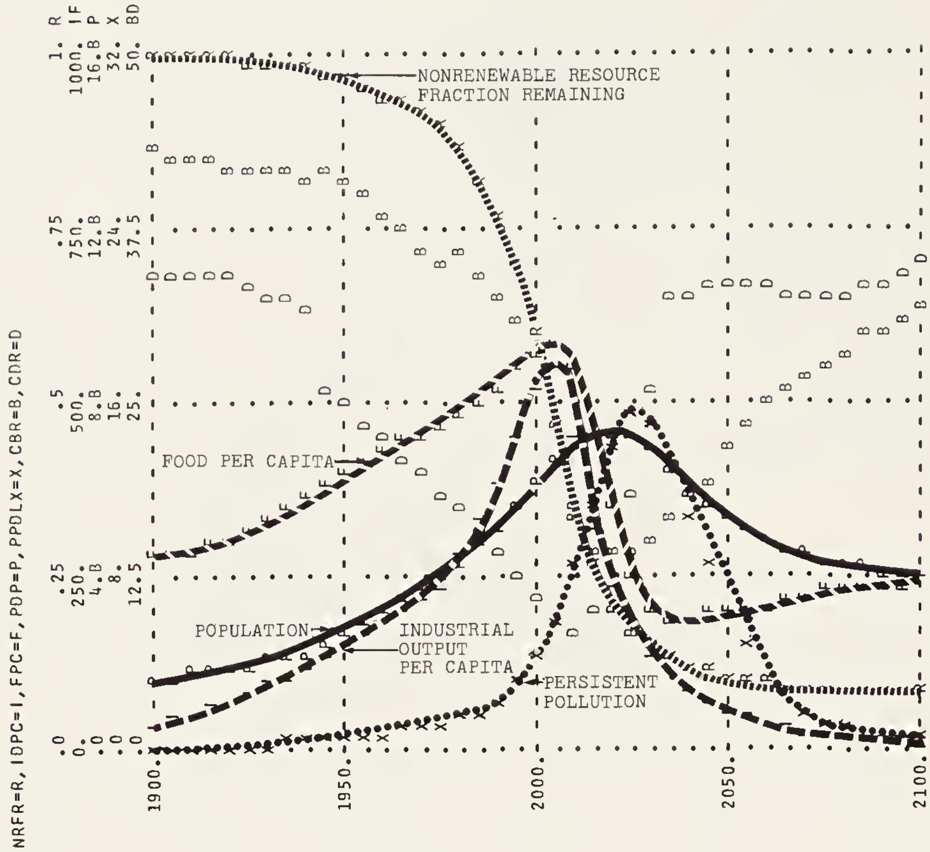


Figure 7-35 Run 7-25: increase of industrial and service capital lifetimes

Both the average lifetime of industrial capital ALIC and the lifetime of service capital ALSC are increased 50 percent in 1975, thereby extending the productivity of capital. When implemented without additional policies to reduce the capital investment rate, this policy proves to be counter-productive in the long run. Compared with the reference run, the extension of product lifetimes allows industrial output to grow more rapidly, leading to a quicker depletion of resources. The rise in resource costs forces industrial output per capita IOPC to decline earlier than in the reference run.

illustrates the effects of a 50 percent increase in both the amount of services and the amount of food desired by the population at each stage in industrial development. After 1975 the heavy emphasis on food and services causes industrial output per capita IOPC to stabilize near a level of 250 dollars per person-year (however, the size of the industrial capital stock is still rising at the same rate as the population). Any excess industrial output is allocated to increasing service capital or food production rather than to increasing the output of manufactured goods.

This value change alone is ineffective in avoiding a decline in food per capita FPC, population POP, and industrial output per capita IOPC. In the short run, the stabilization of IOPC reduces agricultural investments and thus land yields, forcing food per capita FPC to level off at 500 vegetable-equivalent kilograms per person-year in 1980 and to decline after 2020. In the long run, continued growth in population POP increases resource usage, which causes the fraction of capital allocated to obtaining resources FCAOR to rise after the year 2040. This rise again forces IOPC to decline after

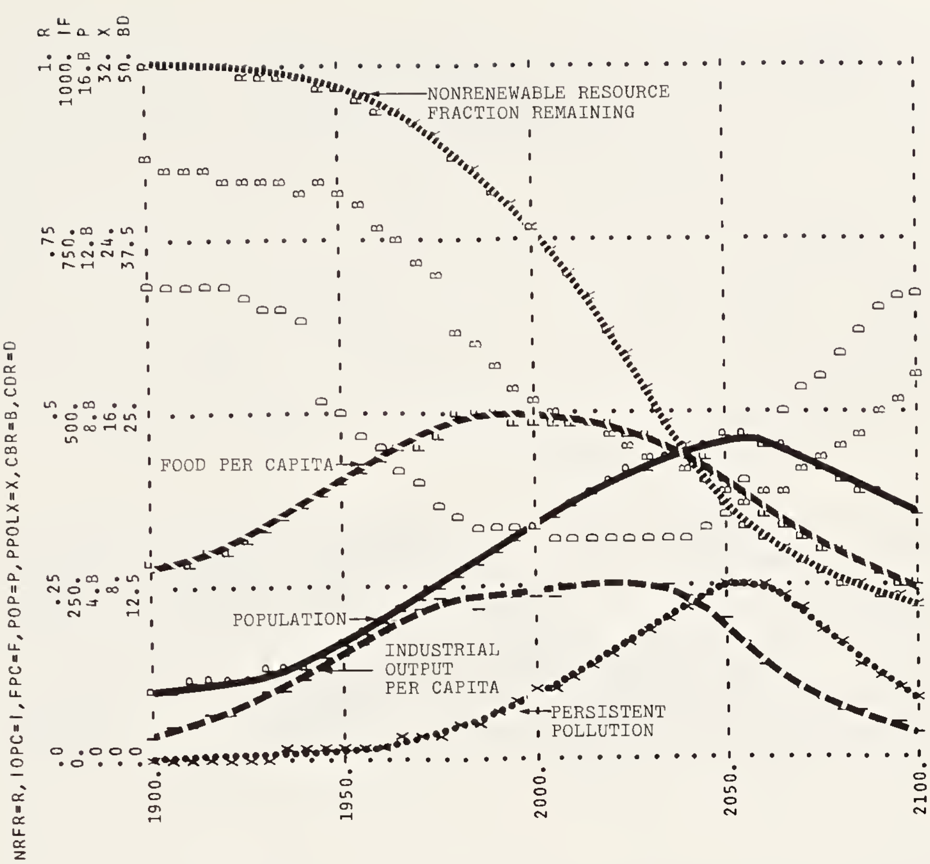


Figure 7-36 Run 7-26: shift in the choice of output forms

The amount of food and services desired by the population per unit of industrial output is increased by 50 percent in 1975. This shift in the choice of output slows the growth in industrial capital and industrial output, putting less pressure on the resource base. In the long run, however, the continually rising population POP thwarts the effectiveness of this policy, forcing a decline in industrial output per capita IOPC due to resource depletion.

the year 2040. The effectiveness of the shift in the choice of outputs seems to be thwarted in the long run by the continually rising population POP. The next run shows the behavior of the model if both POP and IOPC are stabilized by changes in social values.

Population Policy and Shift of Output Choices Run 7-27 (Figure 7-37) tests the effects of social value changes that tend to reduce the growth in both population and industrial capital, the two major contributors to growth in World3. Population POP stabilizes at 5 billion in 2050 after the desired completed family size is set equal to 2 children in 1975. The growth in industrial capital and thus in industrial output per capita IOPC is reduced by a value shift that increases by 50 percent (as in the previous run) the amount of food and services desired by the population at each stage of industrial development.

In this run the overshoot and decline mode of behavior is still evident, but it is

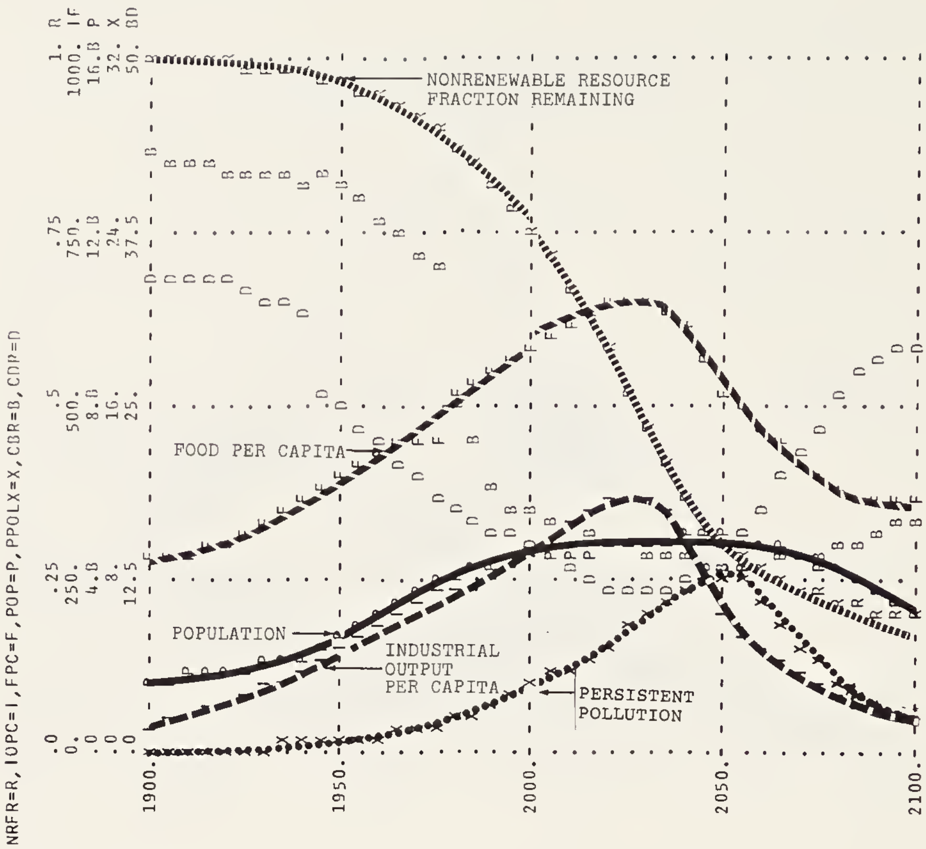


Figure 7-37 Run 7-27: population policy and shift of output choices

A combination of social policies that cause a reduction of growth both in population and in industrial capital is simulated in this run. In 1975 the desired completed family size is reduced to 2 children per family and the amount of services and food per unit of industrial output desired by the population is increased by 50 percent. The resulting behavior is substantially more stable than in the reference run, but the overshoot and decline mode is still evident. In World3, even these reduced levels of population and industrial capital cannot be sustained over the long term; new technological policies must be added to offset the effects of the limits to growth.

less severe than that shown in the reference run (Figure 7-7). The social value changes implemented in Run 7-27 cause population POP and industrial output per capita IOPC to grow at much slower rates than in the reference run. However, Run 7-27 shows that, without additional technological policies, even these lower rates of population and industrial output growth are not sustainable within the time horizon of the model. The lower POP and IOPC still generate a high enough rate of resource usage to deplete nonrenewable resources to the point where resource costs begin to rise. After the year 2030, industrial output and thus IOPC begin to fall. The decreasing industrial output causes shortages in other sectors of the model, and the temporarily stable state degenerates.

This section has examined the effectiveness of several social policies designed to avoid the basic overshoot and decline behavior mode. They reduce the positive pressures toward growth of population and industrial capital in the world system. Although these social changes do tend to improve the stability of the system, it appears that social value changes alone are not sufficient to avoid the unstable behavior mode of the system, just as technological changes alone were insufficient. To stabilize and sustain the model's population and industrial output, the social value changes that reduce the rates of growth of population and industrial output must be augmented by technological policies. The next series of runs examines the behavior of the system when technological and social policies are combined.

7.7 TECHNOLOGICAL AND SOCIAL POLICIES: EQUILIBRIUM

In the preceding sections we have concluded that, of the three possible behavior modes of World3, overshoot and decline seems to be dominant. Under the assumption of a finite world, continued exponential growth is not a realistic option. The third possible alternative, a smooth transition to a state where population and material capital are stabilized and in equilibrium, appears to be the most desirable behavior. What policies or combinations of policies are most likely to move the system toward an orderly transition to equilibrium?

It has been shown in the previous runs that neither technological nor social policy changes *alone* are sufficient to avoid the dominant behavior mode of overshoot and decline. It is the purpose of this section to examine combinations of technological and social value changes that might bring about a smooth transition to a sustainable state of equilibrium. These combinations act to reduce the strength of both the positive feedback loops causing growth of population and industrial output and the negative feedback loops arising from resource depletion, food shortages, and the generation of toxic persistent pollutants. The first run attempts to achieve this behavior by implementing discrete policy changes in 1975; the final runs test the possibilities for arriving at equilibrium by a combination of adaptive technological and social policy changes.

Equilibrium through Discrete Policy Changes Run 7-28 (Figure 7-38) shows one example of an equilibrium state achieved by the following combination of discrete technological and social value changes:

1. Population POP is stabilized by assuming that the desired completed family size is reduced to 2 children in 1975.
2. Growth in industrial capital is controlled in 1990 by reinvesting only enough industrial output in industrial capital to ensure the stabilization of industrial output per capita at a desired level of 350 dollars per person-year.
3. To avoid a nonrenewable resource shortage, resource recycling is increased in 1975 so that the per capita resource usage is reduced to one-eighth of its 1970 value.

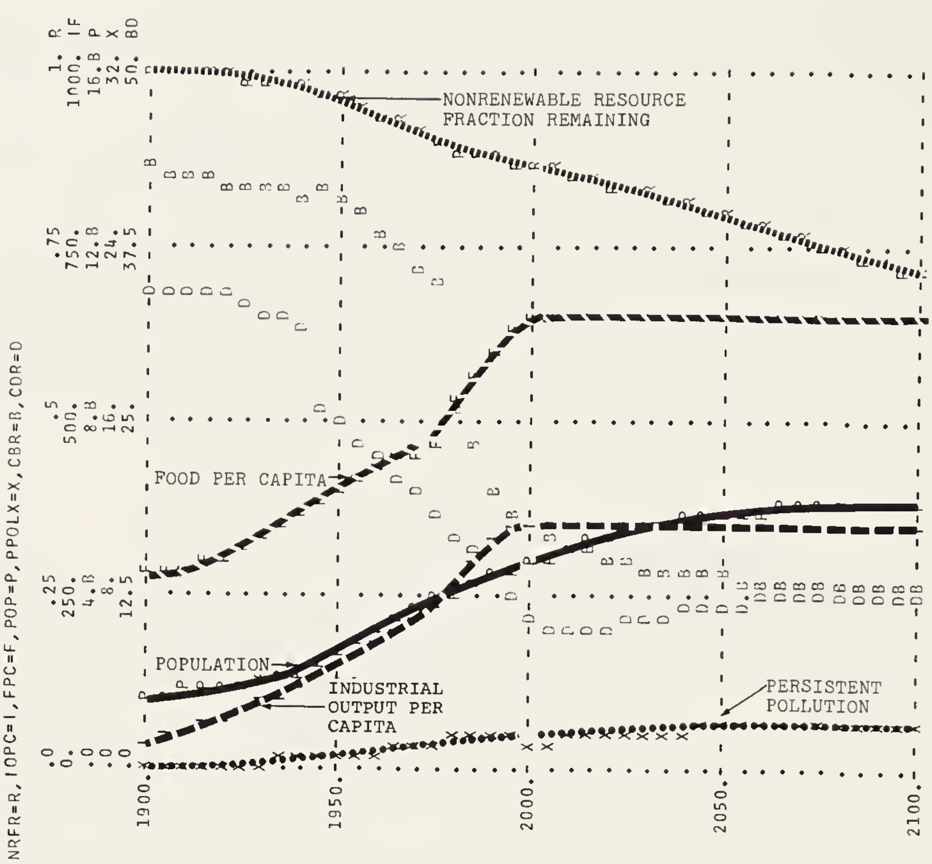


Figure 7-38 Run 7-28: equilibrium through discrete policy changes

To obtain one example of a sustainable state of equilibrium, this run combines discrete policy changes in both technology and social values. To stabilize the population POP, the desired completed family size is reduced to 2 children per family in 1975. The growth in industrial capital is reduced in 1990 by reinvesting only enough industrial output to keep industrial output per capita IOPC at a constant level. In addition, new recycling and pollution control technologies are developed, capital lifetimes are increased, and social choices of output forms are shifted toward a preference for food and services. Population POP stabilizes in 2050 at 5 billion people, industrial output per capita IOPC levels off in 1990 at 350 dollars per person-year, and food per capita FPC stabilizes by the year 2000 at three times the subsistence level. The index of persistent pollution PPOLX is kept at very low levels, and the rate of resource depletion is slow enough to permit technology and industrial processes to adjust to changes in the availability of resources.

4. The preferences of society for the mix of output of the economic system are shifted toward food and services in 1975. This policy is accomplished by increasing the indicated food output per capita and indicated service output per capita tables IFPC2T and ISOPC2T by 50 percent.
5. In 1975, pollution generation per unit of industrial and agricultural output is reduced to one-fourth of its 1970 value.
6. To minimize the amount of industrial throughput necessary to sustain the capital stock, the average lifetime of industrial capital ALIC and the average lifetime of service capital ALSC are increased by 50 percent in 1975.

This combination of technological and social policies enables the model system to move into a sustainable stable state. The rate of growth of population declines gradually after 1975, and population POP slowly levels off at 5 billion people by the year 2050. Industrial output per capita IOPC levels off in 1990 at 350 dollars per person-year, which is 75 percent above its 1970 value. Food per capita FPC reaches a value over 50 percent higher than the 1970 world average. Advances in pollution control technologies allow the index of persistent pollution PPOLX to remain below its 1970 level even though industrial output per capita IOPC and population POP continue to grow beyond their 1970 levels. Advances in resource recycling technologies, combined with the slower rate of growth of population POP and industrial output per capita IOPC, greatly reduce the rate of usage of nonrenewable resources. Resources are still slowly depleted over time (as they must be according to the second law of thermodynamics), but the rate of depletion is slow enough to enable technology and industrial processes to adjust to changes in resource availability.

The exact set of policies tested here is just one of many possible combinations of technological and social policies that could lead to a stable equilibrium state. The individual policies suggested in this run represent only hypothetical examples of the general types of policies needed to reach such a state. Two types of policies are necessary: technological policies that reduce the limitations to growth, and social policies that reduce the pressures toward growth. The next run gives an example of a stable equilibrium reached through a combination of adaptive technological and social policies.

Equilibrium through Adaptive Policies Run 7-29 (Figure 7-39) illustrates the second example of a set of policies that could result in a stable long-term model behavior. In this case the stable state is reached through an adaptive process; policies are initiated in response to a perceived need for them, measured in the model by a discrepancy between a desired system state and the actual system state. Figure 7-40 illustrates the structural changes assumed for this run. The technological policies included in this run are the same as in Run 7-22: advances in resource recycling, pollution control, and land yield technologies are developed as resource usage, persistent pollutants, and food per capita deviate from their desired levels. Figure 7-40 shows that these advances are not immediately effective because of a 10-year delay in technological development and implementation. The new technologies are also not free; their development and implementation require additional capital, which in turn raises the industrial capital-output ratio. As in Run-22, additional resource exploration and development technologies, air pollution technologies, and land erosion control technologies are assumed to be implemented in 1975. These additional technologies are modeled as discrete policies only to simplify the presentation—they could be represented adaptively, as the other technological policies were.

In addition to the preceding technological policies, Run 7-29 includes social policies that tend to stabilize population POP and industrial output per capita IOPC near their 1975 levels. Population POP is stabilized by setting the desired completed family size to 2 children in 1975. Figure 7-40 shows the structural additions included

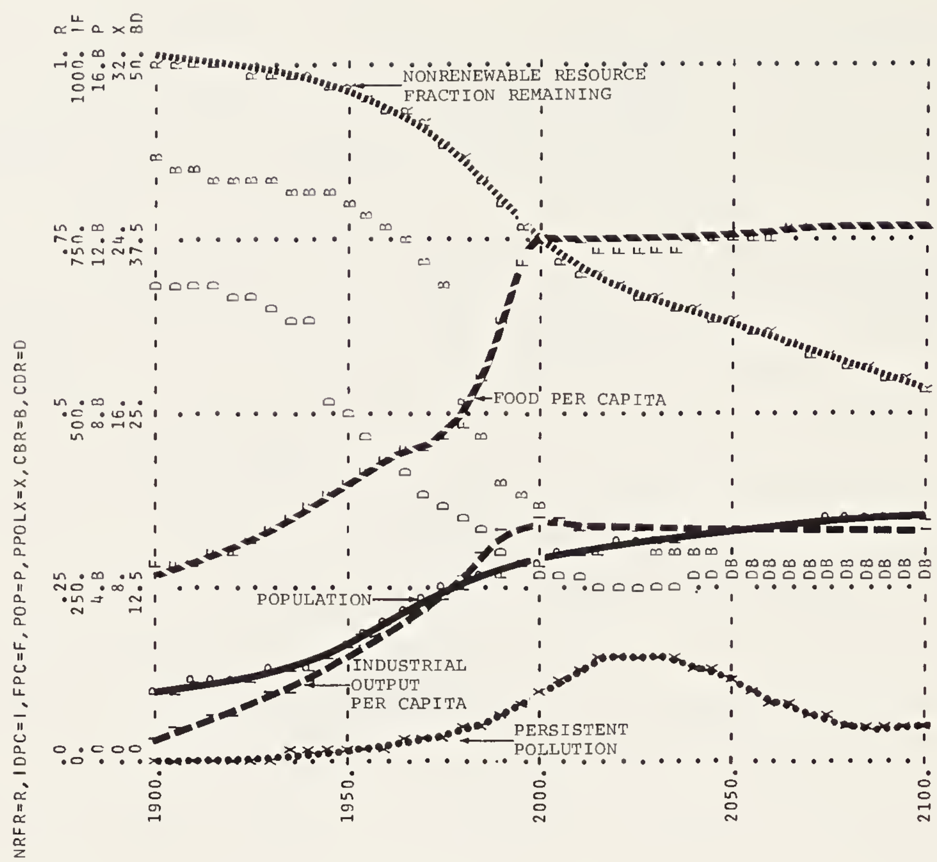


Figure 7-39 Run 7-29: equilibrium through adaptive policies

Adaptive technological policies that increase resource recycling, reduce persistent pollution generation, and increase land yields are combined with social policies that stabilize population POP and industrial output per capita IOPC. The technological advances in recycling, pollution control, and land yields are assumed to be effective only after a delay and to require capital for their development and implementation. As in the adaptive technological runs described in section 7.5, additional technologies are assumed to be implemented in 1975. These policies lower resource costs, decrease the effects of air pollution, and reduce land erosion. The resulting model behavior reaches equilibrium because the stable population and capital reduce the need for new technologies. Thus the newly implemented technologies are less costly, and the delays in their development and implementation are less critical to their effectiveness.

in Run 7-29 that stabilize industrial output per capita. When industrial output per capita deviates from the desired level, the consumption of industrial output is adjusted to offset the discrepancy, changing the amount of industrial output available for reinvestment as industrial capital. This change in the industrial capital investment rate changes the level of the capital stock, which directly affects the production of industrial output. Thus the amount of industrial output produced each year is adjusted to ensure that actual industrial output per capita is equilibrated to the desired industrial output per capita.

In Run 7-29 population POP stabilizes at 5 billion people in the year 2050, and industrial output per capita IOPC levels off at a value near 350 dollars per person-year in 1990. The stabilization of population and industrial capital reduces the pres-

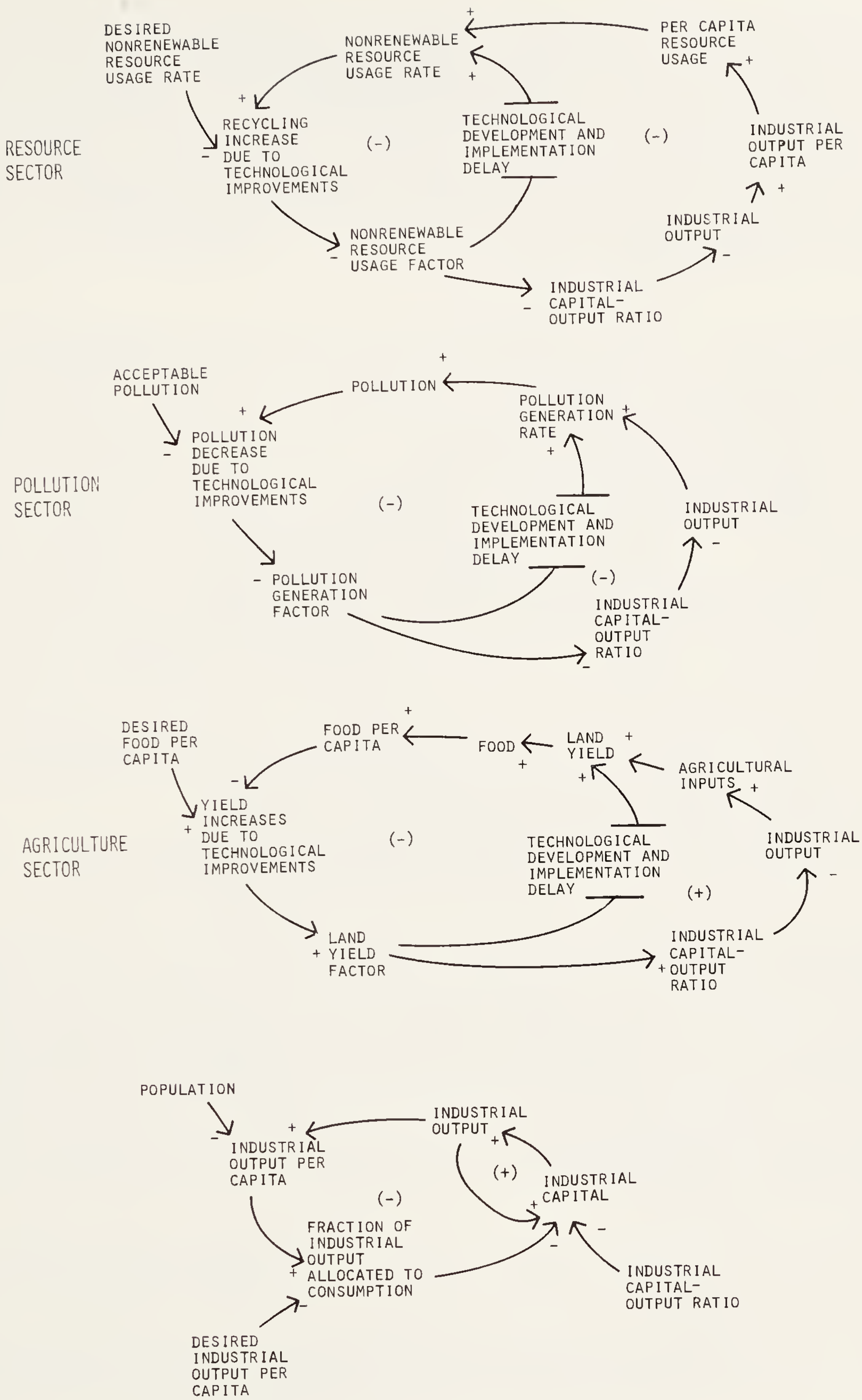


Figure 7-40 Structural additions to achieve equilibrium through adaptive technological and social policies

sure on the adaptive technological process, for technological advances of smaller magnitudes and costs are now able to keep resource usage, pollution, and food per capita at their desired levels. Since physical growth has been slowed, the delays in technological development and implementation are also less critical to their effectiveness. In Run 7-29 the stable behavior is maintained through the year 2100, whereas in earlier runs (7-22 and 7-23) the attempts to maintain growth by the continual application of technological policies caused the system to decline within the 200-year time horizon of the model.

Stabilization Policies Introduced in the Year 2000 Run 7-30 (Figure 7-41) shows the behavior of the model if the adaptive technological and social policies outlined in the previous run are not implemented until the year 2000. Postponing the implementation of these policies allows the growth of population POP and industrial output per capita IOPC to continue for an additional 25 years. In this period, population POP increases by another 2 billion people and industrial output per capita IOPC almost doubles. In the year 2000, social and technological policies are implemented in an attempt to stabilize population and industrial output per capita. Because of the higher population POP and industrial output per capita IOPC in that year, however, the magnitude of the technological advances required to reduce resource consumption, reduce pollution, and increase food per capita to their desired levels is considerably greater than in the previous run. Thus the capital costs of the new technologies must be considerably higher than those of the technologies developed 25 years earlier (Run 7-29). These higher costs cause industrial output per capita IOPC to decline after the year 2030.

Run 7-30 shows that, in the growing world system, the postponement of stabilization policies for a number of years may render the policies less and less effective. At any given time numerous equilibrium states are possible for the system, each having various combinations of population, capital, and food, service, or agricultural outputs. However, continued physical growth limits society's options for achieving a stable state. In addition, the policies necessary to reach an equilibrium state become more stringent and more costly. Runs 7-28 and 7-29 suggest that, because of the delays in the system, equilibrium cannot be attained immediately—even with rather optimistic assumptions about technological and social changes. Run 7-30 indicates that the sooner the approach to such a state is begun, the more favorable and sustainable the outcome will be.

The general conclusions reached from our analysis of the World3 model are summarized in Chapter 8. The runs described in this section demonstrate that a carefully planned combination of social and technological policies can circumvent the overshoot and decline mode of behavior and move the model system toward long-term equilibrium (Runs 7-28 and 7-29). The selected combinations of policies in those runs are successful because they act to offset the three system characteristics that cause overshoot and decline: (1) the stabilization of population and capital eliminates the continually increasing pressures on the global carrying capacity; (2) by anticipat-

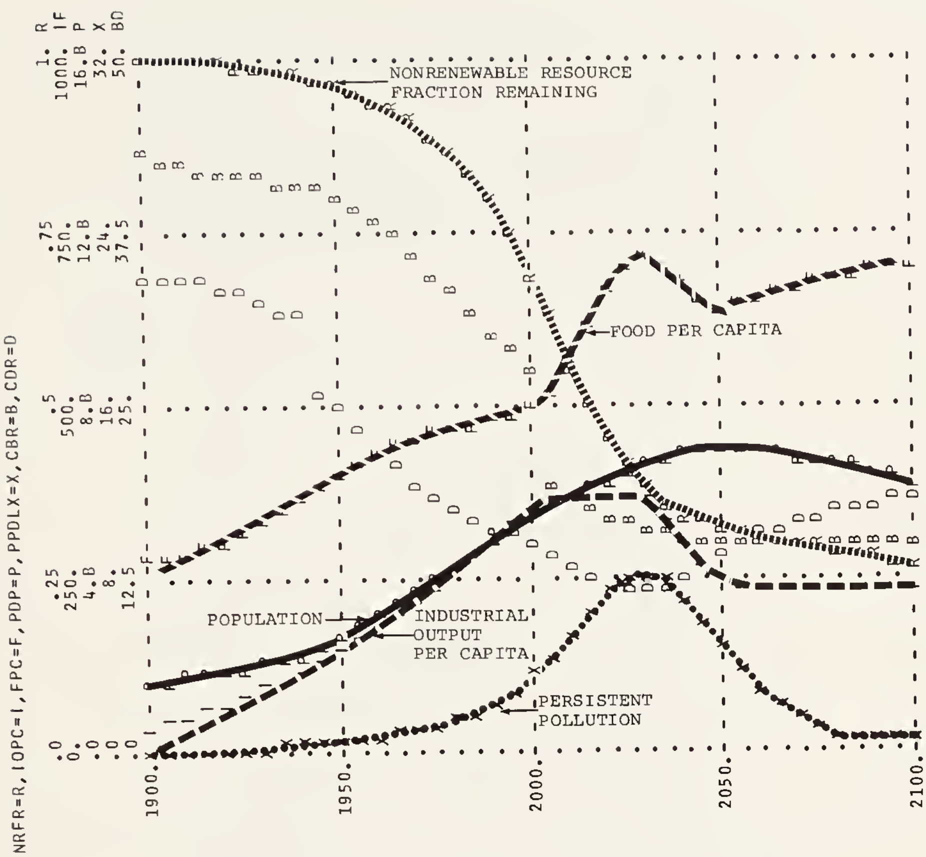


Figure 7-41 Run 7-30: stabilization policies introduced in the year 2000
The combination of adaptive technological and social policies of the previous run are not introduced until the year 2000. The continuation of growth for an additional 25 years further erodes the carrying capacity of World3; therefore, the policies that led to equilibrium 25 years earlier are no longer effective.

ing the signals that indicate the detrimental effects of continued growth, the stabilization of population and capital circumvents the delays in the feedback processes that control growth; and (3) even though growth is stabilized, new and improved technologies are needed to offset the continuing depletion of nonrenewable resources, pollution accumulation, land erosion, and land fertility degradation in the World3 model. Finally, Run 7-30 indicates that even a 25-year postponement of the combined social and technological policies of the two previous runs will severely reduce their effectiveness. In the finite world system modeled in World3, society will attain a more favorable and sustainable equilibrium state the sooner it begins to manage the transition to global equilibrium.

APPENDIX: PROGRAM LISTING OF WORLD MODEL EQUATIONS

```
*      WORLD3: THE DYNAMICS OF GROWTH IN A FINITE WORLD
NOTE   STANDARD MODEL
NOTE
NOTE   POPULATION SECTOR
```

```
        NOTE
 1      A       POP.K=P1.K+P2.K+P3.K+P4.K
 2      L       P1.K=P1.J+(DT)(B.JK-D1.JK-MAT1.JK)
        N       P1=P1I
        C       P1I=65E7
 3      R       D1.KL=P1.K*M1.K
 4      A       M1.K=TABHL(M1T,LE.K,20,80,10)
        T       M1T=.0567/.0366/.0243/.0155/.0082/.0023/.001
 5      R       MAT1.KL=(P1.K)(1-M1.K)/15
 6      L       P2.K=P2.J+(DT)(MAT1.JK-D2.JK-MAT2.JK)
        N       P2=P2I
        C       P2I=70E7
 7      R       D2.KL=P2.K*M2.K
 8      A       M2.K=TABHL(M2T,LE.K,20,80,10)
        T       M2T=.0266/.0171/.0110/.0065/.0040/.0016/.0008
 9      R       MAT2.KL=(P2.K)(1-M2.K)/30
10      L       P3.K=P3.J+(DT)(MAT2.JK-D3.JK-MAT3.JK)
        N       P3=P3I
        C       P3I=19E7
11      R       D3.KL=P3.K*M3.K
12      A       M3.K=TABHL(M3T,LE.K,20,80,10)
        T       M3T=.0562/.0373/.0252/.0171/.0118/.0083/.006
13      R       MAT3.KL=(P3.K)(1-M3.K)/20
14      L       P4.K=P4.J+(DT)(MAT3.JK-D4.JK)
        N       P4=P4I
        C       P4I=6E7
15      R       D4.KL=P4.K*M4.K
16      A       M4.K=TABHL(M4T,LE.K,20,80,10)
        T       M4T=.13/.11/.09/.07/.06/.05/.04
        NOTE
        NOTE    DEATH RATE SUBSECTOR
        NOTE
17      A       D.K=D1.JK+D2.JK+D3.JK+D4.JK
18      S       CDR.K=1000*D.K/POP.K
19      A       LE.K=LEN*LMF.K*LMHS.K*LMP.K*LMC.K
        C       LEN=28
20      A       LMF.K=TABHL(LMFT,FPC.K/SFPC,0,5,1)
        T       LMFT=0/1/1.2/1.3/1.35/1.4
21      A       HSAPC.K=TABHL(HSAPCT,SOPC.K,0,2000,250)
        T       HSAPCT=0/20/50/95/140/175/200/220/230
22      A       EHSPC.K=SMOOTH(HSAPC.K,HSID)
        C       HSID=20
23      A       LMHS.K=CLIP(LMHS2.K,LMHS1.K,TIME.K,1940)
24      A       LMHS1.K=TABHL(LMHS1T,EHSPC.K,0,100,20)
        T       LMHS1T=1/1.1/1.4/1.6/1.7/1.8
25      A       LMHS2.K=TABHL(LMHS2T,EHSPC.K,0,100,20)
        T       LMHS2T=1/1.4/1.6/1.8/1.95/2.0
26      A       FPU.K=TABHL(FPUT,POP.K,0,16E9,2E9)
        T       FPUT=0/.2/.4/.5/.58/.65/.72/.78/.80
27      A       CMI.K=TABHL(CMIT,IOPC.K,0,1600,200)
        T       CMIT=.5/.05/-.1/-.08/-.02/.05/.1/.15/.2
28      A       LMC.K=1-(CMI.K*FPU.K)
29      A       LMP.K=TABHL(LMPT,PPOLX.K,0,100,10)
        T       LMPT=1.0/.99/.97/.95/.90/.85/.75/.65/.55/.40/.20
        NOTE
        NOTE    BIRTH RATE SUBSECTOR
        NOTE
30      R       B.KL=CLIP(D.K,(TF.K*P2.K*0.5/RLT),TIME.K,PET)
        C       RLT=30
        C       PET=4000
31      S       CBR.K=1000*B.JK/POP.K
32      A       TF.K=MIN(MTF.K,(MTF.K*(1-FCE.K)+DTF.K*FCE.K))
33      A       MTF.K=MTFN*FM.K
        C       MTFN=12
34      A       FM.K=TABHL(FMT,LE.K,0,80,10)
        T       FMT=0/.2/.4/.6/.8/.9/1/1.05/1.1
35      A       DTF.K=DCFS.K*CMPLE.K
36      A       CMPLE.K=TABHL(CMPLET,PLE.K,0,80,10)
        T       CMPLET=3/2.1/1.6/1.4/1.3/1.2/1.1/1.05/1
37      A       PLE.K=DLINF3(LE.K,LPD)
        C       LPD=20
38      A       DCFS.K=CLIP(2.0,DCFSN*FRSN.K*SFSN.K,TIME.K,ZPGT)
        C       ZPGT=4000
        C       DCFSN=4
39      A       SFSN.K=TABHL(SFSNT,DIOPC.K,0,800,200)
        T       SFSNT=1.25/1/.9/.8/.75
40      A       DIOPC.K=DLINF3(IOPC.K,SAD)
        C       SAD=20
41      A       FRSN.K=TABHL(FRSNT,FIE.K,-.2,.2,.1)
        T       FRSNT=.5/.6/.7/.85/1
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        N       FRSN=.82
42      A       FIE.K=(IOPC.K-AIOPC.K)/AIOPC.K
43      A       AIOPC.K=SMOOTH(IOPC.K,IEAT)
        C       IEAT=3
44      A       NFC.K=(MTF.K/DTF.K)-1
45      A       FCE.K=CLIP(1.0,(TABHL(FCET,FCFPC.K,0,3,.5)),TIME.K,FCEST)
        C       FCEST=4000
        T       FCET=.75/.85/.9/.95/.98/.99/1
46      A       FCFPC.K=DLINF3(FCAPC.K,HSID)
47      A       FCAPC.K=FSAFC.K*SOPC.K
48      A       FSAFC.K=TABHL(FSAFCT,NFC.K,0,10,2)
        T       FSAFCT=0/.005/.015/.025/.03/.035
        NOTE
        NOTE    CAPITAL SECTOR
        NOTE
        NOTE    INDUSTRIAL SUBSECTOR
        NOTE
49      A       IOPC.K=IO.K/POP.K
50      A       IO.K=(IC.K)(1-FCAOR.K)(CUF.K)/ICOR.K
51      A       ICOR.K=CLIP(ICOR2,ICOR1,TIME.K,PYEAR)
        C       ICOR1=3
        C       ICOR2=3
52      L       IC.K=IC.J+(DT)(ICIR.JK-ICDR.JK)
        N       IC=ICI
        C       ICI=2.1E11
53      R       ICDR.KL=IC.K/ALIC.K
54      A       ALIC.K=CLIP(ALIC2,ALIC1,TIME.K,PYEAR)
        C       ALIC1=14
        C       ALIC2=14
55      R       ICIR.KL=(IO.K)(FIOAI.K)
56      A       FIOAI.K=(1-FIOAA.K-FIOAS.K-FIOAC.K)
57      A       FIOAC.K=CLIP(FIOACV.K,FIOACC.K,TIME.K,IET)
        C       IET=4000
58      A       FIOACC.K=CLIP(FIOAC2,FIOAC1,TIME.K,PYEAR)
        C       FIOAC1=.43
        C       FIOAC2=.43
59      A       FIOACV.K=TABHL(FIOACVT,IOPC.K/IOPCD,0,2,.2)
        T       FIOACVT=.3/.32/.34/.36/.38/.43/.73/.77/.81/.82/.83
        C       IOPCD=400
        NOTE
        NOTE    SERVICE SUBSECTOR
        NOTE
60      A       ISOPC.K=CLIP(ISOPC2.K,ISOPC1.K,TIME.K,PYEAR)
61      A       ISOPC1.K=TABHL(ISOPC1T,IOPC.K,0,1600,200)
        T       ISOPC1T=40/300/640/1000/1220/1450/1650/1800/2000
62      A       ISOPC2.K=TABHL(ISOPC2T,IOPC.K,0,1600,200)
        T       ISOPC2T=40/300/640/1000/1220/1450/1650/1800/2000
63      A       FIOAS.K=CLIP(FIOAS2.K,FIOAS1.K,TIME.K,PYEAR)
64      A       FIOAS1.K=TABHL(FIOAS1T,SOPC.K/ISOPC.K,0,2,.5)
        T        FIOAS1T=.3/.2/.1/.05/0
65      A       FIOAS2.K=TABHL(FIOAS2T,SOPC.K/ISOPC.K,0,2,.5)
        T       FIOAS2T=.3/.2/.1/.05/0
66      R       SCIR.KL=(IO.K)(FIOAS.K)
67      L       SC.K=SC.J+(DT)(SCIR.JK-SCDR.JK)
        N       SC=SCI
        C       SCI=1.44E11
68      R       SCDR.KL=SC.K/ALSC.K
69      A       ALSC.K=CLIP(ALSC2,ALSC1,TIME.K,PYEAR)
        C       ALSC1=20
        C       ALSC2=20
70      A       SO.K=(SC.K*CUF.K)/(SCOR.K)
71      A       SOPC.K=SO.K/POP.K
72      A       SCOR.K=CLIP(SCOR2,SCOR1,TIME.K,PYEAR)
        C       SCOR1=1
        C       SCOR2=1
        NOTE
        NOTE    JOB SUBSECTOR
        NOTE
73      A       J.K=PJIS.K+PJAS.K+PJSS.K
74      A       PJIS.K=(IC.K)(JPICU.K)
75      A       JPICU.K=(TABHL(JPICUT,IOPC.K,50,800,150))*1E-3
        T       JPICUT=.37/.18/.12/.09/.07/.06
76      A       PJSS.K=(SC.K)(JPSCU.K)
77      A       JPSCU.K=(TABHL(JPSCUT,SOPC.K,50,800,150))*1E-3
        T       JPSCUT=1.1/.6/.35/.2/.15/.15
78      A       PJAS.K=(JPH.K)(AL.K)
79      A       JPH.K=TABHL(JPHT,AIPH.K,2,30,4)
        T       JPHT=2/.5/.4/.3/.27/.24/.2/.2
80      A       LF.K=(P2.K+P3.K)*LFPF
        C       LFPF=.75
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 81    A     LUF.K=J.K/LF.K
 82    A     LUFD.K=SMOOTH(LUF.K,LUFDT)
       C     LUFDT=2
 83    A     CUF.K=TABHL(CUFT,LUFD.K,1,11,2)
       N     CUF=1
       T     CUFT=1/.9/.7/.3/.1/.1
       NOTE
       NOTE  AGRICULTURAL SECTOR
       NOTE
       NOTE  LOOP 1: FOOD FROM INVESTMENT IN LAND DEVELOPMENT
       NOTE
 84    A     LFC.K=AL.K/PALT
       C     PALT=3.2E9
 85    L     AL.K=AL.J+(DT)(LDR.JK-LER.JK-LRUI.JK)
       N     AL=ALI
       C     ALI=.9E9
 86    L     PAL.K=PAL.J+(DT)(-LDR.JK)
       N     PAL=PALI
       C     PALI=2.3E9
 87    A     F.K=LY.K*AL.K*LFH*(1-PL)
       C     LFH=.7
       C     PL=.1
 88    A     FPC.K=F.K/POP.K
 89    A     IFPC.K=CLIP(IFPC2.K,IFPC1.K,TIME.K,PYEAR)
 90    A     IFPC1.K=TABHL(IFPC1T,IOPC.K,0,1600,200)
       T     IFPC1T=230/480/690/850/970/1070/1150/1210/1250
 91    A     IFPC2.K=TABHL(IFPC2T,IOPC.K,0,1600,200)
       T     IFPC2T=230/480/690/850/970/1070/1150/1210/1250
 92    A     TAI.K=IO.K*FIOAA.K
 93    A     FIOAA.K=CLIP(FIOAA2.K,FIOAA1.K,TIME.K,PYEAR)
 94    A     FIOAA1.K=TABHL(FIOAA1T,FPC.K/IFPC.K,0,2.5,.5)
       T     FIOAA1T=.4/.2/.1/.025/0/0
 95    A     FIOAA2.K=TABHL(FIOAA2T,FPC.K/IFPC.K,0,2.5,.5)
       T     FIOAA2T=.4/.2/.1/.025/0/0
 96    R     LDR.KL=TAI.K*FIALD.K/DCPH.K
 97    A     DCPH.K=TABHL(DCPHT,PAL.K/PALT,0,1,.1)
       T     DCPHT=1E5/7400/5200/3500/2400/1500/750/300/150/75/50
       NOTE
       NOTE  LOOP 2: FOOD FROM INVESTMENT IN AGRICULTURAL INPUTS
       NOTE
 98    A     CAI.K=TAI.K*(1-FIALD.K)
 99    A     AI.K=SMOOTH(CAI.K,ALAI.K)
       N     AI=5E9
100    A     ALAI.K=CLIP(ALAI2,ALAI1,TIME.K,PYEAR)
       C     ALAI1=2
       C     ALAI2=2
101    A     AIPH.K=AI.K*(1-FALM.K)/AL.K
102    A     LYMC.K=TABHL(LYMCT,AIPH.K,0,1000,40)
       T     LYMCT=1/3/3.8/4.4/4.9/5.4/5.7/6/6.3/6.6/6.9/7.2/7.4
       X     /7.6/7.8/8/8.2/8.4/8.6/8.8/9/9.2/9.4/9.6/9.8/10
103    A     LY.K=LYF.K*LFERT.K*LYMC.K*LYMAP.K
104    A     LYF.K=CLIP(LYF2,LYF1,TIME.K,PYEAR)
       C     LYF1=1
       C     LYF2=1
105    A     LYMAP.K=CLIP(LYMAP2.K,LYMAP1.K,TIME.K,PYEAR)
106    A     LYMAP1.K=TABHL(LYMAP1T,IO.K/IO70,0,30,10)
       T     LYMAP1T=1/1/.7/.4
107    A     LYMAP2.K=TABHL(LYMAP2T,IO.K/IO70,0,30,10)
       T     LYMAP2T=1/1/.7/.4
       C     IO70=7.9E11
       NOTE
       NOTE  LOOPS 1 & 2: THE INVESTMENT ALLOCATION DECISION
       NOTE
108    A     FIALD.K=TABHL(FIALDT,(MPLD.K/MPAI.K),0,2,.25)
       T     FIALDT=0/.05/.15/.30/.50/.70/.85/.95/1
109    A     MPLD.K=LY.K/(DCPH.K*SD)
       C     SD=.07
110    A     MPAI.K=ALAI.K*LY.K*MLYMC.K/LYMC.K
111    A     MLYMC.K=TABHL(MLYMCT,AIPH.K,0,600,40)
       T     MLYMCT=.075/.03/.015/.011/.009/.008/.007/.006/
       X     .005/.005/.005/.005/.005/.005/.005/.005
       NOTE
       NOTE  LOOP 3: LAND EROSION AND URBAN-INDUSTRIAL USE
       NOTE
112    A     ALL.K=ALLN*LLMY.K
       C     ALLN=6000
113    A     LLMY.K=CLIP(LLMY2.K,LLMY1.K,TIME.K,PYEAR)
114    A     LLMY1.K=TABHL(LLMY1T,LY.K/ILF,0,9,1)
       T     LLMY1T=1.2/1/.63/.36/.16/.055/.04/.025/.015/.01
115    A     LLMY2.K=TABHL(LLMY2T,LY.K/ILF,0,9,1)
```

```
        T     LLMY2T=1.2/1/.63/.36/.16/.055/.04/.025/.015/.01
116     R     LER.KL=AL.K/ALL.K
117     A     UILPC.K=TABHL(UILPCT,IOPC.K,0,1600,200)
        T     UILPCT=.005/.008/.015/.025/.04/.055/.07/.08/.09
118     A     UILR.K=UILPC.K*POP.K
119     R     LRUI.KL=MAX(0,(UILR.K-UIL.K)/UILDT)
        C     UILDT=10
120     L     UIL.K=UIL.J+(DT)(LRUI.JK)
        N     UIL=UILI
        C     UILI=8.2E6
        NOTE
        NOTE  LOOP 4: LAND FERTILITY DEGRADATION
        NOTE
121     L     LFERT.K=LFERT.J+(DT)(LFR.JK-LFD.JK)
        N     LFERT=LFERTI
        C     LFERTI=600
122     A     LFDR.K=TABHL(LFDRT,PPOLX.K,0,30,10)
        T     LFDRT=0/.1/.3/.5
123     R     LFD.KL=LFERT.K*LFDR.K
        NOTE
        NOTE  LOOP 5: LAND FERTILITY REGENERATION
        NOTE
124     R     LFR.KL=(ILF-LFERT.K)/LFRT.K
        C     ILF=600
125     A     LFRT.K=TABHL(LFRTT,FALM.K,0,.10,.02)
        T     LFRTT=20/13/8/4/2/2
        NOTE
        NOTE  LOOP 6: DISCONTINUING LAND MAINTENANCE
        NOTE
126     A     FALM.K=TABHL(FALMT,PFR.K,0,4,1)
        T     FALMT=0/.04/.07/.09/.1
127     A     FR.K=FPC.K/SFPC
        C     SFPC=230
128     A     PFR.K=SMOOTH(FR.K,FSPD)
        N     PFR=1
        C     FSPD=2
        NOTE
        NOTE  NONRENEWABLE RESOURCE SECTOR
        NOTE
129     L     NR.K=NR.J+(DT)(-NRUR.JK)
        N     NR=NRI
        C     NRI=1E12
130     R     NRUR.KL=(POP.K)(PCRUM.K)(NRUF.K)
131     A     NRUF.K=CLIP(NRUF2,NRUF1,TIME.K,PYEAR)
        C     NRUF1=1
        C     NRUF2=1
132     A     PCRUM.K=TABHL(PCRUMT,IOPC.K,0,1600,200)
        T     PCRUMT=0/.85/2.6/4.4/5.4/6.2/6.8/7/7
133     A     NRFR.K=NR.K/NRI
134     A     FCAOR.K=CLIP(FCAOR2.K,FCAOR1.K,TIME.K,PYEAR)
135     A     FCAOR1.K=TABHL(FCAOR1T,NRFR.K,0,1,.1)
        T     FCAOR1T=1/.9/.7/.5/.2/.1/.05/.05/.05/.05/.05
136     A     FCAOR2.K=TABHL(FCAOR2T,NRFR.K,0,1,.1)
        T     FCAOR2T=1/.9/.7/.5/.2/.1/.05/.05/.05/.05/.05
        NOTE
        NOTE  PERSISTENT POLLUTION SECTOR
        NOTE
137     R     PPGR.KL=(PPGIO.K+PPGAO.K)*(PPGF.K)
138     A     PPGF.K=CLIP(PPGF2,PPGF1,TIME.K,PYEAR)
        C     PPGF1=1
        C     PPGF2=1
139     A     PPGIO.K=PCRUM.K*POP.K*FRPM*IMEF*IMTI
        C     FRPM=.02
        C     IMEF=.1
        C     IMTI=10
140     A     PPGAO.K=AIPH.K*AL.K*FIPM*AMTI
        C     FIPM=.001
        C     AMTI=1
141     R     PPAPR.KL=DELAY3(PPGR.JK,PPTD)
        C     PPTD=20
142     L     PPOL.K=PPOL.J+(DT)(PPAPR.JK-PPASR.JK)
        N     PPOL=2.5E7
143     A     PPOLX.K=PPOL.K/PPOL70
        C     PPOL70=1.36E8
144     R     PPASR.KL=PPOL.K/(AHL.K*1.4)
145     A     AHLM.K=TABHL(AHLMT,PPOLX.K,1,1001,250)
        T     AHLMT=1/11/21/31/41
146     A     AHL.K=AHL70*AHLM.K
        C     AHL70=1.5
        NOTE
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            NOTE   SUPPLEMENTARY EQUATIONS
            NOTE
147         S      FOA.K=(.22)(F.K)/(.22*F.K+SO.K+IO.K)
148         S      FOI.K=IO.K/(.22*F.K+SO.K+IO.K)
149         S      FOS.K=SO.K/(.22*F.K+SO.K+IO.K)
            NOTE
            NOTE   CONTROL CARDS FOR SIMULATION
            NOTE
            SPEC   DT=.5/LENGTH=2100
            C      PYEAR=1975
            N      TIME=1900
151         A      PLTPER.K=STEP(PLP,PLIT)
            C      PLP=5
            C      PLIT=1900
            C      PRP=0
152         A      PRTPER.K=STEP(PRP,PRIT)+STEP(-PRP,PRTT)
            C      PRIT=1900
            C      PRTT=2100
            PLOT   NRFR=R(0,1)/IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/PPOLX=X(0,32)
            X      /CBR=B,CDR=D(0,50)
            RUN    STANDARD
            NOTE
            NOTE   PARAMETER AND STRUCTURAL CHANGES FOR THE WORLD3 RUNS
            NOTE
            NOTE   HISTORICAL RUNS
            NOTE
            C      LENGTH=1970
            C      PLP=2
            PLOT   POP=P(0,4E9)/CBR=B,CDR=D(0,50)/LE=L(0,60)/
            X      LMF=F,LMP=X,LMHS=H,LMC=C(.75,1.75)/TF=T,DTF=*(0,8)
            RUN    FIGURE 7-2: POPULATION STANDARD
            C      LENGTH=1970
            C      PLP=2
            PLOT   IC=C,IO=O(0,4E12)/IOPC=I,SOPC=S(0,400)/
            X      FOA=1,FOI=2,FOS=3(0,1)
            RUN    FIGURE 7-3: CAPITAL STANDARD
            C      LENGTH=1970
            C      PLP=2
            PLOT   F=*(0,2E12)/FPC=F(0,800)/AL=A(0,1.6E9)/LY=Y(0,2000)/
            X      AIPH=$(0,80)/LFERT=T(0,800)
            RUN    FIGURE 7-4: AGRICULTURE STANDARD
            C      LENGTH=1970
            C      PLP=2
            PLOT   NRUR=U(0,4E9)/NRFR=R,FCAOR=C,PCRUM=P(0,1)
            RUN    FIGURE 7-5: RESOURCE STANDARD
            C      LENGTH=1970
            C      PLP=2
            PLOT   PPGIO=I,PPGAO=A,PPGR=G,PPAPR=R(0,2E8)/PPOLX=X(0,1)/
            X      AHL=L,LMP=M(0,4)
            RUN    FIGURE 7-6: POLLUTION STANDARD
            NOTE
            NOTE   GLOBAL STANDARD RUNS
            NOTE
            PLOT   NRFR=R(0,1)/IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/PPOLX=X(0,32)/
            X      CBR=B,CDR=D(0,50)
            RUN    FIGURE 7-7: GLOBAL STANDARD
            PLOT   FCAOR=C(0,1)/IO=O,TAI=A(0,4E12)/AIPH=$(0,200)/
            X      FIOAA=F(0,.2)
            RUN    FIGURE 7-8: GLOBAL STANDARD, B
            PLOT   LY=Y(0,4000)/AL=A(0,4E9)/FPC=F(0,800)/LMF=L(0,1.6)/
            X      POP=P(0,16E9)
            RUN    FIGURE 7-9: GLOBAL STANDARD, C
            NOTE
            NOTE   SENSITIVITY TESTS
            NOTE
            C      NRI=2E12
            PLOT   NRFR=R(0,1)/IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/PPOLX=X(0,32)/
            X      CBR=B,CDR=D(0,50)
            RUN    FIGURE 7-10: DOUBLE RESOURCES
            C      NRI=1E13
            RUN    FIGURE 7-11: TEN TIMES RESOURCES
            T      FIOAA1T=.5/.3/.1/0/0/0
            T      FIOAA2T=.5/.3/.1/0/0/0
            RUN    FIGURE 7-13: NEW FIOAA
            C      ALIC1=21
            C      ALIC2=21
            RUN    FIGURE 7-14: ALIC=21 YEARS
            C      ALIC1=21
            C      ALIC2=21
            C      ICOR1=3.75
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C       ICOR2=3.75
RUN     FIGURE 7-15: ALIC=21 YEARS, ICOR=3.75 YEARS
NOTE
NOTE    TECHNOLOGICAL POLICY RUNS
NOTE
NOTE    RUNS SIMULATING DISCRETE CHANGES IN TECHNOLOGIES
NOTE
T       FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
RUN     FIGURE 7-16: EXPLORATION TECHNOLOGIES
T       FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
C       NRUF2=.125
RUN     FIGURE 7-18: RECYCLING TECHNOLOGIES
T       FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
C       NRUF2=.125
T       LYMAP2T=1/1/.98/.95
RUN     FIGURE 7-19: RESOURCE, AIR POLLUTION TECHNOLOGIES
T       FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
C       NRUF2=.125
T       LYMAP2T=1/1/.98/.95
C       PPGF2=.1
PLOT    NRFR=R(0,1)/IOPC=I(0,2000)/FPC=F(0,1000)/
X       POP=P(0,16E9)/PPOLX=X(0,32)/CBR=B,CDR=D(0,50)
RUN     FIGURE 7-20: RESOURCE, POLLUTION TECHNOLOGIES
T       FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
C       NRUF2=.125
T       LYMAP2T=1/1/.98/.95
C       PPGF2=.1
C       LYF2=2
PLOT    NRFR=R(0,1)/IOPC=I(0,2000)/FPC=F(0,1000)/
X       POP=P(0,16E9)/PPOLX=X(0,32)/CBR=B,CDR=D(0,50)
RUN     FIGURE 7-21: RESOURCE, POLLUTION, YIELD TECHNOLOGIES
T       FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
C       NRUF2=.125
T       LYMAP2T=1/1/.98/.95
C       PPGF2=.1
C       LYF2=2
T       LLMY2T=1.2/1/.9/.8/.75/.7/.67/.64/.62/.6
PLOT    NRFR=R(0,1)/IOPC=I(0,8000)/FPC=F(0,1000)/
X       POP=P(0,16E9)/PPOLX=X(0,32)/CBR=B,CDR=D(0,50)
RUN     FIGURE 7-22: RESOURCE, POLLUTION, AGRICULTURAL TECHNOLOGIES
NOTE
NOTE    RUN SIMULATING EXPONENTIALLY GROWING TECHNOLOGIES
NOTE
NOTE    ** THE FOLLOWING CHANGES MUST BE MADE IN EDIT MODE:
NOTE    ** IN ORDER TO MODEL EXPONENTIALLY GROWING TECHNOLOGIES...
NOTE    ** ...CHANGE:
NOTE    ** A NRUF.K=CLIP(NRUF2.K,NRUF1,TIME.K,PYEAR)
NOTE    ** A PPGF.K=CLIP(PPGF2.K,PPGF1,TIME.K,PYEAR)
NOTE    ** A LYF.K=CLIP(LYF2.K,LYF1,TIME.K,PYEAR)
NOTE    ** A NRUF2.K=EXP(-EXPON.K)
NOTE    ** A PPGF2.K=EXP(-EXPON.K)
NOTE    ** A LYF2.K=EXP(EXPON.K)
NOTE    ** A LLMY.K=CLIP(LLMY2.K,LLMY1.K,TIME.K,PYEAR)+(1-EXP(-EXPON.K))
NOTE    ** A UILR.K=UILPC.K*POP.K*EXP(-EXPON.K)
NOTE    ** ...INSERT:
NOTE    ** A EXPON.K=CLIP(ALPHA*(TIME.K-PYEAR),0,TIME.K,PYEAR)
NOTE    ** C ALPHA=.04
T       LYMAP2T=1/1/.98/.95
T       CUFT=1/1/1/1/1/1
C       DT=.1
PLOT    NRFR=R(0,1)/IOPC=I,FPC=F(0,1000)/POP=P(0,16E9)/PPOLX=X(0,32)/
X       CBR=B,CDR=D(0,50)
RUN     FIGURE 7-23: EXPONENTIALLY GROWING TECHNOLOGIES
NOTE
NOTE    RUNS SIMULATING ADAPTIVE CHANGES IN TECHNOLOGY
NOTE
NOTE    ** THE FOLLOWING CHANGES MUST BE MADE IN EDIT MODE:
NOTE    ** IN ORDER TO MODEL RESOURCE CONTROL...
NOTE    ** ...CHANGE:
NOTE    ** A NRUF.K=CLIP(NRUF2.K,NRUF1,TIME.K,PYEAR)
NOTE    ** L NRUF2.K=NRUF2.J+(DT)(NRATE.JK)
NOTE    ** ...INSERT:
NOTE    ** N NRUF2=1
NOTE    ** R NRATE.KL=CLIP(NRUF2.K*NRCM.K,0,TIME.K,PYEAR)
NOTE    ** A NRCM.K=TABHL(NRCMT,1-NRUR.JK/DNRUR,-1,0,1)
NOTE    ** T NRCMT=-.05/0
NOTE    ** C DNRUR=2E9
NOTE    ** IN ORDER TO MODEL YIELD CONTROL...
NOTE    ** ...CHANGE:
NOTE    ** A LYF.K=CLIP(LYF2.K,LYF1,TIME.K,PYEAR)
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NOTE    ** L LYF2.K=LYF2.J+(DT)(LYF2R.JK)
NOTE    ** ...INSERT:
NOTE    ** N LYF2=1
NOTE    ** R LYF2R.KL=CLIP(LYF2.K*LYCM.K,0,TIME.K,PYEAR)
NOTE    ** A LYCM.K=TABHL(LYCMT,DFR-FR.K,0,1,1)
NOTE    ** T LYCMT=0/.05
NOTE    ** C DFR=3
NOTE    ** IN ORDER TO MODEL POLLUTION CONTROL...
NOTE    ** ...CHANGE:
NOTE    ** A PPGF.K=CLIP(PPGF2.K,PPGF1,TIME.K,PYEAR)
NOTE    ** L PPGF2.K=PPGF2.J+(DT)(PRATE.JK)
NOTE    ** ...INSERT:
NOTE    ** N PPGF2=1
NOTE    ** R PRATE.KL=CLIP(PPGF2.K*POLGFM.K,0,TIME.K,PYEAR)
NOTE    ** A POLGFM.K=TABHL(POLGFMT,1-PPOLX.K/DPOLX,-1,0,1)
NOTE    ** T POLGFMT=-.05/0
NOTE    ** C DPOLX=3
T       FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
T       LLMY2T=1.2/1/.9/.8/.75/.7/.67/.64/.62/.6
T       LYMAP2T=1/1/.98/.95
RUN     FIGURE 7-24: ADAPTIVE TECHNOLOGICAL POLICIES
NOTE    ** MAKE THE SAME EDIT MODE CHANGES AS IN FIGURE 7-24
T       FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
T       LLMY2T=1.2/1/.9/.8/.75/.7/.67/.64/.62/.6
T       LYMAP2T=1/1/.98/.95
T       NRCMT=-.02/0
T       LYCMT=0/.02
T       POLGFMT=-.02/0
RUN     FIGURE 7-26: 2%/YEAR UPPER LIMIT ON TECHNOLOGICAL GROWTH
NOTE    ** MAKE THE SAME EDIT MODE CHANGES AS IN FIGURE 7-24, AND
NOTE    ** IN ORDER TO MODEL TECHNOLOGICAL COSTS...
NOTE    ** ...CHANGE:
NOTE    ** A ICOR.K=CLIP(ICOR2.K,ICOR1,TIME.K,PYEAR)
NOTE    ** A ICOR2.K=TABHL(ICOR2T,NRUF2.K,0,1,.2)*COPM.K*COYM.K
NOTE    ** ...INSERT:
NOTE    ** T ICOR2T=6/3.3/3.1/3.06/3.02/3
NOTE    ** A COPM.K=TABHL(COPMT,PPGF2.K,0,1,.2)
NOTE    ** T COPMT=2/1.1/1.05/1.02/1.01/1
NOTE    ** A COYM.K=TABHL(COYMT,LYF2.K,1,9,2)
NOTE    ** T COYMT=1/1.1/1.25/1.5/2
T       FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
T       LLMY2T=1.2/1/.9/.8/.75/.7/.67/.64/.62/.6
T       LYMAP2T=1/1/.98/.95
RUN     FIGURE 7-27: ADAPTIVE TECHNOLOGIES WITH COSTS
NOTE    ** THE FOLLOWING CHANGES MUST BE MADE IN EDIT MODE:
NOTE    ** IN ORDER TO MODEL DELAYED RESOURCE CONTROL...
NOTE    ** ...CHANGE:
NOTE    ** A NRUF.K=CLIP(NRUF2.K,NRUF1,TIME.K,PYEAR)
NOTE    ** A NRUF2.K=DLINF3(NRTD.K,TDD)
NOTE    ** ...INSERT:
NOTE    ** C TDD=10
NOTE    ** L NRTD.K=NRTD.J+(DT)(NRATE.JK)
NOTE    ** N NRTD=1
NOTE    ** R NRATE.KL=CLIP(NRTD.K*NRCM.K,0,TIME.K,PYEAR)
NOTE    ** A NRCM.K=TABHL(NRCMT,1-NRUR.JK/DNRUR,-1,0,1)
NOTE    ** T NRCMT=-.05/0
NOTE    ** C DNRUR=2E9
NOTE    ** IN ORDER TO MODEL DELAYED YIELD CONTROL...
NOTE    ** ...CHANGE:
NOTE    ** A LYF.K=CLIP(LYF2.K,LYF1,TIME.K,PYEAR)
NOTE    ** A LYF2.K=DLINF3(LYTD.K,TDD)
NOTE    ** ...INSERT:
NOTE    ** L LYTD.K=LYTD.J+(DT)(LYTDR.JK)
NOTE    ** N LYTD=1
NOTE    ** R LYTDR.KL=CLIP(LYTD.K*LYCM.K,0,TIME.K,PYEAR)
NOTE    ** A LYCM.K=TABHL(LYCMT,DFR-FR.K,0,1,1)
NOTE    ** T LYCMT=0/.05
NOTE    ** C DFR=3
NOTE    ** IN ORDER TO MODEL DELAYED POLLUTION CONTROL...
NOTE    ** ...CHANGE:
NOTE    ** A PPGF.K=CLIP(PPGF2.K,PPGF1,TIME.K,PYEAR)
NOTE    ** A PPGF2.K=DLINF3(PTD.K,TDD)
NOTE    ** ...INSERT:
NOTE    ** L PTD.K=PTD.J+(DT)(PTDR.JK)
NOTE    ** N PTD=1
NOTE    ** R PTDR.KL=CLIP(PTD.K*POLGFM.K,0,TIME.K,PYEAR)
NOTE    ** A POLGFM.K=TABHL(POLGFMT,1-PPOLX.K/DPOLX,-1,0,1)
NOTE    ** T POLGFMT=-.05/0
NOTE    ** C DPOLX=3
NOTE    ** IN ORDER TO MODEL TECHNOLOGICAL COSTS...
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NOTE   ** ...CHANGE:
NOTE   ** A ICOR.K=CLIP(ICOR2.K,ICOR1,TIME.K,PYEAR)
NOTE   ** A ICOR2.K=TABHL(ICOR2T,NRTD.K,0,1,.2)*COYM.K*COPM.K
NOTE   ** ...INSERT:
NOTE   ** T ICOR2T=6/3.3/3.1/3.06/3.02/3
NOTE   ** A COPM.K=TABHL(COPMT,PTD.K,0,1,.2)
NOTE   ** T COPMT=2/1.1/1.05/1.02/1.01/1
NOTE   ** A COYM.K=TABHL(COYMT,LYTD.K,1,9,2)
NOTE   ** T COYMT=1/1.1/1.25/1.5/2
T      FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
T      LLMY2T=1.2/1/.9/.8/.75/.7/.67/.64/.62/.6
T      LYMAP2T=1/1/.98/.95
RUN    FIGURE 7-30: ADAPTIVE TECHNOLOGIES, COSTS, AND DELAYS
NOTE   ** MAKE THE SAME EDIT MODE CHANGES AS IN FIGURE 7-30, AND
NOTE   ** IN ORDER TO MODEL A BIAS TOWARD GROWTH...
NOTE   ** ...CHANGE:
NOTE   ** A NRCM.K=TABHL(NRCMT,1-NRUR.JK/DNRUR,-1,0,1)*ICM.K
NOTE   ** A LYCM.K=TABHL(LYCMT,DFR-FR.K,0,1,1)*ICM.K
NOTE   ** A POLGFM.K=TABHL(POLGFMT,1-PPOLX.K/DPOLX,-1,0,1)*ICM.K
NOTE   ** ...INSERT:
NOTE   ** A ICM.K=TABHL(ICMT,(IOPC.K-SMOOTH(IOPC.K,2))/IOPC.K,0,.05,.05)
NOTE   ** T ICMT=0/1
T      FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
T      LLMY2T=1.2/1/.9/.8/.75/.7/.67/.64/.62/.6
T      LYMAP2T=1/1/.98/.95
RUN    FIGURE 7-32: GROWTH BIAS
NOTE
NOTE   SOCIAL POLICY RUNS
NOTE
C      ZPGT=1975
RUN    FIGURE 7-34: DCFS=2 CHILDREN/FAMILY IN 1975
C      ALIC2=21
C      ALSC2=30
RUN    FIGURE 7-35: CAPITAL LIFETIMES
T      ISOPC2T=60/450/960/1500/1830/2175/2475/2700/3000
T      IFPC2T=345/720/1035/1275/1455/1605/1725/1815/1875
RUN    FIGURE 7-36: HIGHER FOOD, SERVICES
C      ZPGT=1975
T      ISOPC2T=60/450/960/1500/1830/2175/2475/2700/3000
T      IFPC2T=345/720/1035/1275/1455/1605/1725/1815/1875
RUN    FIGURE 7-37: POPULATION POLICY AND OUTPUT CHOICES
NOTE
NOTE   EQUILIBRIUM POLICY RUNS
NOTE
C      ZPGT=1975
C      IET=1990
C      IOPCD=320
C      NRUF2=.125
T      ISOPC2T=60/450/960/1500/1830/2175/2475/2700/3000
T      IFPC2T=345/720/1035/1275/1455/1605/1725/1815/1875
C      PPGF2=.25
C      ALIC2=21
C      ALSC2=30
RUN    FIGURE 7-38: EQUILIBRIUM THROUGH DISCRETE POLICIES
NOTE   ** MAKE THE SAME EDIT MODE CHANGES AS IN FIGURE 7-30
T      FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
T      LLMY2T=1.2/1/.9/.8/.75/.7/.67/.64/.62/.6
T      LYMAP2T=1/1/.98/.95
C      ZPGT=1975
C      IET=1990
C      IOPCD=320
RUN    FIGURE 7-39: EQUILIBRIUM THROUGH ADAPTIVE POLICIES
NOTE   ** MAKE THE SAME EDIT MODE CHANGES AS IN FIGURE 7-30
T      FCAOR2T=1/.2/.1/.05/.05/.05/.05/.05/.05/.05/.05
T      LLMY2T=1.2/1/.9/.8/.75/.7/.67/.64/.62/.6
T      LYMAP2T=1/1/.98/.95
C      ZPGT=2000
C      IET=2000
C      IOPCD=350
C      PYEAR=2000
RUN    FIGURE 7-41: POLICIES IN 2000
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REFERENCES

Chenery and Taylor 1968	Chenery, Hollis B., and Lance Taylor. "Development Patterns: Among Countries and Over Time." *Review of Economics and Statistics* 50, no. 4 (November 1968).
Meadows et al. 1972	Meadows, D. H. et al. *The Limits to Growth*. New York: Universe Books, 1972.
NCMP 1972	United States. National Commission on Materials Policy. *Towards a National Materials Policy: Basic Data and Issues*. Interim report. Washington, D.C.: Government Printing Office, April 1972.
U.N. 1970	United Nations. Department of Economic and Social Affairs. *Statistical Yearbook, 1969*. New York, 1970.

8 Conclusions

When a man does not know what harbor he is making for, no wind is the right wind.
Seneca, Epistles to Lucilus

Every physical quantity growing in a finite space must eventually exhibit one of three basic behavior modes: a smooth transition to a steady state, oscillation around an equilibrium position, or overshoot and decline. The World3 model was designed to investigate which of these behavior modes is most likely to characterize the evolution of population and capital on this finite earth and to identify the policies that would increase the probability of an orderly transition to global equilibrium.

Through the process of elaborating the model's feedback loops, we were forced to clarify our assumptions about the causes and consequences of growth. These assumptions about the global system are quantified and discussed in detail in Chapters 2 through 7. The mathematical equations presented in those chapters were necessary to ensure the internal consistency of our assumptions and to test the sensitivity of the model to potential errors in our estimates. The equations also express concepts that may assist future research.

However, the purpose of the project was not to construct an elaborate model: our objective was to increase the sophistication and clarity of mental models. Of course, no one is able to carry in his head all the numbers and functional relationships of World3. Thus it is useful to abstract the basic conclusions of the study that can be comprehended intuitively, so that they can be evaluated as possible additions to the evolving conceptual framework that helps each person interpret and respond to the complex world around him. In this conclusion we will summarize the book's message about the relative stability of alternative systems and indicate the future research required to test, extend, and apply our analysis.

8.1 THE BASIC ASSUMPTIONS AND CONCLUSIONS OF WORLD3

The dominant behavior mode of World3 is caused by three basic assumptions about the population-capital system:

1. The prevailing social value system strongly favors the growth of population and capital. Therefore, these quantities tend to grow unless severely pressed by physical limitations. Their growth is exponential because of the inherent positive feedback nature of industrial production and human reproduction.
2. Feedback signals about the negative consequences of growth are generated by the environmental systems that support population and capital. These signals take the form of pressures against growth, such as diminishing returns to investment in agricultural inputs, the buildup of harmful pollutants, increased development costs for new land, increased resource costs, and less food per capita. The negative feedback signals become stronger as population and capital grow toward environmental limits.

3. Delays in the negative feedback signals arise for two reasons. First, some delays, such as those inherent in population aging, pollution transfers, and land fertility regeneration, are inescapable consequences of physical or biological laws. Second, some delays are caused by the time intervals necessary for society to perceive new environmental situations and to adjust its values, institutions, and technologies in response.

A system that possesses these three characteristics—rapid growth, environmental limits, and feedback delays—is inherently unstable. Because the rapid growth persists while the feedback signals that oppose it are delayed, the physical system can temporarily expand well beyond its ultimately sustainable limits. During this period of overshoot, the short-term efforts required to maintain the excess population and capital are especially likely to erode or deplete the resource base. The environmental carrying capacity may be so diminished that it can support only a much smaller population and lower material standard of living than would have been possible before the overshoot. The result is an uncontrollable decline to lower levels of population and capital.

With this understanding of the system characteristics that lead to instability, it becomes relatively easy to evaluate alternative policies for increasing stability and bringing about a sustainable equilibrium. For example:

1. Short-term technologies designed to mask the initial signals of impending limits and to promote further growth will not be effective in the long term. Rather, they will disguise the need for social value change, lengthen the system's response delays, and increase the probability, the speed, and the magnitude of the eventual overshoot and collapse.
2. Policies that combat the erosion of the earth's resource base will certainly reduce the severity of decline after an overshoot. However, so long as growth is still emphasized and feedback delays persist, resource conservation will not in itself prevent overshoot. Furthermore, the overstressed system may not be able to afford the costs of conservation during a period of overshoot.
3. Social value changes that reduce the forces causing growth, institutional innovations that raise the rate of technological or social adaptation, and long-term forecasting methods that shorten feedback delays may be very effective in reducing system instability.
4. A judicious combination of policies designed to prevent the erosion of resources, foresee the effects of approaching limits, and bring a deliberate end to material and demographic growth can circumvent the overshoot mode altogether and lead to a sustainable equilibrium.

Although these conclusions seem to be simple and self-evident, most economic and political decisions made today are based implicitly on a world view very different from the one presented here. The dominant contemporary model contains the assumptions that physical growth can and should continue; that technology and the price system can eliminate scarcities with little delay; that the resource base can be expanded but never reduced; that the solution of short-term problems will yield desirable long-term results; and that population and capital, if they must ever stabilize, will do so automatically and at an optimal level.

The world views implicit in World3 and the mental model underlying most current decisions are diametrically opposed in their policy implications. World3 identifies basic instabilities in the socioeconomic system and suggests that significant changes in social institutions and values are necessary to avoid collapse. Current policy models are based on the assumption that the requisite stabilizing mechanisms do already exist and that no future events will necessitate more than minor adjustments in current policies. Selection of the wrong model as the basis for growth policy would drastically reduce society's long-term options, but the choice cannot be avoided. It is implicit in every policy or action that has long-term influences on population or capital growth.

Unfortunately, there is no straightforward, objective process to prove conclusively that one social model is correct and another is false. Instead, every person must examine the assumptions underlying each model and then base his decisions on the one he finds most consistent with his own knowledge of the world. The process of establishing confidence in any social model is always difficult and uncertain. The debate over which policies should guide growth will continue for at least several decades. Much remains to be done to clarify that debate and to guide it to an informed and satisfactory conclusion.

8.2 THE STEPS AHEAD

Advocates of a world view that is different from the one presented here would enhance future discussions greatly if they would express their theory as a formal model, so that persons in various fields could personally scrutinize its assumptions and independently determine its implications. As Jay W. Forrester suggested in the Preface to his volume on World2:

> It is to be hoped that those who believe they already have some different model that is more valid will present it in the same explicit detail, so that its assumptions and consequences can be examined and compared. To reject this model because of its shortcomings without offering concrete and tangible alternatives would be equivalent to asking that time be stopped.
>
> It seems traditional for explicit models of social systems to be greeted by vague criticisms about their lack of perfection. Instead, we need equally explicit alternatives with a demonstration that the alternative leads to a *different* and *more plausible* set of conclusions. By proposal and counter proposition our understanding of social systems can advance. [Forrester, *World Dynamics*]

Those who agree with the basic concepts expressed in World3 can go on to test, improve, and disaggregate the model and to use it where appropriate as a basis for policy in local, regional, or national systems. However, since World3 was formulated to provide global perspectives, it can supply only general guidance for short-term, local policies. The same characteristics of growth, limits, delays, and erodable resources that make World3 unstable also produce instability in subregions of the globe. But the understanding that will provide concrete regional plans for reaching sustainable equilibria can come only from more specific, detailed models made in collaboration with the institutions and individuals they will affect.

Before citizens can choose from among alternative equilibria, there must be new images of those steady states which are consistent with the limits to growth. These will require contributions from every field of human knowledge. New economic theories are necessary for an industrialized society in which productive capital is stabilized, material flows are reduced, equality is dealt with directly, and the future is not discounted exponentially. New political understanding is required to provide procedures through which democratic choice can be exercised to reward politicians for the long-term implications of their acts. Technologies are needed that place a high emphasis on the recycling of nonrenewable resources, on the use of pollution-free, renewable energy sources, and on the reduction of both matter and energy flows. Psychological and sociological advances are necessary to design the educational systems and social institutions that could reinforce a new self-image for man, one that would give him a set of feasible aspirations within an environment where man-made material output is in balance with the globe's finite limits.

But something beyond the scope of the traditional disciplines is also needed. A new emphasis on social *systems* is required to connect and coordinate research among all disciplines so that every type of wisdom and knowledge can be used in managing the difficult transition from growth to equilibrium. The philosophical concepts of holism, feedback, and the dynamic properties of systems could be usefully applied in every field of human effort and in education at all levels.

Systems understanding must be coupled with still another effort, the greatest of all—the construction of a consistent, feasible set of long-term values for human society. Under the false assumption that everything can be maximized for everyone with sufficient material growth, the present, temporary period of material growth has allowed social institutions to avoid all discussion of ultimate goals and value conflicts. The transition to equilibrium must begin with a broad discussion of what is and is not important to human society, where priorities lie, how trade-offs are to be made, and in what condition the human race would like to find itself when growth on this finite earth finally ceases.

REFERENCES

Forrester 1971	Forrester, Jay W. *World Dynamics.* Cambridge, Mass.: Wright-Allen Press, 1971.
Meadows et al. 1972	Meadows, D. H., et al. *The Limits to Growth.* New York: Universe Books, 1972.
Meadows and Meadows 1973	Meadows, D. L., and D. H. Meadows, eds. *Toward Global Equilibrium.* Cambridge, Mass.: Wright-Allen Press, 1973.

Appendixes

Appendix A: Documentor Listing

```
POPULATION SECTOR

POP.K=P1.K+P2.K+P3.K+P4.K                               1, A
     POP      - POPULATION (PERSONS)
     P1       - POPULATION, AGES 0-14 (PERSONS)
     P2       - POPULATION, AGES 15-44 (PERSONS)
     P3       - POPULATION, AGES 45-64 (PERSONS)
     P4       - POPULATION, AGES 65+ (PERSONS)

P1.K=P1.J+(DT)(B.JK-D1.JK-MAT1.JK)                      2, L
P1=P1I                                                  2.1, N
P1I=65E7                                                2.2, C
     P1       - POPULATION, AGES 0-14 (PERSONS)
     DT       - TIME INTERVAL BETWEEN CONSECUTIVE
                  CALCULATIONS (YEARS)
     B        - BIRTHS PER YEAR (PERSONS/YEAR)
     D1       - DEATHS PER YEAR, AGES 0-14 (PERSONS/YEAR)
     MAT1     - MATURATION RATE, AGE 14-15 (PERSONS/YEAR)
     P1I      - P1 INITIAL (PERSONS)

D1.KL=P1.K*M1.K                                         3, R
     D1       - DEATHS PER YEAR, AGES 0-14 (PERSONS/YEAR)
     P1       - POPULATION, AGES 0-14 (PERSONS)
     M1       - MORTALITY, AGES 0-14 (DEATHS/PERSON-YEAR)

M1.K=TABHL(M1T,LE.K,20,80,10)                           4, A
M1T=.0567/.0366/.0243/.0155/.0082/.0023/.001            4.1, T
     M1       - MORTALITY, AGES 0-14 (DEATHS/PERSON-YEAR)
     TABHL    - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
     M1T      - M1 TABLE
     LE       - LIFE EXPECTANCY (YEARS)

MAT1.KL=(P1.K)(1-M1.K)/15                               5, R
     MAT1     - MATURATION RATE, AGE 14-15 (PERSONS/YEAR)
     P1       - POPULATION, AGES 0-14 (PERSONS)
     M1       - MORTALITY, AGES 0-14 (DEATHS/PERSON-YEAR)

P2.K=P2.J+(DT)(MAT1.JK-D2.JK-MAT2.JK)                   6, L
P2=P2I                                                  6.1, N
P2I=70E7                                                6.2, C
     P2       - POPULATION, AGES 15-44 (PERSONS)
     DT       - TIME INTERVAL BETWEEN CONSECUTIVE
                  CALCULATIONS (YEARS)
     MAT1     - MATURATION RATE, AGE 14-15 (PERSONS/YEAR)
     D2       - DEATHS PER YEAR, AGES 15-44 (PERSONS/YEAR)
     MAT2     - MATURATION RATE, AGE 44-45 (PERSONS/YEAR)
     P2I      - P2 INITIAL (PERSONS)

D2.KL=P2.K*M2.K                                         7, R
     D2       - DEATHS PER YEAR, AGES 15-44 (PERSONS/YEAR)
     P2       - POPULATION, AGES 15-44 (PERSONS)
     M2       - MORTALITY, AGES 15-44 (DEATHS/PERSON-YEAR)
```

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M2.K=TABHL(M2T,LE.K,20,80,10)                              8, A
M2T=.0266/.0171/.0110/.0065/.0040/.0016/.0008              8.1, T
    M2     - MORTALITY, AGES 15-44 (DEATHS/PERSON-YEAR)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    M2T    - M2 TABLE
    LE     - LIFE EXPECTANCY (YEARS)

MAT2.KL=(P2.K)(1-M2.K)/30                                  9, R
    MAT2   - MATURATION RATE, AGE 44-45 (PERSONS/YEAR)
    P2     - POPULATION, AGES 15-44 (PERSONS)
    M2     - MORTALITY, AGES 15-44 (DEATHS/PERSON-YEAR)

P3.K=P3.J+(DT)(MAT2.JK-D3.JK-MAT3.JK)                      10, L
P3=P3I                                                     10.1, N
P3I=19E7                                                   10.2, C
    P3     - POPULATION, AGES 45-64 (PERSONS)
    DT     - TIME INTERVAL BETWEEN CONSECUTIVE
               CALCULATIONS (YEARS)
    MAT2   - MATURATION RATE, AGE 44-45 (PERSONS/YEAR)
    D3     - DEATHS PER YEAR, AGES 45-64 (PERSONS/YEAR)
    MAT3   - MATURATION RATE, AGE 64-65 (PERSONS/YEAR)
    P3I    - P3 INITIAL (PERSONS)

D3.KL=P3.K*M3.K                                            11, R
    D3     - DEATHS PER YEAR, AGES 45-64 (PERSONS/YEAR)
    P3     - POPULATION, AGES 45-64 (PERSONS)
    M3     - MORTALITY, AGES 45-64 (DEATHS/PERSON-YEAR)

M3.K=TABHL(M3T,LE.K,20,80,10)                              12, A
M3T=.0562/.0373/.0252/.0171/.0118/.0083/.006               12.1, T
    M3     - MORTALITY, AGES 45-64 (DEATHS/PERSON-YEAR)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    M3T    - M3 TABLE
    LE     - LIFE EXPECTANCY (YEARS)

MAT3.KL=(P3.K)(1-M3.K)/20                                  13, R
    MAT3   - MATURATION RATE, AGE 64-65 (PERSONS/YEAR)
    P3     - POPULATION, AGES 45-64 (PERSONS)
    M3     - MORTALITY, AGES 45-64 (DEATHS/PERSON-YEAR)

P4.K=P4.J+(DT)(MAT3.JK-D4.JK)                              14, L
P4=P4I                                                     14.1, N
P4I=6E7                                                    14.2, C
    P4     - POPULATION, AGES 65+ (PERSONS)
    DT     - TIME INTERVAL BETWEEN CONSECUTIVE
               CALCULATIONS (YEARS)
    MAT3   - MATURATION RATE, AGE 64-65 (PERSONS/YEAR)
    D4     - DEATHS PER YEAR, AGES 65+ (PERSONS/YEAR)
    P4I    - P4 INITIAL (PERSONS)

D4.KL=P4.K*M4.K                                            15, R
    D4     - DEATHS PER YEAR, AGES 65+ (PERSONS/YEAR)
    P4     - POPULATION, AGES 65+ (PERSONS)
    M4     - MORTALITY, AGES 65+ (DEATHS/PERSON-YEAR)


M4.K=TABHL(M4T,LE.K,20,80,10)                              16, A
M4T=.13/.11/.09/.07/.06/.05/.04                            16.1, T
    M4     - MORTALITY, AGES 65+ (DEATHS/PERSON-YEAR)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    M4T    - M4 TABLE
    LE     - LIFE EXPECTANCY (YEARS)

  DEATH RATE SUBSECTOR

D.K=D1.JK+D2.JK+D3.JK+D4.JK                                17, A
    D      - DEATHS PER YEAR (PERSONS/YEAR)
    D1     - DEATHS PER YEAR, AGES 0-14 (PERSONS/YEAR)
    D2     - DEATHS PER YEAR, AGES 15-44 (PERSONS/YEAR)
    D3     - DEATHS PER YEAR, AGES 45-64 (PERSONS/YEAR)
    D4     - DEATHS PER YEAR, AGES 65+ (PERSONS/YEAR)

CDR.K=1000*D.K/POP.K                                       18, S
    CDR    - CRUDE DEATH RATE (DEATHS/1000 PERSON-YEARS)
    D      - DEATHS PER YEAR (PERSONS/YEAR)
    POP    - POPULATION (PERSONS)

LE.K=LEN*LMF.K*LMHS.K*LMP.K*LMC.K                          19, A
LEN=28                                                     19.1, C
```

```
    LE      - LIFE EXPECTANCY (YEARS)
    LEN     - LIFE EXPECTANCY NORMAL (YEARS)
    LMF     - LIFETIME MULTIPLIER FROM FOOD
                (DIMENSIONLESS)
    LMHS    - LIFETIME MULTIPLIER FROM HEALTH SERVICES
                (DIMENSIONLESS)
    LMP     - LIFETIME MULTIPLIER FROM PERSISTENT
                POLLUTION (DIMENSIONLESS)
    LMC     - LIFETIME MULTIPLIER FROM CROWDING
                (DIMENSIONLESS)

LMF.K=TABHL(LMFT,FPC.K/SFPC,0,5,1)                         20, A
LMFT=0/1/1.2/1.3/1.35/1.4                                  20.1, T
    LMF     - LIFETIME MULTIPLIER FROM FOOD
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LMFT    - LMF TABLE
    FPC     - FOOD PER CAPITA (VEGETABLE-EQUIVALENT
                KILOGRAMS/PERSON-YEAR)
    SFPC    - SUBSISTENCE FOOD PER CAPITA (VEGETABLE-
                EQUIVALENT KILOGRAMS/PERSON-YEAR)

HSAPC.K=TABHL(HSAPCT,SOPC.K,0,2000,250)                    21, A
HSAPCT=0/20/50/95/140/175/200/220/230                      21.1, T
    HSAPC   - HEALTH SERVICES ALLOCATIONS PER CAPITA
                (DOLLARS/PERSON-YEAR)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    HSAPCT  - HSAPC TABLE
    SOPC    - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
                YEAR)

EHSPC.K=SMOOTH(HSAPC.K,HSID)                               22, A
HSID=20                                                    22.1, C
    EHSPC   - EFFECTIVE HEALTH SERVICES PER CAPITA
                (DOLLARS/PERSON-YEAR)
    SMOOTH  - FIRST-ORDER EXPONENTIAL INFORMATION DELAY
    HSAPC   - HEALTH SERVICES ALLOCATIONS PER CAPITA
                (DOLLARS/PERSON-YEAR)
    HSID    - HEALTH SERVICES IMPACT DELAY (YEARS)
LMHS.K=CLIP(LMHS2.K,LMHS1.K,TIME.K,1940)                   23, A
    LMHS    - LIFETIME MULTIPLIER FROM HEALTH SERVICES
                (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    LMHS2   - LMHS, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    LMHS1   - LMHS, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN

LMHS1.K=TABHL(LMHS1T,EHSPC.K,0,100,20)                     24, A
LMHS1T=1/1.1/1.4/1.6/1.7/1.8                               24.1, T
    LMHS1   - LMHS, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LMHS1T  - LMHS1 TABLE
    EHSPC   - EFFECTIVE HEALTH SERVICES PER CAPITA
                (DOLLARS/PERSON-YEAR)

LMHS2.K=TABHL(LMHS2T,EHSPC.K,0,100,20)                     25, A
LMHS2T=1/1.4/1.6/1.8/1.95/2.0                              25.1, T
    LMHS2   - LMHS, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LMHS2T  - LMHS2 TABLE
    EHSPC   - EFFECTIVE HEALTH SERVICES PER CAPITA
                (DOLLARS/PERSON-YEAR)

FPU.K=TABHL(FPUT,POP.K,0,16E9,2E9)                         26, A
FPUT=0/.2/.4/.5/.58/.65/.72/.78/.80                        26.1, T
    FPU     - FRACTION OF POPULATION URBAN
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FPUT    - FPU TABLE
    POP     - POPULATION (PERSONS)

CMI.K=TABHL(CMIT,IOPC.K,0,1600,200)                        27, A
CMIT=.5/.05/-.1/-.08/-.02/.05/.1/.15/.2                    27.1, T
    CMI     - CROWDING MULTIPLIER FROM INDUSTRIALIZATION
                (DIMENSIONLESS)
```

```
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    CMIT    - CMI TABLE
    IOPC    - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                PERSON-YEAR)


LMC.K=1-(CMI.K*FPU.K)                                      28, A
    LMC     - LIFETIME MULTIPLIER FROM CROWDING
                (DIMENSIONLESS)
    CMI     - CROWDING MULTIPLIER FROM INDUSTRIALIZATION
                (DIMENSIONLESS)
    FPU     - FRACTION OF POPULATION URBAN
                (DIMENSIONLESS)

LMP.K=TABHL(LMPT,PPOLX.K,0,100,10)                         29, A
LMPT=1.0/.99/.97/.95/.90/.85/.75/.65/.55/.40/.20           29.1, T
    LMP     - LIFETIME MULTIPLIER FROM PERSISTENT
                POLLUTION (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LMPT    - LMP TABLE
    PPOLX   - INDEX OF PERSISTENT POLLUTION
                (DIMENSIONLESS)

  BIRTH RATE SUBSECTOR

B.KL=CLIP(D.K,(TF.K*P2.K*0.5/RLT),TIME.K,PET)              30, R
RLT=30                                                     30.1, C
PET=4000                                                   30.2, C
    B       - BIRTHS PER YEAR (PERSONS/YEAR)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    D       - DEATHS PER YEAR (PERSONS/YEAR)
    TF      - TOTAL FERTILITY (DIMENSIONLESS)
    P2      - POPULATION, AGES 15-44 (PERSONS)
    RLT     - REPRODUCTIVE LIFETIME (YEARS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PET     - POPULATION EQUILIBRIUM TIME (YEAR)

CBR.K=1000*B.JK/POP.K                                      31, S
    CBR     - CRUDE BIRTH RATE (BIRTHS/1000 PERSON-YEARS)
    B       - BIRTHS PER YEAR (PERSONS/YEAR)
    POP     - POPULATION (PERSONS)

TF.K=MIN(MTF.K,(MTF.K*(1-FCE.K)+DTF.K*FCE.K))              32, A
    TF      - TOTAL FERTILITY (DIMENSIONLESS)
    MIN     - MINIMUM VALUE FUNCTION
    MTF     - MAXIMUM TOTAL FERTILITY (DIMENSIONLESS)
    FCE     - FERTILITY CONTROL EFFECTIVENESS
                (DIMENSIONLESS)
    DTF     - DESIRED TOTAL FERTILITY (DIMENSIONLESS)

MTF.K=MTFN*FM.K                                            33, A
MTFN=12                                                    33.1, C
    MTF     - MAXIMUM TOTAL FERTILITY (DIMENSIONLESS)
    MTFN    - MAXIMUM TOTAL FERTILITY NORMAL
                (DIMENSIONLESS)
    FM      - FECUNDITY MULTIPLIER  (DIMENSIONLESS)

FM.K=TABHL(FMT,LE.K,0,80,10)                               34, A
FMT=0/.2/.4/.6/.8/.9/1/1.05/1.1                            34.1, T
    FM      - FECUNDITY MULTIPLIER  (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FMT     - FM TABLE
    LE      - LIFE EXPECTANCY (YEARS)


DTF.K=DCFS.K*CMPLE.K                                       35, A
    DTF     - DESIRED TOTAL FERTILITY (DIMENSIONLESS)
    DCFS    - DESIRED COMPLETED FAMILY SIZE (DIMENSIONLESS)
    CMPLE   - COMPENSATORY MULTIPLIER FROM PERCEIVED LIFE
                EXPECTANCY (DIMENSIONLESS)

CMPLE.K=TABHL(CMPLET,PLE.K,0,80,10)                        36, A
CMPLET=3/2.1/1.6/1.4/1.3/1.2/1.1/1.05/1                    36.1, T
    CMPLE   - COMPENSATORY MULTIPLIER FROM PERCEIVED LIFE
                EXPECTANCY (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    CMPLET  - CMPLE TABLE
    PLE     - PERCEIVED LIFE EXPECTANCY (YEARS)
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```
PLE.K=DLINF3(LE.K,LPD)                                37, A
LPD=20                                                37.1, C
    PLE    - PERCEIVED LIFE EXPECTANCY (YEARS)
    DLINF3 - THIRD-ORDER EXPONENTIAL INFORMATION DELAY
    LE     - LIFE EXPECTANCY (YEARS)
    LPD    - LIFETIME PERCEPTION DELAY (YEARS)

DCFS.K=CLIP(2.0,DCFSN*FRSN.K*SFSN.K,TIME.K,ZPGT)     38, A
ZPGT=4000                                             38.1, C
DCFSN=4                                               38.2, C
    DCFS   - DESIRED COMPLETED FAMILY SIZE (DIMENSIONLESS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    DCFSN  - DESIRED COMPLETED FAMILY SIZE NORMAL
               (DIMENSIONLESS)
    FRSN   - FAMILY RESPONSE TO SOCIAL NORM
               (DIMENSIONLESS)
    SFSN   - SOCIAL FAMILY SIZE NORM (DIMENSIONLESS)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    ZPGT   - TIME WHEN DESIRED FAMILY SIZE EQUALS 2
               CHILDREN (YEAR)

SFSN.K=TABHL(SFSNT,DIOPC.K,0,800,200)                 39, A
SFSNT=1.25/1/.9/.8/.75                                39.1, T
    SFSN   - SOCIAL FAMILY SIZE NORM (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    SFSNT  - SFSN TABLE
    DIOPC  - DELAYED INDUSTRIAL OUTPUT PER CAPITA
               (DOLLARS/PERSON-YEAR)

DIOPC.K=DLINF3(IOPC.K,SAD)                            40, A
SAD=20                                                40.1, C
    DIOPC  - DELAYED INDUSTRIAL OUTPUT PER CAPITA
               (DOLLARS/PERSON-YEAR)
    DLINF3 - THIRD-ORDER EXPONENTIAL INFORMATION DELAY
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
               PERSON-YEAR)
    SAD    - SOCIAL ADJUSTMENT DELAY (YEARS)


FRSN.K=TABHL(FRSNT,FIE.K,-.2,.2,.1)                   41, A
FRSNT=.5/.6/.7/.85/1                                  41.1, T
FRSN=.82                                              41.2, N
    FRSN   - FAMILY RESPONSE TO SOCIAL NORM
               (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FRSNT  - FRSN TABLE
    FIE    - FAMILY INCOME EXPECTATION (DIMENSIONLESS)


FIE.K=(IOPC.K-AIOPC.K)/AIOPC.K                        42, A
    FIE    - FAMILY INCOME EXPECTATION (DIMENSIONLESS)

    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
               PERSON-YEAR)
    AIOPC  - AVERAGE INDUSTRIAL OUTPUT PER CAPITA
               (DOLLARS/PERSON-YEAR)

AIOPC.K=SMOOTH(IOPC.K,IEAT)                           43, A
IEAT=3                                                43.1, C
    AIOPC  - AVERAGE INDUSTRIAL OUTPUT PER CAPITA
               (DOLLARS/PERSON-YEAR)
    SMOOTH - FIRST-ORDER EXPONENTIAL INFORMATION DELAY
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
               PERSON-YEAR)
    IEAT   - INCOME EXPECTATION AVERAGING TIME (YEARS)

NFC.K=(MTF.K/DTF.K)-1                                 44, A
    NFC    - NEED FOR FERTILITY CONTROL (DIMENSIONLESS)
    MTF    - MAXIMUM TOTAL FERTILITY (DIMENSIONLESS)
    DTF    - DESIRED TOTAL FERTILITY (DIMENSIONLESS)

FCE.K=CLIP(1.0,(TABHL(FCET,FCFPC.K,0,3,.5)),TIME.K,  45, A
  FCEST)
FCEST=4000                                            45.1, C
FCET=.75/.85/.9/.95/.98/.99/1                         45.2, T
    FCE    - FERTILITY CONTROL EFFECTIVENESS
               (DIMENSIONLESS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
```

```
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FCET   - FCE TABLE
    FCFPC  - FERTILITY CONTROL FACILITIES PER CAPITA
               (DOLLARS/PERSON-YEAR)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    FCEST  - FERTILITY CONTROL EFFECTIVENESS SET TIME
               (YEAR)

FCFPC.K=DLINF3(FCAPC.K,HSID)                           46, A
    FCFPC  - FERTILITY CONTROL FACILITIES PER CAPITA
               (DOLLARS/PERSON-YEAR)
    DLINF3 - THIRD-ORDER EXPONENTIAL INFORMATION DELAY
    FCAPC  - FERTILITY CONTROL ALLOCATIONS PER CAPITA
               (DOLLARS/PERSON-YEAR)
    HSID   - HEALTH SERVICES IMPACT DELAY (YEARS)

FCAPC.K=FSAFC.K*SOPC.K                                 47, A
    FCAPC  - FERTILITY CONTROL ALLOCATIONS PER CAPITA
               (DOLLARS/PERSON-YEAR)
    FSAFC  - FRACTION OF SERVICES ALLOCATED TO FERTILITY
               CONTROL (DIMENSIONLESS)
    SOPC   - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
               YEAR)

FSAFC.K=TABHL(FSAFCT,NFC.K,0,10,2)                     48, A
FSAFCT=0/.005/.015/.025/.03/.035                       48.1, T
    FSAFC  - FRACTION OF SERVICES ALLOCATED TO FERTILITY
               CONTROL (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FSAFCT - FSAFC TABLE
    NFC    - NEED FOR FERTILITY CONTROL (DIMENSIONLESS)

  CAPITAL SECTOR
  INDUSTRIAL SUBSECTOR

IOPC.K=IO.K/POP.K                                      49, A
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
               PERSON-YEAR)
    IO     - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    POP    - POPULATION (PERSONS)

IO.K=(IC.K)(1-FCAOR.K)(CUF.K)/ICOR.K                   50, A
    IO     - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    IC     - INDUSTRIAL CAPITAL (DOLLARS)
    FCAOR  - FRACTION OF CAPITAL ALLOCATED TO OBTAINING
               RESOURCES (DIMENSIONLESS)
    CUF    - CAPITAL UTILIZATION FRACTION
               (DIMENSIONLESS)
    ICOR   - INDUSTRIAL CAPITAL-OUTPUT RATIO (YEARS)

ICOR.K=CLIP(ICOR2,ICOR1,TIME.K,PYEAR)                  51, A
ICOR1=3                                                51.1, C
ICOR2=3                                                51.2, C
    ICOR   - INDUSTRIAL CAPITAL-OUTPUT RATIO (YEARS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    ICOR2  - ICOR, VALUE AFTER TIME=PYEAR (YEARS)
    ICOR1  - ICOR, VALUE BEFORE TIME=PYEAR (YEARS)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

IC.K=IC.J+(DT)(ICIR.JK-ICDR.JK)                        52, L
IC=ICI                                                 52.1, N
ICI=2.1E11                                             52.2, C
    IC     - INDUSTRIAL CAPITAL (DOLLARS)
    DT     - TIME INTERVAL BETWEEN CONSECUTIVE
               CALCULATIONS (YEARS)
    ICIR   - INDUSTRIAL CAPITAL INVESTMENT RATE
               (DOLLARS/YEAR)
    ICDR   - INDUSTRIAL CAPITAL DEPRECIATION RATE
               (DOLLARS/YEAR)
    ICI    - INDUSTRIAL CAPITAL INITIAL (DOLLARS)

ICDR.KL=IC.K/ALIC.K                                    53, R
    ICDR   - INDUSTRIAL CAPITAL DEPRECIATION RATE
               (DOLLARS/YEAR)
    IC     - INDUSTRIAL CAPITAL (DOLLARS)
    ALIC   - AVERAGE LIFETIME OF INDUSTRIAL CAPITAL
               (YEARS)
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ALIC.K=CLIP(ALIC2,ALIC1,TIME.K,PYEAR)                        54, A
ALIC1=14                                                     54.1, C
ALIC2=14                                                     54.2, C
    ALIC    - AVERAGE LIFETIME OF INDUSTRIAL CAPITAL
                (YEARS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    ALIC2   - ALIC, VALUE AFTER TIME=PYEAR (YEARS)
    ALIC1   - ALIC, VALUE BEFORE TIME=PYEAR (YEARS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
ICIR.KL=(IO.K)(FIOAI.K)                                      55, R
    ICIR    - INDUSTRIAL CAPITAL INVESTMENT RATE
                (DOLLARS/YEAR)
    IO      - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    FIOAI   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                INDUSTRY (DIMENSIONLESS)

FIOAI.K=(1-FIOAA.K-FIOAS.K-FIOAC.K)                          56, A
    FIOAI   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                INDUSTRY (DIMENSIONLESS)
    FIOAA   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                AGRICULTURE (DIMENSIONLESS)
    FIOAS   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                SERVICES (DIMENSIONLESS)
    FIOAC   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                CONSUMPTION (DIMENSIONLESS)

FIOAC.K=CLIP(FIOACV.K,FIOACC.K,TIME.K,IET)                   57, A
IET=4000                                                     57.1, C
    FIOAC   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                CONSUMPTION (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    FIOACV  - FIOAC VARIABLE (DIMENSIONLESS)
    FIOACC  - FIOAC CONSTANT (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    IET     - INDUSTRIAL EQUILIBRIUM TIME (YEAR)

FIOACC.K=CLIP(FIOAC2,FIOAC1,TIME.K,PYEAR)                    58, A
FIOAC1=.43                                                   58.1, C
FIOAC2=.43                                                   58.2, C
    FIOACC  - FIOAC CONSTANT (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    FIOAC2  - FIOAC, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    FIOAC1  - FIOAC, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)


FIOACV.K=TABHL(FIOACVT,IOPC.K/IOPCD,0,2,.2)                  59, A
FIOACVT=.3/.32/.34/.36/.38/.43/.73/.77/.81/.82/.83           59.1, T
IOPCD=400                                                    59.2, C
    FIOACV  - FIOAC VARIABLE (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FIOACVT- FIOACV TABLE
    IOPC    - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                PERSON-YEAR)
    IOPCD   - INDUSTRIAL OUTPUT PER CAPITA DESIRED
                (DOLLARS/PERSON-YEAR)

  SERVICE SUBSECTOR

ISOPC.K=CLIP(ISOPC2.K,ISOPC1.K,TIME.K,PYEAR)                 60, A
    ISOPC   - INDICATED SERVICE OUTPUT PER CAPITA
                (DOLLARS/PERSON-YEAR)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    ISOPC2  - ISOPC, VALUE AFTER TIME=PYEAR (DOLLARS/
                PERSON-YEAR)
    ISOPC1  - ISOPC, VALUE BEFORE TIME=PYEAR (DOLLARS/
                PERSON-YEAR)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

ISOPC1.K=TABHL(ISOPC1T,IOPC.K,0,1600,200)                    61, A
ISOPC1T=40/300/640/1000/1220/1450/1650/1800/2000             61.1, T
    ISOPC1  - ISOPC, VALUE BEFORE TIME=PYEAR (DOLLARS/
                PERSON-YEAR)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
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        ISOPC1T- ISOPC1 TABLE
        IOPC    - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                    PERSON-YEAR)

    ISOPC2.K=TABHL(ISOPC2T,IOPC.K,0,1600,200)              62, A
    ISOPC2T=40/300/640/1000/1220/1450/1650/1800/2000       62.1, T
        ISOPC2 - ISOPC, VALUE AFTER TIME=PYEAR (DOLLARS/
                    PERSON-YEAR)
        TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
        ISOPC2T- ISOPC2 TABLE
        IOPC    - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                    PERSON-YEAR)

    FIOAS.K=CLIP(FIOAS2.K,FIOAS1.K,TIME.K,PYEAR)           63, A
        FIOAS   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                    SERVICES (DIMENSIONLESS)
        CLIP    - A FUNCTION SWITCHED DURING THE RUN
        FIOAS2 - FIOAS, VALUE AFTER TIME=PYEAR
                    (DIMENSIONLESS)
        FIOAS1 - FIOAS, VALUE BEFORE TIME=PYEAR
                    (DIMENSIONLESS)
        TIME    - CURRENT TIME IN THE SIMULATION RUN
        PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)


    FIOAS1.K=TABHL(FIOAS1T,SOPC.K/ISOPC.K,0,2,.5)          64, A
    FIOAS1T=.3/.2/.1/.05/0                                 64.1, T
        FIOAS1 - FIOAS, VALUE BEFORE TIME=PYEAR
                    (DIMENSIONLESS)
        TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
        FIOAS1T- FIOAS1 TABLE
        SOPC    - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
                    YEAR)
        ISOPC   - INDICATED SERVICE OUTPUT PER CAPITA
                    (DOLLARS/PERSON-YEAR)

    FIOAS2.K=TABHL(FIOAS2T,SOPC.K/ISOPC.K,0,2,.5)          65, A
    FIOAS2T=.3/.2/.1/.05/0                                 65.1, T
        FIOAS2 - FIOAS, VALUE AFTER TIME=PYEAR
                    (DIMENSIONLESS)
        TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
        FIOAS2T- FIOAS2 TABLE
        SOPC    - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
                    YEAR)
        ISOPC   - INDICATED SERVICE OUTPUT PER CAPITA
                    (DOLLARS/PERSON-YEAR)
    SCIR.KL=(IO.K)(FIOAS.K)                                66, R
        SCIR    - SERVICE CAPITAL INVESTMENT RATE (DOLLARS/
                    YEAR)
        IO      - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
        FIOAS   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                    SERVICES (DIMENSIONLESS)

    SC.K=SC.J+(DT)(SCIR.JK-SCDR.JK)                        67, L
    SC=SCI                                                 67.1, N
    SCI=1.44E11                                            67.2, C
        SC      - SERVICE CAPITAL (DOLLARS)
        DT      - TIME INTERVAL BETWEEN CONSECUTIVE
                    CALCULATIONS (YEARS)
        SCIR    - SERVICE CAPITAL INVESTMENT RATE (DOLLARS/
                    YEAR)
        SCDR    - SERVICE CAPITAL DEPRECIATION RATE (DOLLARS/
                    YEAR)
        SCI     - SERVICE CAPITAL INITIAL (DOLLARS)

    SCDR.KL=SC.K/ALSC.K                                    68, R
        SCDR    - SERVICE CAPITAL DEPRECIATION RATE (DOLLARS/
                    YEAR)
        SC      - SERVICE CAPITAL (DOLLARS)
        ALSC    - AVERAGE LIFETIME OF SERVICE CAPITAL (YEARS)

    ALSC.K=CLIP(ALSC2,ALSC1,TIME.K,PYEAR)                  69, A
    ALSC1=20                                               69.1, C
    ALSC2=20                                               69.2, C
        ALSC    - AVERAGE LIFETIME OF SERVICE CAPITAL (YEARS)
        CLIP    - A FUNCTION SWITCHED DURING THE RUN
        ALSC2   - ALSC, VALUE AFTER TIME=PYEAR (YEARS)
        ALSC1   - ALSC, VALUE BEFORE TIME=PYEAR (YEARS)
        TIME    - CURRENT TIME IN THE SIMULATION RUN
        PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
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SO.K=(SC.K*CUF.K)/(SCOR.K)                              70, A
    SO      - SERVICE OUTPUT (DOLLARS/YEAR)
    SC      - SERVICE CAPITAL (DOLLARS)
    CUF     - CAPITAL UTILIZATION FRACTION
                (DIMENSIONLESS)
    SCOR    - SERVICE CAPITAL-OUTPUT RATIO (YEARS)

SOPC.K=SO.K/POP.K                                       71, A
    SOPC    - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
                YEAR)
    SO      - SERVICE OUTPUT (DOLLARS/YEAR)
    POP     - POPULATION (PERSONS)

SCOR.K=CLIP(SCOR2,SCOR1,TIME.K,PYEAR)                   72, A
SCOR1=1                                                 72.1, C
SCOR2=1                                                 72.2, C
    SCOR    - SERVICE CAPITAL-OUTPUT RATIO (YEARS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    SCOR2   - SCOR, VALUE AFTER TIME=PYEAR (YEAR)
    SCOR1   - SCOR, VALUE BEFORE TIME=PYEAR (YEAR)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
  JOB SUBSECTOR

J.K=PJIS.K+PJAS.K+PJSS.K                                73, A
    J       - JOBS (PERSONS)
    PJIS    - POTENTIAL JOBS IN INDUSTRIAL SECTOR
                (PERSONS)
    PJAS    - POTENTIAL JOBS IN AGRICULTURAL SECTOR
                (PERSONS)
    PJSS    - POTENTIAL JOBS IN SERVICE SECTOR (PERSONS)

PJIS.K=(IC.K)(JPICU.K)                                  74, A
    PJIS    - POTENTIAL JOBS IN INDUSTRIAL SECTOR
                (PERSONS)
    IC      - INDUSTRIAL CAPITAL (DOLLARS)
    JPICU   - JOBS PER INDUSTRIAL CAPITAL UNIT (PERSONS/
                DOLLAR)

JPICU.K=(TABHL(JPICUT,IOPC.K,50,800,150))*1E-3          75, A
JPICUT=.37/.18/.12/.09/.07/.06                          75.1, T
    JPICU   - JOBS PER INDUSTRIAL CAPITAL UNIT (PERSONS/
                DOLLAR)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    JPICUT  - JPICU TABLE
    IOPC    - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                PERSON-YEAR)

PJSS.K=(SC.K)(JPSCU.K)                                  76, A
    PJSS    - POTENTIAL JOBS IN SERVICE SECTOR (PERSONS)
    SC      - SERVICE CAPITAL (DOLLARS)
    JPSCU   - JOBS PER SERVICE CAPITAL UNIT (PERSONS/
                DOLLAR)


JPSCU.K=(TABHL(JPSCUT,SOPC.K,50,800,150))*1E-3          77, A
JPSCUT=1.1/.6/.35/.2/.15/.15                            77.1, T
    JPSCU   - JOBS PER SERVICE CAPITAL UNIT (PERSONS/
                DOLLAR)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    JPSCUT  - JPSCU TABLE
    SOPC    - SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-
                YEAR)

PJAS.K=(JPH.K)(AL.K)                                    78, A
    PJAS    - POTENTIAL JOBS IN AGRICULTURAL SECTOR
                (PERSONS)
    JPH     - JOBS PER HECTARE (PERSONS/HECTARE)
    AL      - ARABLE LAND (HECTARES)


JPH.K=TABHL(JPHT,AIPH.K,2,30,4)                         79, A
JPHT=2/.5/.4/.3/.27/.24/.2/.2                           79.1, T
    JPH     - JOBS PER HECTARE (PERSONS/HECTARE)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    JPHT    - JPH TABLE
    AIPH    - AGRICULTURAL INPUTS PER HECTARE (DOLLARS/
                HECTARE-YEAR)

LF.K=(P2.K+P3.K)*LFPF                                   80, A
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LFPF=.75                                                   80.1, C
    LF      - LABOR FORCE (PERSONS)
    P2      - POPULATION, AGES 15-44 (PERSONS)
    P3      - POPULATION, AGES 45-64 (PERSONS)
    LFPF    - LABOR FORCE PARTICIPATION FRACTION
                (DIMENSIONLESS)

LUF.K=J.K/LF.K                                             81, A
    LUF     - LABOR UTILIZATION FRACTION (DIMENSIONLESS)
    J       - JOBS (PERSONS)
    LF      - LABOR FORCE (PERSONS)

LUFD.K=SMOOTH(LUF.K,LUFDT)                                 82, A
LUFDT=2                                                    82.1, C
    LUFD    - LABOR UTILIZATION FRACTION DELAYED
                (DIMENSIONLESS)
    SMOOTH  - FIRST-ORDER EXPONENTIAL INFORMATION DELAY
    LUF     - LABOR UTILIZATION FRACTION (DIMENSIONLESS)
    LUFDT   - LABOR UTILIZATION FRACTION DELAY TIME
                (YEARS)

CUF.K=TABHL(CUFT,LUFD.K,1,11,2)                            83, A
CUF=1                                                      83.1, N
CUFT=1/.9/.7/.3/.1/.1                                      83.2, T
    CUF     - CAPITAL UTILIZATION FRACTION
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    CUFT    - CUF TABLE
    LUFD    - LABOR UTILIZATION FRACTION DELAYED
                (DIMENSIONLESS)


  AGRICULTURAL SECTOR
  LOOP 1: FOOD FROM INVESTMENT IN LAND DEVELOPMENT

LFC.K=AL.K/PALT                                            84, A
PALT=3.2E9                                                 84.1, C
    LFC     - LAND FRACTION CULTIVATED (DIMENSIONLESS)
    AL      - ARABLE LAND (HECTARES)
    PALT    - POTENTIALLY ARABLE LAND TOTAL (HECTARES)

AL.K=AL.J+(DT)(LDR.JK-LER.JK-LRUI.JK)                      85, L
AL=ALI                                                     85.1, N
ALI=.9E9                                                   85.2, C
    AL      - ARABLE LAND (HECTARES)
    DT      - TIME INTERVAL BETWEEN CONSECUTIVE
                CALCULATIONS (YEARS)
    LDR     - LAND DEVELOPMENT RATE (HECTARES/YEAR)
    LER     - LAND EROSION RATE (HECTARES/YEAR)
    LRUI    - LAND REMOVAL FOR URBAN-INDUSTRIAL USE
                (HECTARES/YEAR)
    ALI     - ARABLE LAND INITIAL (HECTARES)

PAL.K=PAL.J+(DT)(-LDR.JK)                                  86, L
PAL=PALI                                                   86.1, N
PALI=2.3E9                                                 86.2, C
    PAL     - POTENTIALLY ARABLE LAND (HECTARES)
    DT      - TIME INTERVAL BETWEEN CONSECUTIVE
                CALCULATIONS (YEARS)
    LDR     - LAND DEVELOPMENT RATE (HECTARES/YEAR)
    PALI    - POTENTIALLY ARABLE LAND INITIAL (HECTARES)

F.K=LY.K*AL.K*LFH*(1-PL)                                   87, A
LFH=.7                                                     87.1, C
PL=.1                                                      87.2, C
    F       - FOOD (VEGETABLE-EQUIVALENT KILOGRAMS/YEAR)
    LY      - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
                HECTARE-YEAR)
    AL      - ARABLE LAND (HECTARES)
    LFH     - LAND FRACTION HARVESTED (DIMENSIONLESS)
    PL      - PROCESSING LOSS (DIMENSIONLESS)

FPC.K=F.K/POP.K                                            88, A
    FPC     - FOOD PER CAPITA (VEGETABLE-EQUIVALENT
                KILOGRAMS/PERSON-YEAR)
    F       - FOOD (VEGETABLE-EQUIVALENT KILOGRAMS/YEAR)
    POP     - POPULATION (PERSONS)
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IFPC.K=CLIP(IFPC2.K,IFPC1.K,TIME.K,PYEAR)              89, A
    IFPC    - INDICATED FOOD PER CAPITA (VEGETABLE-
                EQUIVALENT KILOGRAMS/PERSON-YEAR)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    IFPC2   - IFPC, VALUE AFTER TIME=PYEAR (VEGETABLE-
                EQUIVALENT KILOGRAMS/PERSON-YEAR)
    IFPC1   - IFPC, VALUE BEFORE TIME=PYEAR (VEGETABLE-
                EQUIVALENT KILOGRAMS/PERSON-YEAR)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)


IFPC1.K=TABHL(IFPC1T,IOPC.K,0,1600,200)                90, A
IFPC1T=230/480/690/850/970/1070/1150/1210/1250         90.1, T
    IFPC1   - IFPC, VALUE BEFORE TIME=PYEAR (VEGETABLE-
                EQUIVALENT KILOGRAMS/PERSON-YEAR)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    IFPC1T  - IFPC1 TABLE
    IOPC    - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                PERSON-YEAR)

IFPC2.K=TABHL(IFPC2T,IOPC.K,0,1600,200)                91, A
IFPC2T=230/480/690/850/970/1070/1150/1210/1250         91.1, T
    IFPC2   - IFPC, VALUE AFTER TIME=PYEAR (VEGETABLE-
                EQUIVALENT KILOGRAMS/PERSON-YEAR)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    IFPC2T  - IFPC2 TABLE
    IOPC    - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                PERSON-YEAR)

TAI.K=IO.K*FIOAA.K                                     92, A
    TAI     - TOTAL AGRICULTURAL INVESTMENT (DOLLARS/
                YEAR)
    IO      - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    FIOAA   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                AGRICULTURE (DIMENSIONLESS)

FIOAA.K=CLIP(FIOAA2.K,FIOAA1.K,TIME.K,PYEAR)           93, A
    FIOAA   - FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO
                AGRICULTURE (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    FIOAA2  - FIOAA, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    FIOAA1  - FIOAA, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

FIOAA1.K=TABHL(FIOAA1T,FPC.K/IFPC.K,0,2.5,.5)          94, A
FIOAA1T=.4/.2/.1/.025/0/0                              94.1, T
    FIOAA1  - FIOAA, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FIOAA1T- FIOAA1 TABLE
    FPC     - FOOD PER CAPITA (VEGETABLE-EQUIVALENT
                KILOGRAMS/PERSON-YEAR)
    IFPC    - INDICATED FOOD PER CAPITA (VEGETABLE-
                EQUIVALENT KILOGRAMS/PERSON-YEAR)

FIOAA2.K=TABHL(FIOAA2T,FPC.K/IFPC.K,0,2.5,.5)          95, A
FIOAA2T=.4/.2/.1/.025/0/0                              95.1, T
    FIOAA2  - FIOAA, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FIOAA2T- FIOAA2 TABLE
    FPC     - FOOD PER CAPITA (VEGETABLE-EQUIVALENT
                KILOGRAMS/PERSON-YEAR)
    IFPC    - INDICATED FOOD PER CAPITA (VEGETABLE-
                EQUIVALENT KILOGRAMS/PERSON-YEAR)


LDR.KL=TAI.K*FIALD.K/DCPH.K                            96, R
    LDR     - LAND DEVELOPMENT RATE (HECTARES/YEAR)
    TAI     - TOTAL AGRICULTURAL INVESTMENT (DOLLARS/
                YEAR)
    FIALD   - FRACTION OF INPUTS ALLOCATED TO LAND
                DEVELOPMENT (DIMENSIONLESS)
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DCPH    - DEVELOPMENT COST PER HECTARE (DOLLARS/
          HECTARE)

DCPH.K=TABHL(DCPHT,PAL.K/PALT,0,1,.1)                  97, A
DCPHT=1E5/7400/5200/3500/2400/1500/750/300/150/75/     97.1, T
  50
    DCPH    - DEVELOPMENT COST PER HECTARE (DOLLARS/
              HECTARE)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    DCPHT   - DCPH TABLE
    PAL     - POTENTIALLY ARABLE LAND (HECTARES)
    PALT    - POTENTIALLY ARABLE LAND TOTAL (HECTARES)

  LOOP 2: FOOD FROM INVESTMENT IN AGRICULTURAL
  INPUTS

CAI.K=TAI.K*(1-FIALD.K)                                98, A
    CAI     - CURRENT AGRICULTURAL INPUTS (DOLLARS/YEAR)
    TAI     - TOTAL AGRICULTURAL INVESTMENT (DOLLARS/
              YEAR)
    FIALD   - FRACTION OF INPUTS ALLOCATED TO LAND
              DEVELOPMENT (DIMENSIONLESS)

AI.K=SMOOTH(CAI.K,ALAI.K)                              99, A
AI=5E9                                                 99.1, N
    AI      - AGRICULTURAL INPUTS (DOLLARS/YEAR)
    SMOOTH  - FIRST-ORDER EXPONENTIAL INFORMATION DELAY
    CAI     - CURRENT AGRICULTURAL INPUTS (DOLLARS/YEAR)
    ALAI    - AVERAGE LIFETIME OF AGRICULTURAL INPUTS
              (YEARS)

ALAI.K=CLIP(ALAI2,ALAI1,TIME.K,PYEAR)                  100, A
ALAI1=2                                                100.1, C
ALAI2=2                                                100.2, C
    ALAI    - AVERAGE LIFETIME OF AGRICULTURAL INPUTS
              (YEARS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    ALAI2   - ALAI, VALUE AFTER TIME=PYEAR (YEARS)
    ALAI1   - ALAI, VALUE BEFORE TIME=PYEAR (YEARS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

AIPH.K=AI.K*(1-FALM.K)/AL.K                            101, A
    AIPH    - AGRICULTURAL INPUTS PER HECTARE (DOLLARS/
              HECTARE-YEAR)
    AI      - AGRICULTURAL INPUTS (DOLLARS/YEAR)
    FALM    - FRACTION OF INPUTS ALLOCATED TO LAND
              MAINTENANCE (DIMENSIONLESS)
    AL      - ARABLE LAND (HECTARES)


LYMC.K=TABHL(LYMCT,AIPH.K,0,1000,40)                   102, A
LYMCT=1/3/3.8/4.4/4.9/5.4/5.7/6/6.3/6.6/6.9/7.2/       102.1, T
  7.4/7.6/7.8/8/8.2/8.4/8.6/8.8/9/9.2/9.4/9.6/9.8/
  10
    LYMC    - LAND YIELD MULTIPLIER FROM CAPITAL
              (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LYMCT   - LYMC TABLE
    AIPH    - AGRICULTURAL INPUTS PER HECTARE (DOLLARS/
              HECTARE-YEAR)

LY.K=LYF.K*LFERT.K*LYMC.K*LYMAP.K                      103, A
    LY      - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
              HECTARE-YEAR)
    LYF     - LAND YIELD FACTOR (DIMENSIONLESS)
    LFERT   - LAND FERTILITY (VEGETABLE-EQUIVALENT
              KILOGRAMS/HECTARE-YEAR)
    LYMC    - LAND YIELD MULTIPLIER FROM CAPITAL
              (DIMENSIONLESS)
    LYMAP   - LAND YIELD MULTIPLIER FROM AIR POLLUTION
              (DIMENSIONLESS)

LYF.K=CLIP(LYF2,LYF1,TIME.K,PYEAR)                     104, A
LYF1=1                                                 104.1, C
LYF2=1                                                 104.2, C
    LYF     - LAND YIELD FACTOR (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    LYF2    - LYF, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)
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    LYF1    - LYF, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

LYMAP.K=CLIP(LYMAP2.K,LYMAP1.K,TIME.K,PYEAR)          105, A
    LYMAP   - LAND YIELD MULTIPLIER FROM AIR POLLUTION
                (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    LYMAP2  - LYMAP, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    LYMAP1  - LYMAP, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

LYMAP1.K=TABHL(LYMAP1T,IO.K/IO70,0,30,10)             106, A
LYMAP1T=1/1/.7/.4                                      106.1, T
    LYMAP1  - LYMAP, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LYMAP1T- LYMAP1 TABLE
    IO      - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    IO70    - INDUSTRIAL OUTPUT IN 1970 (DOLLARS/YEAR)


LYMAP2.K=TABHL(LYMAP2T,IO.K/IO70,0,30,10)             107, A
LYMAP2T=1/1/.7/.4                                      107.1, T
IO70=7.9E11                                            107.2, C
    LYMAP2  - LYMAP, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LYMAP2T- LYMAP2 TABLE
    IO      - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    IO70    - INDUSTRIAL OUTPUT IN 1970 (DOLLARS/YEAR)

  LOOPS 1 & 2: THE INVESTMENT ALLOCATION DECISION

FIALD.K=TABHL(FIALDT,(MPLD.K/MPAI.K),0,2,.25)         108, A
FIALDT=0/.05/.15/.30/.50/.70/.85/.95/1                 108.1, T
    FIALD   - FRACTION OF INPUTS ALLOCATED TO LAND
                DEVELOPMENT (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FIALDT  - FIALD TABLE
    MPLD    - MARGINAL PRODUCTIVITY OF LAND DEVELOPMENT
                (VEGETABLE-EQUIVALENT KILOGRAMS/DOLLAR)
    MPAI    - MARGINAL PRODUCTIVITY OF AGRICULTURAL
                INPUTS (VEGETABLE EQUIVALENT KILOGRAMS/
                DOLLAR)

MPLD.K=LY.K/(DCPH.K*SD)                                109, A
SD=.07                                                 109.1, C
    MPLD    - MARGINAL PRODUCTIVITY OF LAND DEVELOPMENT
                (VEGETABLE-EQUIVALENT KILOGRAMS/DOLLAR)
    LY      - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
                HECTARE-YEAR)
    DCPH    - DEVELOPMENT COST PER HECTARE (DOLLARS/
                HECTARE)
    SD      - SOCIAL DISCOUNT (1/YEAR)

MPAI.K=ALAI.K*LY.K*MLYMC.K/LYMC.K                      110, A
    MPAI    - MARGINAL PRODUCTIVITY OF AGRICULTURAL
                INPUTS (VEGETABLE EQUIVALENT KILOGRAMS/
                DOLLAR)
    ALAI    - AVERAGE LIFETIME OF AGRICULTURAL INPUTS
                (YEARS)
    LY      - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
                HECTARE-YEAR)
    MLYMC   - MARGINAL LAND YIELD MULTIPLIER FROM CAPITAL
                (HECTARES/DOLLAR)
    LYMC    - LAND YIELD MULTIPLIER FROM CAPITAL
                (DIMENSIONLESS)

MLYMC.K=TABHL(MLYMCT,AIPH.K,0,600,40)                  111, A
MLYMCT=.075/.03/.015/.011/.009/.008/.007/.006/.005/    111.1, T
  .005/.005/.005/.005/.005/.005/.005
    MLYMC   - MARGINAL LAND YIELD MULTIPLIER FROM CAPITAL
                (HECTARES/DOLLAR)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
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    MLYMCT - MLYMC TABLE
    AIPH   - AGRICULTURAL INPUTS PER HECTARE (DOLLARS/
               HECTARE-YEAR)


  LOOP 3: LAND EROSION AND URBAN-INDUSTRIAL USE

ALL.K=ALLN*LLMY.K                                         112, A
ALLN=6000                                                 112.1, C
    ALL    - AVERAGE LIFE OF LAND (YEARS)
    ALLN   - AVERAGE LIFE OF LAND NORMAL (YEARS)
    LLMY   - LAND LIFE MULTIPLIER FROM YIELD
               (DIMENSIONLESS)

LLMY.K=CLIP(LLMY2.K,LLMY1.K,TIME.K,PYEAR)                 113, A
    LLMY   - LAND LIFE MULTIPLIER FROM YIELD
               (DIMENSIONLESS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    LLMY2  - LLMY, VALUE AFTER TIME=PYEAR
               (DIMENSIONLESS)
    LLMY1  - LLMY, VALUE BEFORE TIME=PYEAR
               (DIMENSIONLESS)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

LLMY1.K=TABHL(LLMY1T,LY.K/ILF,0,9,1)                      114, A
LLMY1T=1.2/1/.63/.36/.16/.055/.04/.025/.015/.01           114.1, T
    LLMY1  - LLMY, VALUE BEFORE TIME=PYEAR
               (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LLMY1T - LLMY1 TABLE
    LY     - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
               HECTARE-YEAR)
    ILF    - INHERENT LAND FERTILITY (VEGETABLE-
               EQUIVALENT KILOGRAMS/HECTARE-YEAR)
LLMY2.K=TABHL(LLMY2T,LY.K/ILF,0,9,1)                      115, A
LLMY2T=1.2/1/.63/.36/.16/.055/.04/.025/.015/.01           115.1, T
    LLMY2  - LLMY, VALUE AFTER TIME=PYEAR
               (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LLMY2T - LLMY2 TABLE
    LY     - LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/
               HECTARE-YEAR)
    ILF    - INHERENT LAND FERTILITY (VEGETABLE-
               EQUIVALENT KILOGRAMS/HECTARE-YEAR)

LER.KL=AL.K/ALL.K                                         116, R
    LER    - LAND EROSION RATE (HECTARES/YEAR)
    AL     - ARABLE LAND (HECTARES)
    ALL    - AVERAGE LIFE OF LAND (YEARS)

UILPC.K=TABHL(UILPCT,IOPC.K,0,1600,200)                   117, A
UILPCT=.005/.008/.015/.025/.04/.055/.07/.08/.09           117.1, T
    UILPC  - URBAN-INDUSTRIAL LAND PER CAPITA (HECTARES/
               PERSON)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    UILPCT - UILPC TABLE
    IOPC   - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
               PERSON-YEAR)


UILR.K=UILPC.K*POP.K                                      118, A
    UILR   - URBAN-INDUSTRIAL LAND REQUIRED (HECTARES)
    UILPC  - URBAN-INDUSTRIAL LAND PER CAPITA (HECTARES/
               PERSON)
    POP    - POPULATION (PERSONS)

LRUI.KL=MAX(0,(UILR.K-UIL.K)/UILDT)                       119, R
UILDT=10                                                  119.1, C
    LRUI   - LAND REMOVAL FOR URBAN-INDUSTRIAL USE
               (HECTARES/YEAR)
    UILR   - URBAN-INDUSTRIAL LAND REQUIRED (HECTARES)
    UIL    - URBAN-INDUSTRIAL LAND (HECTARES)
    UILDT  - URBAN-INDUSTRIAL LAND DEVELOPMENT TIME
               (YEARS)

UIL.K=UIL.J+(DT)(LRUI.JK)                                 120, L
UIL=UILI                                                  120.1, N
UILI=8.2E6                                                120.2, C
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    UIL     - URBAN-INDUSTRIAL LAND (HECTARES)
    DT      - TIME INTERVAL BETWEEN CONSECUTIVE
                CALCULATIONS (YEARS)
    LRUI    - LAND REMOVAL FOR URBAN-INDUSTRIAL USE
                (HECTARES/YEAR)
    UILI    - URBAN-INDUSTRIAL LAND INITIAL (HECTARES)

  LOOP 4: LAND FERTILITY DEGRADATION

LFERT.K=LFERT.J+(DT)(LFR.JK-LFD.JK)                     121, L
LFERT=LFERTI                                            121.1, N
LFERTI=600                                              121.2, C
    LFERT   - LAND FERTILITY (VEGETABLE-EQUIVALENT
                KILOGRAMS/HECTARE-YEAR)
    DT      - TIME INTERVAL BETWEEN CONSECUTIVE
                CALCULATIONS (YEARS)
    LFR     - LAND FERTILITY REGENERATION (VEGETABLE-
                EQUIVALENT KILOGRAMS/HECTARE-YEAR-YEAR)
    LFD     - LAND FERTILITY DEGRADATION (VEGETABLE-
                EQUIVALENT KILOGRAMS/HECTARE-YEAR-YEAR)
    LFERTI  - LAND FERTILITY INITIAL (VEGETABLE-
                EQUIVALENT KILOGRAMS/HECTARE-YEAR)

LFDR.K=TABHL(LFDRT,PPOLX.K,0,30,10)                     122, A
LFDRT=0/.1/.3/.5                                        122.1, T
    LFDR    - LAND FERTILITY DEGRADATION RATE (1/YEAR)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LFDRT   - LFDR TABLE
    PPOLX   - INDEX OF PERSISTENT POLLUTION
                (DIMENSIONLESS)

LFD.KL=LFERT.K*LFDR.K                                   123, R
    LFD     - LAND FERTILITY DEGRADATION (VEGETABLE-
                EQUIVALENT KILOGRAMS/HECTARE-YEAR-YEAR)
    LFERT   - LAND FERTILITY (VEGETABLE-EQUIVALENT
                KILOGRAMS/HECTARE-YEAR)
    LFDR    - LAND FERTILITY DEGRADATION RATE (1/YEAR)


  LOOP 5: LAND FERTILITY REGENERATION

LFR.KL=(ILF-LFERT.K)/LFRT.K                             124, R
ILF=600                                                 124.1, C
    LFR     - LAND FERTILITY REGENERATION (VEGETABLE-
                EQUIVALENT KILOGRAMS/HECTARE-YEAR-YEAR)
    ILF     - INHERENT LAND FERTILITY (VEGETABLE-
                EQUIVALENT KILOGRAMS/HECTARE-YEAR)
    LFERT   - LAND FERTILITY (VEGETABLE-EQUIVALENT
                KILOGRAMS/HECTARE-YEAR)
    LFRT    - LAND FERTILITY REGENERATION TIME (YEARS)

LFRT.K=TABHL(LFRTT,FALM.K,0,.10,.02)                    125, A
LFRTT=20/13/8/4/2/2                                     125.1, T
    LFRT    - LAND FERTILITY REGENERATION TIME (YEARS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    LFRTT   - LFRT TABLE
    FALM    - FRACTION OF INPUTS ALLOCATED TO LAND
                MAINTENANCE (DIMENSIONLESS)

  LOOP 6: DISCONTINUING LAND MAINTENANCE

FALM.K=TABHL(FALMT,PFR.K,0,4,1)                         126, A
FALMT=0/.04/.07/.09/.1                                  126.1, T
    FALM    - FRACTION OF INPUTS ALLOCATED TO LAND
                MAINTENANCE (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FALMT   - FALM TABLE
    PFR     - PERCEIVED FOOD RATIO (DIMENSIONLESS)

FR.K=FPC.K/SFPC                                         127, A
SFPC=230                                                127.1, C
    FR      - FOOD RATIO (DIMENSIONLESS)
    FPC     - FOOD PER CAPITA (VEGETABLE-EQUIVALENT
                KILOGRAMS/PERSON-YEAR)
    SFPC    - SUBSISTENCE FOOD PER CAPITA (VEGETABLE-
                EQUIVALENT KILOGRAMS/PERSON-YEAR)

PFR.K=SMOOTH(FR.K,FSPD)                                 128, A
PFR=1                                                   128.1, N
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FSPD=2                                                  128.2, C
    PFR     - PERCEIVED FOOD RATIO (DIMENSIONLESS)
    SMOOTH  - FIRST-ORDER EXPONENTIAL INFORMATION DELAY
    FR      - FOOD RATIO (DIMENSIONLESS)
    FSPD    - FOOD SHORTAGE PERCEPTION DELAY (YEARS)


  NONRENEWABLE RESOURCE SECTOR

NR.K=NR.J+(DT)(-NRUR.JK)                                129, L
NR=NRI                                                  129.1, N
NRI=1E12                                                129.2, C
    NR      - NONRENEWABLE RESOURCES (RESOURCE UNITS)
    DT      - TIME INTERVAL BETWEEN CONSECUTIVE
                CALCULATIONS (YEARS)
    NRUR    - NONRENEWABLE RESOURCE USAGE RATE (RESOURCE
                UNITS/YEAR)
    NRI     - NONRENEWABLE RESOURCES INITIAL (RESOURCE
                UNITS)

NRUR.KL=(POP.K)(PCRUM.K)(NRUF.K)                        130, R
    NRUR    - NONRENEWABLE RESOURCE USAGE RATE (RESOURCE
                UNITS/YEAR)
    POP     - POPULATION (PERSONS)
    PCRUM   - PER CAPITA RESOURCE USAGE MULTIPLIER
                (RESOURCE UNITS/PERSON-YEAR)
    NRUF    - NONRENEWABLE RESOURCE USAGE FACTOR
                (DIMENSIONLESS)

NRUF.K=CLIP(NRUF2,NRUF1,TIME.K,PYEAR)                   131, A
NRUF1=1                                                 131.1, C
NRUF2=1                                                 131.2, C
    NRUF    - NONRENEWABLE RESOURCE USAGE FACTOR
                (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    NRUF2   - NRUF, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    NRUF1   - NRUF, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

PCRUM.K=TABHL(PCRUMT,IOPC.K,0,1600,200)                 132, A
PCRUMT=0/.85/2.6/4.4/5.4/6.2/6.8/7/7                    132.1, T
    PCRUM   - PER CAPITA RESOURCE USAGE MULTIPLIER
                (RESOURCE UNITS/PERSON-YEAR)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    PCRUMT  - PCRUM TABLE
    IOPC    - INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/
                PERSON-YEAR)
NRFR.K=NR.K/NRI                                         133, A
    NRFR    - NONRENEWABLE RESOURCE FRACTION REMAINING
                (DIMENSIONLESS)
    NR      - NONRENEWABLE RESOURCES (RESOURCE UNITS)
    NRI     - NONRENEWABLE RESOURCES INITIAL (RESOURCE
                UNITS)


FCAOR.K=CLIP(FCAOR2.K,FCAOR1.K,TIME.K,PYEAR)            134, A
    FCAOR   - FRACTION OF CAPITAL ALLOCATED TO OBTAINING
                RESOURCES (DIMENSIONLESS)
    CLIP    - A FUNCTION SWITCHED DURING THE RUN
    FCAOR2  - FCAOR, VALUE AFTER TIME=PYEAR
                (DIMENSIONLESS)
    FCAOR1  - FCAOR, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TIME    - CURRENT TIME IN THE SIMULATION RUN
    PYEAR   - YEAR NEW POLICY IS IMPLEMENTED (YEAR)

FCAOR1.K=TABHL(FCAOR1T,NRFR.K,0,1,.1)                   135, A
FCAOR1T=1/.9/.7/.5/.2/.1/.05/.05/.05/.05/.05            135.1, T
    FCAOR1  - FCAOR, VALUE BEFORE TIME=PYEAR
                (DIMENSIONLESS)
    TABHL   - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FCAOR1T- FCAOR1 TABLE
    NRFR    - NONRENEWABLE RESOURCE FRACTION REMAINING
                (DIMENSIONLESS)

FCAOR2.K=TABHL(FCAOR2T,NRFR.K,0,1,.1)                   136, A
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FCAOR2T=1/.9/.7/.5/.2/.1/.05/.05/.05/.05/.05          136.1, T
    FCAOR2 - FCAOR, VALUE AFTER TIME=PYEAR
               (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    FCAOR2T- FCAOR2 TABLE
    NRFR   - NONRENEWABLE RESOURCE FRACTION REMAINING
               (DIMENSIONLESS)

  PERSISTENT POLLUTION SECTOR

PPGR.KL=(PPGIO.K+PPGAO.K)*(PPGF.K)                    137, R
    PPGR   - PERSISTENT POLLUTION GENERATION RATE
               (POLLUTION UNITS/YEAR)
    PPGIO  - PERSISTENT POLLUTION GENERATED BY
               INDUSTRIAL OUTPUT (POLLUTION UNITS/YEAR)
    PPGAO  - PERSISTENT POLLUTION GENERATED BY
               AGRICULTURAL OUTPUT (POLLUTIONUNITS/YEAR)
    PPGF   - PERSISTENT POLLUTION GENERATION FACTOR
               (DIMENSIONLESS)

PPGF.K=CLIP(PPGF2,PPGF1,TIME.K,PYEAR)                 138, A
PPGF1=1                                               138.1, C
PPGF2=1                                               138.2, C
    PPGF   - PERSISTENT POLLUTION GENERATION FACTOR
               (DIMENSIONLESS)
    CLIP   - A FUNCTION SWITCHED DURING THE RUN
    PPGF2  - PPGF, VALUE AFTER TIME=PYEAR
               (DIMENSIONLESS)
    PPGF1  - PPGF, VALUE BEFORE TIME=PYEAR
               (DIMENSIONLESS)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)


PPGIO.K=PCRUM.K*POP.K*FRPM*IMEF*IMTI                  139, A
FRPM=.02                                              139.1, C
IMEF=.1                                               139.2, C
IMTI=10                                               139.3, C
    PPGIO  - PERSISTENT POLLUTION GENERATED BY
               INDUSTRIAL OUTPUT (POLLUTION UNITS/YEAR)
    PCRUM  - PER CAPITA RESOURCE USAGE MULTIPLIER
               (RESOURCE UNITS/PERSON-YEAR)
    POP    - POPULATION (PERSONS)
    FRPM   - FRACTION OF RESOURCES AS PERSISTENT
               MATERIALS (DIMENSIONLESS)
    IMEF   - INDUSTRIAL MATERIALS EMISSION FACTOR
               (DIMENSIONLESS)
    IMTI   - INDUSTRIAL MATERIALS TOXICITY INDEX
               (POLLUTION UNITS/RESOURCE UNIT)

PPGAO.K=AIPH.K*AL.K*FIPM*AMTI                         140, A
FIPM=.001                                             140.1, C
AMTI=1                                                140.2, C
    PPGAO  - PERSISTENT POLLUTION GENERATED BY
               AGRICULTURAL OUTPUT (POLLUTIONUNITS/YEAR)
    AIPH   - AGRICULTURAL INPUTS PER HECTARE (DOLLARS/
               HECTARE-YEAR)
    AL     - ARABLE LAND (HECTARES)
    FIPM   - FRACTION OF INPUTS AS PERSISTENT MATERIALS
               (DIMENSIONLESS)
    AMTI   - AGRICULTURAL MATERIALS TOXICITY INDEX
               (POLLUTION UNITS/DOLLAR)

PPAPR.KL=DELAY3(PPGR.JK,PPTD)                         141, R
PPTD=20                                               141.1, C
    PPAPR  - PERSISTENT POLLUTION APPEARANCE RATE
               (POLLUTION UNITS/YEAR)
    DELAY3 - THIRD-ORDER EXPONENTIAL MATERIAL DELAY
    PPGR   - PERSISTENT POLLUTION GENERATION RATE
               (POLLUTION UNITS/YEAR)
    PPTD   - PERSISTENT POLLUTION TRANSMISSION DELAY
               (YEARS)

PPOL.K=PPOL.J+(DT)(PPAPR.JK-PPASR.JK)                 142, L
PPOL=2.5E7                                            142.1, N
    PPOL   - PERSISTENT POLLUTION (POLLUTION UNITS)
    DT     - TIME INTERVAL BETWEEN CONSECUTIVE
               CALCULATIONS (YEARS)
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    PPAPR  - PERSISTENT POLLUTION APPEARANCE RATE
               (POLLUTION UNITS/YEAR)
    PPASR  - PERSISTENT POLLUTION ASSIMILATION RATE
               (POLLUTION UNITS/YEAR)

PPOLX.K=PPOL.K/PPOL70                                      143, A
PPOL70=1.36E8                                              143.1, C
    PPOLX  - INDEX OF PERSISTENT POLLUTION
               (DIMENSIONLESS)
    PPOL   - PERSISTENT POLLUTION (POLLUTION UNITS)
    PPOL70 - PERSISTENT POLLUTION IN 1970 (POLLUTION
               UNITS)


PPASR.KL=PPOL.K/(AHL.K*1.4)                                144, R
    PPASR  - PERSISTENT POLLUTION ASSIMILATION RATE
               (POLLUTION UNITS/YEAR)
    PPOL   - PERSISTENT POLLUTION (POLLUTION UNITS)
    AHL    - ASSIMILATION HALF-LIFE (YEARS)

AHLM.K=TABHL(AHLMT,PPOLX.K,1,1001,250)                     145, A
AHLMT=1/11/21/31/41                                        145.1, T
    AHLM   - ASSIMILATION HALF-LIFE MULTIPLIER
               (DIMENSIONLESS)
    TABHL  - A FUNCTION WITH VALUES SPECIFIED BY A TABLE
    AHLMT  - AHLM TABLE
    PPOLX  - INDEX OF PERSISTENT POLLUTION
               (DIMENSIONLESS)

AHL.K=AHL70*AHLM.K                                         146, A
AHL70=1.5                                                  146.1, C
    AHL    - ASSIMILATION HALF-LIFE (YEARS)
    AHL70  - ASSIMILATION HALF-LIFE IN 1970 (YEARS)
    AHLM   - ASSIMILATION HALF-LIFE MULTIPLIER
               (DIMENSIONLESS)

  SUPPLEMENTARY EQUATIONS

FOA.K=(.22)(F.K)/(.22*F.K+SO.K+IO.K)                       147, S
    FOA    - FRACTION OF OUTPUT IN AGRICULTURE
               (DIMENSIONLESS)
    F      - FOOD (VEGETABLE-EQUIVALENT KILOGRAMS/YEAR)
    SO     - SERVICE OUTPUT (DOLLARS/YEAR)
    IO     - INDUSTRIAL OUTPUT (DOLLARS/YEAR)

FOI.K=IO.K/(.22*F.K+SO.K+IO.K)                             148, S
    FOI    - FRACTION OF OUTPUT IN INDUSTRY
               (DIMENSIONLESS)
    IO     - INDUSTRIAL OUTPUT (DOLLARS/YEAR)
    F      - FOOD (VEGETABLE-EQUIVALENT KILOGRAMS/YEAR)
    SO     - SERVICE OUTPUT (DOLLARS/YEAR)

FOS.K=SO.K/(.22*F.K+SO.K+IO.K)                             149, S
    FOS    - FRACTION OF OUTPUT IN SERVICES
               (DIMENSIONLESS)
    SO     - SERVICE OUTPUT (DOLLARS/YEAR)
    F      - FOOD (VEGETABLE-EQUIVALENT KILOGRAMS/YEAR)
    IO     - INDUSTRIAL OUTPUT (DOLLARS/YEAR)

  CONTROL CARDS FOR SIMULATION

PYEAR=1975                                                 150.1, C
TIME=1900                                                  150.2, N
    PYEAR  - YEAR NEW POLICY IS IMPLEMENTED (YEAR)
    TIME   - CURRENT TIME IN THE SIMULATION RUN
PLTPER.K=STEP(PLP,PLIT)                                    151, A
PLP=5                                                      151.1, C
PLIT=1900                                                  151.2, C
PRP=0                                                      151.3, C
    PLTPER - INTERVAL BETWEEN PLOTTED OUTPUT POINTS
               (YEARS)
    PLP    - PLOTTING PERIOD (YEARS)
    PLIT   - INITIATION OF PLOTTED OUTPUT (YEAR)
    PRP    - PRINTING PERIOD (YEARS)

PRTPER.K=STEP(PRP,PRIT)+STEP(-PRP,PRTT)                    152, A
PRIT=1900                                                  152.1, C
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PRTT=2100                                               152.2, C
    PRTPER - INTERVAL BETWEEN PRINTED OUTPUT POINTS
               (YEARS)
    PRP    - PRINTING PERIOD (YEARS)
    PRIT   - PRINTED OUTPUT INITIATION TIME (YEAR)
    PRTT   - PRINTED OUTPUT TERMINATION TIME (YEAR)
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Note: The equations constituting the World3 model are written in the notation that is consistent with the DYNAMO compiler. Appendixes A and B were produced with the documentor option of the DYNAMO compiler. DYNAMO II for the IBM/360 and IBM/370 systems, as well as DYNAMO IIF (a precompiler to FORTRAN which is written in FORTRAN), for any medium or large system is available from Pugh-Roberts Associates, Inc., 5 Lee Street, Cambridge, Massachusetts 02139.

Also, a machine language version of DYNAMO for the General Electric and Honeywell systems is available from DTSS, Inc., 35 S. Main Street, Hanover, New Hampshire 03755.

Appendix B: Definition File

NAME	NO	T	DEFINITION
AHL	146	A	ASSIMILATION HALF-LIFE (YEARS)
AHLM	145	A	ASSIMILATION HALF-LIFE MULTIPLIER (DIMENSIONLESS)
AHLMT	145.1	T	AHLM TABLE
AHL70	146.1	C	ASSIMILATION HALF-LIFE IN 1970 (YEARS)
AI	99	A	AGRICULTURAL INPUTS (DOLLARS/YEAR)
	99.1	N	
AIOPC	43	A	AVERAGE INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/PERSON-YEAR)
AIPH	101	A	AGRICULTURAL INPUTS PER HECTARE (DOLLARS/ HECTARE-YEAR)
AL	85	L	ARABLE LAND (HECTARES)
	85.1	N	
ALAI	100	A	AVERAGE LIFETIME OF AGRICULTURAL INPUTS (YEARS)
ALAI1	100.1	C	ALAI, VALUE BEFORE TIME=PYEAR (YEARS)
ALAI2	100.2	C	ALAI, VALUE AFTER TIME=PYEAR (YEARS)
ALI	85.2	C	ARABLE LAND INITIAL (HECTARES)
ALIC	54	A	AVERAGE LIFETIME OF INDUSTRIAL CAPITAL (YEARS)
ALIC1	54.1	C	ALIC, VALUE BEFORE TIME=PYEAR (YEARS)
ALIC2	54.2	C	ALIC, VALUE AFTER TIME=PYEAR (YEARS)
ALL	112	A	AVERAGE LIFE OF LAND (YEARS)
ALLN	112.1	C	AVERAGE LIFE OF LAND NORMAL (YEARS)
ALPHA			PERCENTAGE GROWTH PER YEAR (1/YEAR)
ALSC	69	A	AVERAGE LIFETIME OF SERVICE CAPITAL (YEARS)
ALSC1	69.1	C	ALSC, VALUE BEFORE TIME=PYEAR (YEARS)
ALSC2	69.2	C	ALSC, VALUE AFTER TIME=PYEAR (YEARS)
AMTI	140.2	C	AGRICULTURAL MATERIALS TOXICITY INDEX (POLLUTION UNITS/DOLLAR)
B	30	R	BIRTHS PER YEAR (PERSONS/YEAR)
CAI	98	A	CURRENT AGRICULTURAL INPUTS (DOLLARS/YEAR)
CBR	31	S	CRUDE BIRTH RATE (BIRTHS/1000 PERSON-YEARS)
CDR	18	S	CRUDE DEATH RATE (DEATHS/1000 PERSON-YEARS)
CLIP			A FUNCTION SWITCHED DURING THE RUN
CMI	27	A	CROWDING MULTIPLIER FROM INDUSTRIALIZATION (DIMENSIONLESS)
CMIT	27.1	T	CMI TABLE
CMPLE	36	A	COMPENSATORY MULTIPLIER FROM PERCEIVED LIFE EXPECTANCY (DIMENSIONLESS)
CMPLET	36.1	T	CMPLE TABLE
COPM			CAPITAL OUTPUT PRICE MULTIPLIER (DIMENSIONLESS)
COPMT			COPM TABLE
COYM			CAPITAL OUTPUT YIELD MULTIPLIER (DIMENSIONLESS)
COYMT			COYM TABLE

CUF	83	A	CAPITAL UTILIZATION FRACTION
	83.1	N	(DIMENSIONLESS)
CUFT	83.2	T	CUF TABLE
D	17	A	DEATHS PER YEAR (PERSONS/YEAR)
DCFS	38	A	DESIRED COMPLETED FAMILY SIZE (DIMENSIONLESS)
DCFSN	38.2	C	DESIRED COMPLETED FAMILY SIZE NORMAL (DIMENSIONLESS)
DCPH	97	A	DEVELOPMENT COST PER HECTARE (DOLLARS/ HECTARE)
DCPHT	97.1	T	DCPH TABLE
DELAY3			THIRD-ORDER EXPONENTIAL MATERIAL DELAY
DIOPC	40	A	DELAYED INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/PERSON-YEAR)
DLINF3			THIRD-ORDER EXPONENTIAL INFORMATION DELAY
DNRUR			DESIRED NONRENEWABLE RESOURCE USAGE RATE (RESOURCE UNITS/YEAR)
DPOLX			ACCEPTABLE POLLUTION LEVEL (DIMENSIONLESS)
DT			TIME INTERVAL BETWEEN CONSECUTIVE CALCULATIONS (YEARS)
DTF	35	A	DESIRED TOTAL FERTILITY (DIMENSIONLESS)
D1	3	R	DEATHS PER YEAR, AGES 0-14 (PERSONS/YEAR)
D2	7	R	DEATHS PER YEAR, AGES 15-44 (PERSONS/YEAR)
D3	11	R	DEATHS PER YEAR, AGES 45-64 (PERSONS/YEAR)
D4	15	R	DEATHS PER YEAR, AGES 65+ (PERSONS/YEAR)
EHSPC	22	A	EFFECTIVE HEALTH SERVICES PER CAPITA (DOLLARS/PERSON-YEAR)
EXPON			EXPONENTIAL GROWTH RATE FROM TECHNOLOGY (1/ YEAR)
F	87	A	FOOD (VEGETABLE-EQUIVALENT KILOGRAMS/YEAR)
FALM	126	A	FRACTION OF INPUTS ALLOCATED TO LAND MAINTENANCE (DIMENSIONLESS)
FALMT	126.1	T	FALM TABLE
FCAOR	134	A	FRACTION OF CAPITAL ALLOCATED TO OBTAINING RESOURCES (DIMENSIONLESS)
FCAOR1	135	A	FCAOR, VALUE BEFORE TIME=PYEAR (DIMENSIONLESS)
FCAOR1T	135.1	T	FCAOR1 TABLE
FCAOR2	136	A	FCAOR, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)
FCAOR2T	136.1	T	FCAOR2 TABLE
FCAPC	47	A	FERTILITY CONTROL ALLOCATIONS PER CAPITA (DOLLARS/PERSON-YEAR)
FCE	45	A	FERTILITY CONTROL EFFECTIVENESS (DIMENSIONLESS)
FCEST	45.1	C	FERTILITY CONTROL EFFECTIVENESS SET TIME (YEAR)
FCET	45.2	T	FCE TABLE
FCFPC	46	A	FERTILITY CONTROL FACILITIES PER CAPITA (DOLLARS/PERSON-YEAR)
FIALD	108	A	FRACTION OF INPUTS ALLOCATED TO LAND DEVELOPMENT (DIMENSIONLESS)
FIALDT	108.1	T	FIALD TABLE
FIE	42	A	FAMILY INCOME EXPECTATION (DIMENSIONLESS)
FIOAA	93	A	FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO AGRICULTURE (DIMENSIONLESS)
FIOAA1	94	A	FIOAA, VALUE BEFORE TIME=PYEAR (DIMENSIONLESS)
FIOAA1T	94.1	T	FIOAA1 TABLE
FIOAA2	95	A	FIOAA, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)
FIOAA2T	95.1	T	FIOAA2 TABLE
FIOAC	57	A	FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO CONSUMPTION (DIMENSIONLESS)
FIOACC	58	A	FIOAC CONSTANT (DIMENSIONLESS)
FIOACV	59	A	FIOAC VARIABLE (DIMENSIONLESS)
FIOACVT	59.1	T	FIOACV TABLE
FIOAC1	58.1	C	FIOAC, VALUE BEFORE TIME=PYEAR (DIMENSIONLESS)
FIOAC2	58.2	C	FIOAC, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)
FIOAI	56	A	FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO INDUSTRY (DIMENSIONLESS)
FIOAS	63	A	FRACTION OF INDUSTRIAL OUTPUT ALLOCATED TO SERVICES (DIMENSIONLESS)
FIOAS1	64	A	FIOAS, VALUE BEFORE TIME=PYEAR (DIMENSIONLESS)
FIOAS1T	64.1	T	FIOAS1 TABLE
FIOAS2	65	A	FIOAS, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)

FIOAS2T	65.1	T	FIOAS2 TABLE
FIPM	140.1	C	FRACTION OF INPUTS AS PERSISTENT MATERIALS (DIMENSIONLESS)
FM	34	A	FECUNDITY MULTIPLIER (DIMENSIONLESS)
FMT	34.1	T	FM TABLE
FOA	147	S	FRACTION OF OUTPUT IN AGRICULTURE (DIMENSIONLESS)
FOI	148	S	FRACTION OF OUTPUT IN INDUSTRY (DIMENSIONLESS)
FOS	149	S	FRACTION OF OUTPUT IN SERVICES (DIMENSIONLESS)
FPC	88	A	FOOD PER CAPITA (VEGETABLE-EQUIVALENT KILOGRAMS/PERSON-YEAR)
FPU	26	A	FRACTION OF POPULATION URBAN (DIMENSIONLESS)
FPUT	26.1	T	FPU TABLE
FR	127	A	FOOD RATIO (DIMENSIONLESS)
FRPM	139.1	C	FRACTION OF RESOURCES AS PERSISTENT MATERIALS (DIMENSIONLESS)
FRSN	41	A	FAMILY RESPONSE TO SOCIAL NORM
	41.2	N	(DIMENSIONLESS)
FRSNT	41.1	T	FRSN TABLE
FSAFC	48	A	FRACTION OF SERVICES ALLOCATED TO FERTILITY CONTROL (DIMENSIONLESS)
FSAFCT	48.1	T	FSAFC TABLE
FSPD	128.2	C	FOOD SHORTAGE PERCEPTION DELAY (YEARS)
HSAPC	21	A	HEALTH SERVICES ALLOCATIONS PER CAPITA (DOLLARS/PERSON-YEAR)
HSAPCT	21.1	T	HSAPC TABLE
HSID	22.1	C	HEALTH SERVICES IMPACT DELAY (YEARS)
IC	52	L	INDUSTRIAL CAPITAL (DOLLARS)
	52.1	N	
ICDR	53	R	INDUSTRIAL CAPITAL DEPRECIATION RATE (DOLLARS/YEAR)
ICI	52.2	C	INDUSTRIAL CAPITAL INITIAL (DOLLARS)
ICIR	55	R	INDUSTRIAL CAPITAL INVESTMENT RATE (DOLLARS/YEAR)
ICOR	51	A	INDUSTRIAL CAPITAL-OUTPUT RATIO (YEARS)
ICOR1	51.1	C	ICOR, VALUE BEFORE TIME=PYEAR (YEARS)
ICOR2	51.2	C	ICOR, VALUE AFTER TIME=PYEAR (YEARS)
ICOR2T			CAPITAL OUTPUT TABLE FROM RESOURCES
IEAT	43.1	C	INCOME EXPECTATION AVERAGING TIME (YEARS)
IET	57.1	C	INDUSTRIAL EQUILIBRIUM TIME (YEAR)
IFPC	89	A	INDICATED FOOD PER CAPITA (VEGETABLE-EQUIVALENT KILOGRAMS/PERSON-YEAR)
IFPC1	90	A	IFPC, VALUE BEFORE TIME=PYEAR (VEGETABLE-EQUIVALENT KILOGRAMS/PERSON-YEAR)
IFPC1T	90.1	T	IFPC1 TABLE
IFPC2	91	A	IFPC, VALUE AFTER TIME=PYEAR (VEGETABLE-EQUIVALENT KILOGRAMS/PERSON-YEAR)
IFPC2T	91.1	T	IFPC2 TABLE
ILF	124.1	C	INHERENT LAND FERTILITY (VEGETABLE-EQUIVALENT KILOGRAMS/HECTARE-YEAR)
IMEF	139.2	C	INDUSTRIAL MATERIALS EMISSION FACTOR (DIMENSIONLESS)
IMTI	139.3	C	INDUSTRIAL MATERIALS TOXICITY INDEX (POLLUTION UNITS/RESOURCE UNIT)
IO	50	A	INDUSTRIAL OUTPUT (DOLLARS/YEAR)
IOPC	49	A	INDUSTRIAL OUTPUT PER CAPITA (DOLLARS/PERSON-YEAR)
IOPCD	59.2	C	INDUSTRIAL OUTPUT PER CAPITA DESIRED (DOLLARS/PERSON-YEAR)
IO70	107.2	C	INDUSTRIAL OUTPUT IN 1970 (DOLLARS/YEAR)
ISOPC	60	A	INDICATED SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-YEAR)
ISOPC1	61	A	ISOPC, VALUE BEFORE TIME=PYEAR (DOLLARS/PERSON-YEAR)
ISOPC1T	61.1	T	ISOPC1 TABLE
ISOPC2	62	A	ISOPC, VALUE AFTER TIME=PYEAR (DOLLARS/PERSON-YEAR)
ISOPC2T	62.1	T	ISOPC2 TABLE
J	73	A	JOBS (PERSONS)
JPH	79	A	JOBS PER HECTARE (PERSONS/HECTARE)
JPHT	79.1	T	JPH TABLE
JPICU	75	A	JOBS PER INDUSTRIAL CAPITAL UNIT (PERSONS/DOLLAR)
JPICUT	75.1	T	JPICU TABLE
JPSCU	77	A	JOBS PER SERVICE CAPITAL UNIT (PERSONS/DOLLAR)

JPSCUT	77.1	T	JPSCU TABLE
LDR	96	R	LAND DEVELOPMENT RATE (HECTARES/YEAR)
LE	19	A	LIFE EXPECTANCY (YEARS)
LEN	19.1	C	LIFE EXPECTANCY NORMAL (YEARS)
LENGTH			LENGTH OF THE SIMULATION RUN (YEARS)
LER	116	R	LAND EROSION RATE (HECTARES/YEAR)
LF	80	A	LABOR FORCE (PERSONS)
LFC	84	A	LAND FRACTION CULTIVATED (DIMENSIONLESS)
LFD	123	R	LAND FERTILITY DEGRADATION (VEGETABLE-EQUIVALENT KILOGRAMS/HECTARE-YEAR-YEAR)
LFDR	122	A	LAND FERTILITY DEGRADATION RATE (1/YEAR)
LFDRT	122.1	T	LFDR TABLE
LFERT	121 121.1	L N	LAND FERTILITY (VEGETABLE-EQUIVALENT KILOGRAMS/HECTARE-YEAR)
LFERTI	121.2	C	LAND FERTILITY INITIAL (VEGETABLE-EQUIVALENT KILOGRAMS/HECTARE-YEAR)
LFH	87.1	C	LAND FRACTION HARVESTED (DIMENSIONLESS)
LFPF	80.1	C	LABOR FORCE PARTICIPATION FRACTION (DIMENSIONLESS)
LFR	124	R	LAND FERTILITY REGENERATION (VEGETABLE-EQUIVALENT KILOGRAMS/HECTARE-YEAR-YEAR)
LFRT	125	A	LAND FERTILITY REGENERATION TIME (YEARS)
LFRTT	125.1	T	LFRT TABLE
LLMY	113	A	LAND LIFE MULTIPLIER FROM YIELD (DIMENSIONLESS)
LLMY1	114	A	LLMY, VALUE BEFORE TIME=PYEAR (DIMENSIONLESS)
LLMY1T	114.1	T	LLMY1 TABLE
LLMY2	115	A	LLMY, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)
LLMY2T	115.1	T	LLMY2 TABLE
LMC	28	A	LIFETIME MULTIPLIER FROM CROWDING (DIMENSIONLESS)
LMF	20	A	LIFETIME MULTIPLIER FROM FOOD (DIMENSIONLESS)
LMFT	20.1	T	LMF TABLE
LMHS	23	A	LIFETIME MULTIPLIER FROM HEALTH SERVICES (DIMENSIONLESS)
LMHS1	24	A	LMHS, VALUE BEFORE TIME=PYEAR (DIMENSIONLESS)
LMHS1T	24.1	T	LMHS1 TABLE
LMHS2	25	A	LMHS, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)
LMHS2T	25.1	T	LMHS2 TABLE
LMP	29	A	LIFETIME MULTIPLIER FROM PERSISTENT POLLUTION (DIMENSIONLESS)
LMPT	29.1	T	LMP TABLE
LOGN			NATURAL LOGARITHM
LPD	37.1	C	LIFETIME PERCEPTION DELAY (YEARS)
LRUI	119	R	LAND REMOVAL FOR URBAN-INDUSTRIAL USE (HECTARES/YEAR)
LUF	81	A	LABOR UTILIZATION FRACTION (DIMENSIONLESS)
LUFD	82	A	LABOR UTILIZATION FRACTION DELAYED (DIMENSIONLESS)
LUFDT	82.1	C	LABOR UTILIZATION FRACTION DELAY TIME (YEARS)
LY	103	A	LAND YIELD (VEGETABLE-EQUIVALENT KILOGRAMS/HECTARE-YEAR)
LYCM			LAND YIELD TECHNOLOGY CHANGE MULTIPLIER (1/YEAR)
LYCMT			LYCM TABLE
LYF	104	A	LAND YIELD FACTOR (DIMENSIONLESS)
LYF1	104.1	C	LYF, VALUE BEFORE TIME=PYEAR (DIMENSIONLESS)
LYF2	104.2	C	LYF, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)
LYF2R			LAND YIELD TECHNOLOGY IMPROVEMENT RATE (1/YEAR)
LYMAP	105	A	LAND YIELD MULTIPLIER FROM AIR POLLUTION (DIMENSIONLESS)
LYMAP1	106	A	LYMAP, VALUE BEFORE TIME=PYEAR (DIMENSIONLESS)
LYMAP1T	106.1	T	LYMAP1 TABLE
LYMAP2	107	A	LYMAP, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)
LYMAP2T	107.1	T	LYMAP2 TABLE
LYMC	102	A	LAND YIELD MULTIPLIER FROM CAPITAL (DIMENSIONLESS)
LYMCT	102.1	T	LYMC TABLE
LYTD			LAND YIELD TECHNOLOGY INITIATED (1/YEAR)

MAT1	5	R	MATURATION RATE, AGE 14-15 (PERSONS/YEAR)
MAT2	9	R	MATURATION RATE, AGE 44-45 (PERSONS/YEAR)
MAT3	13	R	MATURATION RATE, AGE 64-65 (PERSONS/YEAR)
MIN			MINIMUM VALUE FUNCTION
MLYMC	111	A	MARGINAL LAND YIELD MULTIPLIER FROM CAPITAL (HECTARES/DOLLAR)
MLYMCT	111.1	T	MLYMC TABLE
MPAI	110	A	MARGINAL PRODUCTIVITY OF AGRICULTURAL INPUTS (VEGETABLE EQUIVALENT KILOGRAMS/ DOLLAR)
MPLD	109	A	MARGINAL PRODUCTIVITY OF LAND DEVELOPMENT (VEGETABLE-EQUIVALENT KILOGRAMS/DOLLAR)
MTF	33	A	MAXIMUM TOTAL FERTILITY (DIMENSIONLESS)
MTFN	33.1	C	MAXIMUM TOTAL FERTILITY NORMAL (DIMENSIONLESS)
M1	4	A	MORTALITY, AGES 0-14 (DEATHS/PERSON-YEAR)
M1T	4.1	T	M1 TABLE
M2	8	A	MORTALITY, AGES 15-44 (DEATHS/PERSON-YEAR)
M2T	8.1	T	M2 TABLE
M3	12	A	MORTALITY, AGES 45-64 (DEATHS/PERSON-YEAR)
M3T	12.1	T	M3 TABLE
M4	16	A	MORTALITY, AGES 65+ (DEATHS/PERSON-YEAR)
M4T	16.1	T	M4 TABLE
NFC	44	A	NEED FOR FERTILITY CONTROL (DIMENSIONLESS)
NR	129	L	NONRENEWABLE RESOURCES (RESOURCE UNITS)
	129.1	N	
NRATE			RESOURCE TECHNOLOGY IMPROVEMENT RATE (1/ YEAR)
NRCM			RESOURCE TECHNOLOGICAL CHANGE MULTIPLIER (1/YEAR)
NRCMT			NRCM TABLE
NRFR	133	A	NONRENEWABLE RESOURCE FRACTION REMAINING (DIMENSIONLESS)
NRI	129.2	C	NONRENEWABLE RESOURCES INITIAL (RESOURCE UNITS)
NRTD			NONRENEWABLE RESOURCE TECHNOLOGY INITIATED (1/YEAR)
NRUF	131	A	NONRENEWABLE RESOURCE USAGE FACTOR (DIMENSIONLESS)
NRUF1	131.1	C	NRUF, VALUE BEFORE TIME=PYEAR (DIMENSIONLESS)
NRUF2	131.2	C	NRUF, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)
NRUR	130	R	NONRENEWABLE RESOURCE USAGE RATE (RESOURCE UNITS/YEAR)
PAL	86	L	POTENTIALLY ARABLE LAND (HECTARES)
	86.1	N	
PALI	86.2	C	POTENTIALLY ARABLE LAND INITIAL (HECTARES)
PALT	84.1	C	POTENTIALLY ARABLE LAND TOTAL (HECTARES)
PCRUM	132	A	PER CAPITA RESOURCE USAGE MULTIPLIER (RESOURCE UNITS/PERSON-YEAR)
PCRUMT	132.1	T	PCRUM TABLE
PET	30.2	C	POPULATION EQUILIBRIUM TIME (YEAR)
PFR	128	A	PERCEIVED FOOD RATIO (DIMENSIONLESS)
	128.1	N	
PJAS	78	A	POTENTIAL JOBS IN AGRICULTURAL SECTOR (PERSONS)
PJIS	74	A	POTENTIAL JOBS IN INDUSTRIAL SECTOR (PERSONS)
PJSS	76	A	POTENTIAL JOBS IN SERVICE SECTOR (PERSONS)
PL	87.2	C	PROCESSING LOSS (DIMENSIONLESS)
PLE	37	A	PERCEIVED LIFE EXPECTANCY (YEARS)
PLIT	151.2	C	INITIATION OF PLOTTED OUTPUT (YEAR)
PLP	151.1	C	PLOTTING PERIOD (YEARS)
PLTPER	151	A	INTERVAL BETWEEN PLOTTED OUTPUT POINTS (YEARS)
POLGFM			POLLUTION CONTROL TECHNOLOGY CHANGE MULTIPLIER (1/YEAR)
POLGFMT			POLGFM TABLE
POP	1	A	POPULATION (PERSONS)
POP1			FRACTION OF THE POPULATION AGE 0-14 (DIMENSIONLESS)
POP2			FRACTION OF THE POPULATION AGE 15-44 (DIMENSIONLESS)
POP3			FRACTION OF THE POPULATION AGE 45-64 (DIMENSIONLESS)
POP4			FRACTION OF THE POPULATION AGE 65+ (DIMENSIONLESS)

PPAPR	141	R	PERSISTENT POLLUTION APPEARANCE RATE (POLLUTION UNITS/YEAR)
PPASR	144	R	PERSISTENT POLLUTION ASSIMILATION RATE (POLLUTION UNITS/YEAR)
PPGAO	140	A	PERSISTENT POLLUTION GENERATED BY AGRICULTURAL OUTPUT (POLLUTIONUNITS/YEAR)
PPGF	138	A	PERSISTENT POLLUTION GENERATION FACTOR (DIMENSIONLESS)
PPGF1	138.1	C	PPGF, VALUE BEFORE TIME=PYEAR (DIMENSIONLESS)
PPGF2	138.2	C	PPGF, VALUE AFTER TIME=PYEAR (DIMENSIONLESS)
PPGIO	139	A	PERSISTENT POLLUTION GENERATED BY INDUSTRIAL OUTPUT (POLLUTION UNITS/YEAR)
PPGR	137	R	PERSISTENT POLLUTION GENERATION RATE (POLLUTION UNITS/YEAR)
PPOL	142	L	PERSISTENT POLLUTION (POLLUTION UNITS)
	142.1	N	
PPOLX	143	A	INDEX OF PERSISTENT POLLUTION (DIMENSIONLESS)
PPOL70	143.1	C	PERSISTENT POLLUTION IN 1970 (POLLUTION UNITS)
PPTD	141.1	C	PERSISTENT POLLUTION TRANSMISSION DELAY (YEARS)
PRATE			POLLUTION CONTROL TECHNOLOGY IMPROVEMENT RATE (1/YEAR)
PRIT	152.1	C	PRINTED OUTPUT INITIATION TIME (YEAR)
PRP	151.3	C	PRINTING PERIOD (YEARS)
PRTPER	152	A	INTERVAL BETWEEN PRINTED OUTPUT POINTS (YEARS)
PRTT	152.2	C	PRINTED OUTPUT TERMINATION TIME (YEAR)
PTD			POLLUTION CONTROL TECHNOLOGY INITIATED (1/YEAR)
PYEAR	150.1	C	YEAR NEW POLICY IS IMPLEMENTED (YEAR)
P1	2	L	POPULATION, AGES 0-14 (PERSONS)
	2.1	N	
P1I	2.2	C	P1 INITIAL (PERSONS)
P2	6	L	POPULATION, AGES 15-44 (PERSONS)
	6.1	N	
P2I	6.2	C	P2 INITIAL (PERSONS)
P3	10	L	POPULATION, AGES 45-64 (PERSONS)
	10.1	N	
P3I	10.2	C	P3 INITIAL (PERSONS)
P4	14	L	POPULATION, AGES 65+ (PERSONS)
	14.1	N	
P4I	14.2	C	P4 INITIAL (PERSONS)
RLT	30.1	C	REPRODUCTIVE LIFETIME (YEARS)
SAD	40.1	C	SOCIAL ADJUSTMENT DELAY (YEARS)
SC	67	L	SERVICE CAPITAL (DOLLARS)
	67.1	N	
SCDR	68	R	SERVICE CAPITAL DEPRECIATION RATE (DOLLARS/YEAR)
SCI	67.2	C	SERVICE CAPITAL INITIAL (DOLLARS)
SCIR	66	R	SERVICE CAPITAL INVESTMENT RATE (DOLLARS/YEAR)
SCOR	72	A	SERVICE CAPITAL-OUTPUT RATIO (YEARS)
SCOR1	72.1	C	SCOR, VALUE BEFORE TIME=PYEAR (YEAR)
SCOR2	72.2	C	SCOR, VALUE AFTER TIME=PYEAR (YEAR)
SD	109.1	C	SOCIAL DISCOUNT (1/YEAR)
SFPC	127.1	C	SUBSISTENCE FOOD PER CAPITA (VEGETABLE-EQUIVALENT KILOGRAMS/PERSON-YEAR)
SFSN	39	A	SOCIAL FAMILY SIZE NORM (DIMENSIONLESS)
SFSNT	39.1	T	SFSN TABLE
SMOOTH			FIRST-ORDER EXPONENTIAL INFORMATION DELAY
SO	70	A	SERVICE OUTPUT (DOLLARS/YEAR)
SOPC	71	A	SERVICE OUTPUT PER CAPITA (DOLLARS/PERSON-YEAR)
TABHL			A FUNCTION WITH VALUES SPECIFIED BY A TABLE
TABLE			A FUNCTION WITH VALUES SPECIFIED BY A TABLE
TAI	92	A	TOTAL AGRICULTURAL INVESTMENT (DOLLARS/YEAR)
TDD			TECHNOLOGICAL DEVELOPMENT AND IMPLEMENTATION DELAY (YEARS)
TF	32	A	TOTAL FERTILITY (DIMENSIONLESS)
TIME	150.2	N	CURRENT TIME IN THE SIMULATION RUN
UIL	120	L	URBAN-INDUSTRIAL LAND (HECTARES)
	120.1	N	

UILDT	119.1	C	URBAN-INDUSTRIAL LAND DEVELOPMENT TIME (YEARS)
UILI	120.2	C	URBAN-INDUSTRIAL LAND INITIAL (HECTARES)
UILPC	117	A	URBAN-INDUSTRIAL LAND PER CAPITA (HECTARES/ PERSON)
UILPCT	117.1	T	UILPC TABLE
UILR	118	A	URBAN-INDUSTRIAL LAND REQUIRED (HECTARES)
ZPGT	38.1	C	TIME WHEN DESIRED FAMILY SIZE EQUALS 2 CHILDREN (YEAR)

Appendix C: How to Read a DYNAMO Flow Diagram

A flow diagram is an illustration of the postulated relationships between the elements in a model system. It depicts the model assumptions with a degree of detail midway between the dynamically suggestive but incomplete causal-loop diagram and the detailed, precise DYNAMO equations. More complete information on DYNAMO flow diagrams, equations, and other conventions can be found in Forrester (1961, 1968) and Pugh (1970).

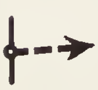
A DYNAMO flow diagram has seven main components (see Figure C-1):

Rectangles represent levels, for example, nonrenewable resources NR, industrial capital IC.

Valves represent rates, for example, nonrenewable resource usage rate NRUR, industrial capital depreciation rate ICDR.

Circles represent auxiliaries, for example, industrial output IO, per capita resource usage multiplier PCRUM. Table functions (see Appendix D) are indicated by overlining and underlining the DYNAMO variable name as in the auxiliary $\overline{\underline{\text{PCRUM}}}$.

Solid arrows represent material flows, for example, the solid arrow leaving nonrenewable resources NR represents the material flow of resources from a stock or inventory of resources. Dashed arrows represent flows of information, for example, information about the level of nonrenewable resources is used to determine the nonrenewable resource fraction remaining NRFR.



Input lines represent information inputs from constant parameters, for example, industrial capital-output ratio ICOR.

A double circle represents an exogenous, time-dependent input, for example, population POP. Since this input is determined in another sector of World3, it is exogenous to the nonrenewable resource sector as it is drawn in Figure C-1.

The "cloud" symbol represents a source or sink for various flows. A cloud effectively delimits the system boundary. After a flow enters a cloud it no longer affects the system. Similarly, what happens to a flow before it enters the system from a cloud is of no importance to the system.

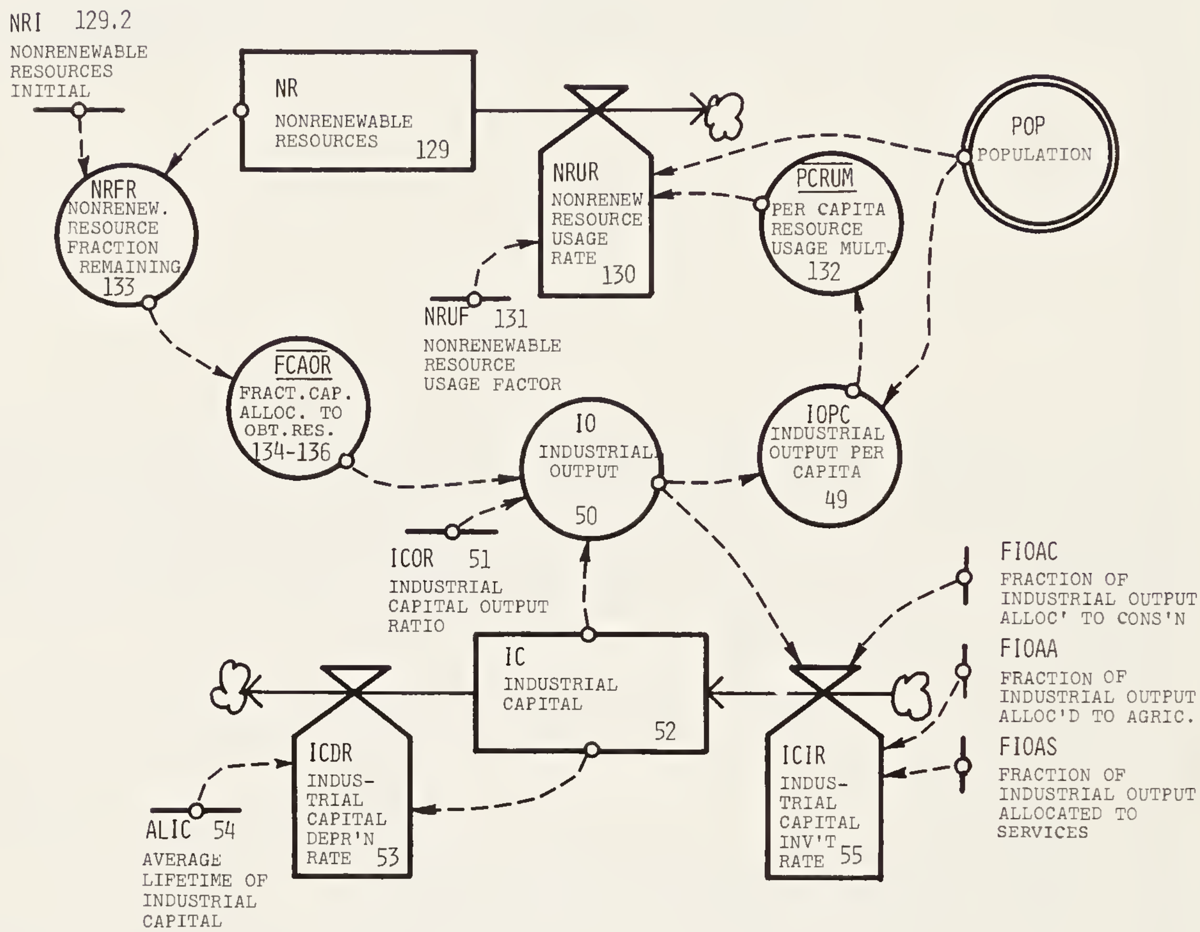


Figure C-1 Example of a DYNAMO flow diagram (nonrenewable resource sector)

Appendix D: How to Read DYNAMO Equations

A DYNAMO equation is written in the following form:

type *variable name* = *expression*

Type: a single letter designating the type of variable being defined:

L indicates a level equation
R indicates a rate equation
A indicates an auxiliary equation
N indicates an initial value
C indicates a constant
T indicates a table
S indicates a supplementary equation

Variable name: the specified abbreviation for the variable being defined by the equation. The name must be followed by the appropriate time subscript, depending on the type of variable it is. Levels and auxiliaries have the subscript .K; rates have the subscript .KL. Initial values, constants, and tables do not have time subscripts.

Expression: any algebraic expression. It may range from a simple number or single variable to a complicated combination of factors and terms involving functions, variables, and numerical values. The operations of addition, subtraction, multiplication, and division are indicated, respectively, by +, −, *, /. Multiplication and division are carried out before addition and subtraction. Expressions enclosed in parentheses are evaluated first, and the value is substituted for the parenthetical expression.

Level Equation

A level equation defines the present value of a level variable in terms of its value from the previous evaluation and its change in value in the intervening time, DT. A level equation represents a simple numerical integration. Numerical instabilities are avoided by taking DT to be a small fraction of the shortest time delay in the model.

The equation for nonrenewable resources NR (from Figure D-1) is an example of a level equation:

$$\text{L} \qquad NR.K = NR.J + (DT)(-NRUR.JK),$$

where

NR.K = the value of NR at the present time K
NR.J = the value of NR at the previous time of evaluation J, DT time units before the present
DT = the length of the computation interval
NRUR.JK = the rate of change of NR over the interval DT

```
            RESTR

            *       NONRENEWABLE RESOURCE SECTOR WITH EXOGENOUS INPUTS
            NOTE
129         L       NR.K=NR.J+(DT)(-NRUR.JK)
            N       NR=NRI
            C       NRI=1E12
130         R       NRUR.KL=(POP.K)(PCRUM.K)(NRUF.K)
131         A       NRUF.K=CLIP(NRUF2,NRUF1,TIME.K,PYEAR)
            C       NRUF1=1
            C       NRUF2=1
132         A       PCRUM.K=TABHL(PCRUMT,IOPC.K,0,1600,200)
            T       PCRUMT=0/.85/2.6/4.4/5.4/6.2/6.8/7/7
133         A       NRFR.K=NR.K/NRI
134         A       FCAOR.K=CLIP(FCAOR2.K,FCAOR1.K,TIME.K,PYEAR)
135         A       FCAOR1.K=TABHL(FCAOR1T,NRFR.K,0,1,.1)
            T       FCAOR1T=1/.9/.7/.5/.2/.1/.05/.05/.05/.05/.05
136         A       FCAOR2.K=TABHL(FCAOR2T,NRFR.K,0,1,.1)
            T       FCAOR2T=1/.9/.7/.5/.2/.1/.05/.05/.05/.05/.05
            NOTE
            NOTE    EXOGENOUS INPUTS TO THE NONRENEWABLE RESOURCE SECTOR
            NOTE
            NOTE    POPULATION
            NOTE
            A       POP.K=CLIP(POP2,POP1.K,TIME.K,ZPGT)
            A       POP1.K=POPI*EXP(GC*(TIME.K-1900))
            C       POPI=1.65E9
            C       GC=.012
            C       POP2=4E9
            C       ZPGT=2500
            NOTE
            NOTE    INDUSTRIAL CAPITAL
            NOTE
            L       IC.K=IC.J+(DT)(ICIR.JK-ICDR.JK)
            N       IC=ICI
            C       ICI=2.1E11
            R       ICIR.KL=(IO.K)(1-FIOAA-FIOAS-FIOAC)
            C       FIOAA=.12
            C       FIOAS=.12
            C       FIOAC=.43
            R       ICDR.KL=IC.K/ALIC
            C       ALIC=14
            NOTE
            NOTE    INDUSTRIAL OUTPUT
            NOTE
            A       IO.K=(IC.K)(1-FCAOR.K)/ICOR
            C       ICOR=3
            A       IOPC.K=IO.K/POP.K
            NOTE
            NOTE    CONTROL CARDS
            NOTE
            N       TIME=1900
            C       PYEAR=1975
            SPEC    DT=1/PLTPER=5/LENGTH=2100
            PLOT    NRFR=N,FCAOR=F(0,1)/IC=C(0,4E13)/
            X       IO=O(0,1E13)/POP=P(0,1.6E10)
```

Figure D-1 Example of DYNAMO equations (nonrenewable resource sector equations)

In the simple numerical integration scheme used by DYNAMO, the rate of change is assumed to be constant during the small time interval DT.

Rate Equation

A rate equation describes how the rate of flow to or from a level changes, depending on other conditions in the system. The expression in the rate equation may contain constants, auxiliaries, and levels. The auxiliaries and levels used in rate equations are written in terms of their values at the present time, represented by the subscript .K. For example, in Figure D-1:

R NRUR.KL = (POP.K)(PCRUM.K) (NRUF.K).

In this example the rate, NRUR.KL, is defined as the product of a level, POP.K, and two auxiliaries, NRUF.K and PCRUM.K.

Auxiliary Equation

An auxiliary equation defines a component of a rate. Rates are separated algebraically into auxiliaries to clarify their structure. All auxiliary variables could be substituted back into rate equations, making them dependent exclusively on levels and constants. Auxiliaries are separated from rate equations only if they represent real-world quantities or concepts. The expression in an auxiliary equation can contain constants, functions (including table functions), levels, and other auxiliaries.

Initial-Value Equation

An initial-value equation defines the value of a level at the beginning of the simulated time period. The variable name in such an equation is the name of the level without subscripts. Its expression can be a number, the variable name of a constant, or a combination of other model variables specified without time subscripts.

Constant Equation

A constant equation defines the numerical value of a constant. The value must be given explicitly by the programmer.

Table Equation

A table equation lists the numerical values of a dependent variable as a function of an independent variable over a specified range. The independent variable and its range are specified in an auxiliary equation preceding the table, as in the following example:

A PCRUM.K = TABHL(PCRUMT,IOPC.K,0,1600,200)
T PCRUMT = 0/.85/2.6/4.4/5.4/6.2/6.8/7/7

The auxiliary equation defines a variable PCRUM as a table function of IOPC. It further specifies that the table PCRUMT gives the values of PCRUM for corresponding values of IOPC between 0 and 1600 units at intervals of 200 units. Since IOPC.K is the value of a continuously variable quantity, its values may not be exact multiples of 200. For values of IOPC.K between the specified points of the table, DYNAMO linearly interpolates the value of PCRUM.K. When IOPC.K is less than zero, DYNAMO uses the first value in the PCRUM table; when IOPC.K is greater than 1600, it uses the last value.

Supplementary Equation

A supplementary equation defines an auxiliary variable that is used only to produce output such as indices of interest to the user. Crude birth rate CBR is a supplementary variable. Supplementary variables cannot be used to compute the values of other variables.

Special Functions: CLIP

```
A      NRUF.K = CLIP(NRUF2,NRUF1,TIME.K,PYEAR)
```

The CLIP function is one of several special functions available in DYNAMO. It is used to change the value of a variable, depending on the relative magnitude of two other variables. In the example given, NRUF has the value NRUF1 until TIME in the simulation run reaches PYEAR; then NRUF changes to NRUF2 and remains there for the duration of the run. Other special functions are described in Pugh (1970).

Specification Statement

The specification statement is identified by the letters SPEC. It contains information about the size of the time step DT, the time interval between plotted points PLTPER, and the time interval covered by a model run LENGTH.

```
SPEC     DT = 1/PLTPER = 5/LENGTH = 2100
```

In the example, DT was chosen to be 1 time unit. In this model, the time unit is one year. DT can be set to any fraction or multiple of a year; it is usually set small enough to avoid computational instabilities, yet large enough to keep the computing time reasonably short.

The quantities to be plotted are defined by a PLOT statement (described next). PLTPER was set to 5 time units in the preceding example, so that only the values at every fifth time unit are actually plotted. The LENGTH specification can take two forms. The internal variable, TIME, can be initialized by the programmer, for example:

```
N      TIME = 1900.
```

Here LENGTH = 2100 means that the run proceeds until TIME = 2100, that is, for 200 time units. If TIME is not explicitly initialized, the compiler supplies the initial value, TIME = 0, and the LENGTH specification then defines the number of time units for the run.

PLOT Statement

```
PLOT     NRFR = N,FCAOR = F(0,1)/IC = C(0,4E13)/
X        IO = O(0,1E13)/POP = P(0,1.6E10)
```

The variables whose values are to be plotted in graphical output are specified in a PLOT statement, which gives both the symbol used to plot the value of a variable and the range of values to be plotted. For example, NRFR = N means that NRFR is plotted with the symbol N. The range of NRFR is determined implicitly by the compiler so that all values of NRFR that occur in a run are included in the graph. The specification POP = P (0,1.6E10) means that POP is plotted on a scale from 0 to 1.6×10^{10}. Values of POP outside this range do not appear on the graphical output. An X in the first column of a card indicates that the contents of the card are to be considered an extension of the expression on the preceding card.

Appendix E: How to Read a DYNAMO Graphical Output

Figure E-1 is an example of a typical DYNAMO output (from the nonrenewable resource sector). The first line on the left lists the symbols used for plotting each variable. For example, NRFR is the variable name for nonrenewable resource fraction remaining, in the DYNAMO program, and the symbol used for plotting NRFR is N.

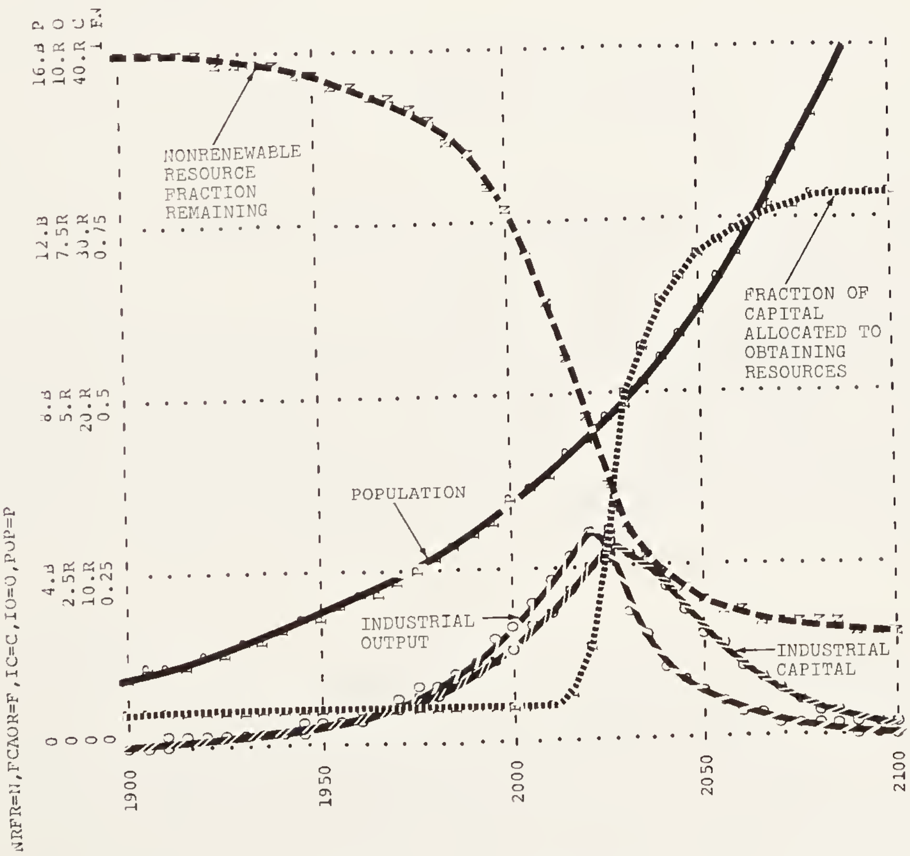


Figure E-1 Standard run for the nonrenewable resource sector

The remaining lines to the left of the graph give the scales for the plotted variables. The scales are divided into four equal parts by the compiler. Scientific notation is used and the power of ten employed as a scaling factor is indicated either with a standard exponential designation, for example 5 E+10 or with an alphabetic character (see Figure E-2). For example, the scale for IC, plotted as C in Figure E-1, has an upper value of 40.R, which is 40×10^{12} units. In the model run shown in Figure E-1, both the nonrenewable resource fraction remaining NRFR (plot symbol N) and the fraction of capital allocated to obtaining resources FCAOR (plot symbol F) are plotted on the same scale.

Letter	Multiply Plotted Value by	Letter	Multiply Plotted Value by
A	10^{-3}	N	10^{30}
B	10^{9}	P	10^{24}
C	10^{27}	Q	10^{15}
D	10^{33}	R	10^{12}
E	10^{-6}	S	10^{21}
F	10^{-9}	T	10^{3}
G	10^{-12}	U	10^{-24}
H	10^{-15}	V	10^{18}
J	10^{-18}	W	10^{-27}
K	$<10^{-30}$ (off scale)	X	1
L	10^{-21}	Y	10^{-30}
M	10^{6}	Z	$>10^{33}$ (off scale)

Figure E-2 Scaling letters used in DYNAMO

Time is plotted along the horizontal axis of the graph. The compiler attaches a "date" to the scale at every tenth plot period.

The series of letter groups that sometimes appear along the top of the graphical output indicate points at which two or more plot symbols overlap. The first letter is the one that is actually plotted in the output. The other letters identify the other variables whose plotted values intersect at that point. The intersections are purely geometric features of a given set of curves and scales; they are of no dynamic significance.

Appendix F: Delays

The concept and characteristics of delays are important in understanding the dynamics of social systems. Complex social systems do not respond immediately and completely to changing conditions and inputs. One hundred letters mailed in the same mailbox to equidistant points will not arrive at their destinations simultaneously; the full effect of an advance in medical technology will not be reflected immediately in the average life expectancy of the population; an increasing number of births will be followed only many years later by an increasing number of deaths—all these illustrations are examples of delays.

In system dynamics models, a delay is represented by a combination of rates and levels. These combinations may be explicit: in the industrial sector the industrial capital depreciation rate ICDR (equation 53) is a delayed version of the capital investment rate ICIR (equation 55). The intervening level is the industrial capital stock IC (equation 52). The combination of rates and levels in a delay may also be implicit, as in the persistent pollution appearance rate PPAPR. The implicit combinations, denoted by SMOOTH and DELAY3, for example, are macro functions that are available in DYNAMO.

Delays have two dynamically significant characteristics. First, a delay postpones to a later time the full effect of a change in the input to the delay. The average displacement in time is determined by the delay "time constant," which may be either a constant or a variable during the run. Second, a delay modifies the time shape of an input. For example, a sudden increase in the input to a delay will be followed by a more gradual increase in the delay output.

Information Delays

The information delays available in DYNAMO involve a smoothing, or averaging, of information about a variable, where the greatest weight is given to the most recent value of the variable and proportionately less weight is given to older information about the variable. This averaging procedure is often used to represent an intuitive averaging process in which the freshest, most recent events influence decisions more than the hazy recollections of past events. Dynamically, the smoothing process filters out rapid, noisy fluctuations but only slightly modifies long-term trends. The attentuation of fluctuations is more severe as the smoothing or delay time increases (Figure F-1).

The two information delay structures, or macros, provided in DYNAMO are SMOOTH (also called DLINF1) and DLINF3. They are represented symbolically by a rectangle (Figure F-2). X is the input to the delay; it may be a level, a rate, or an auxiliary. AX is the output of the delay, representing the averaged, smoothed, or delayed value of X, with the same dimensional units as X. AT is the averaging time, which may be a constant or a variable. The DYNAMO equations for these information delays are:

A AX.K = SMOOTH(X.K,AT)
A AX.K = DLINF3(X.K,AT)

SMOOTH is a first-order delay containing one internal level. DLINF3 is a third-order delay containing three internal levels. For details of the internal equations generated by DYNAMO to give the output variable, see Forrester (1961, 1968).

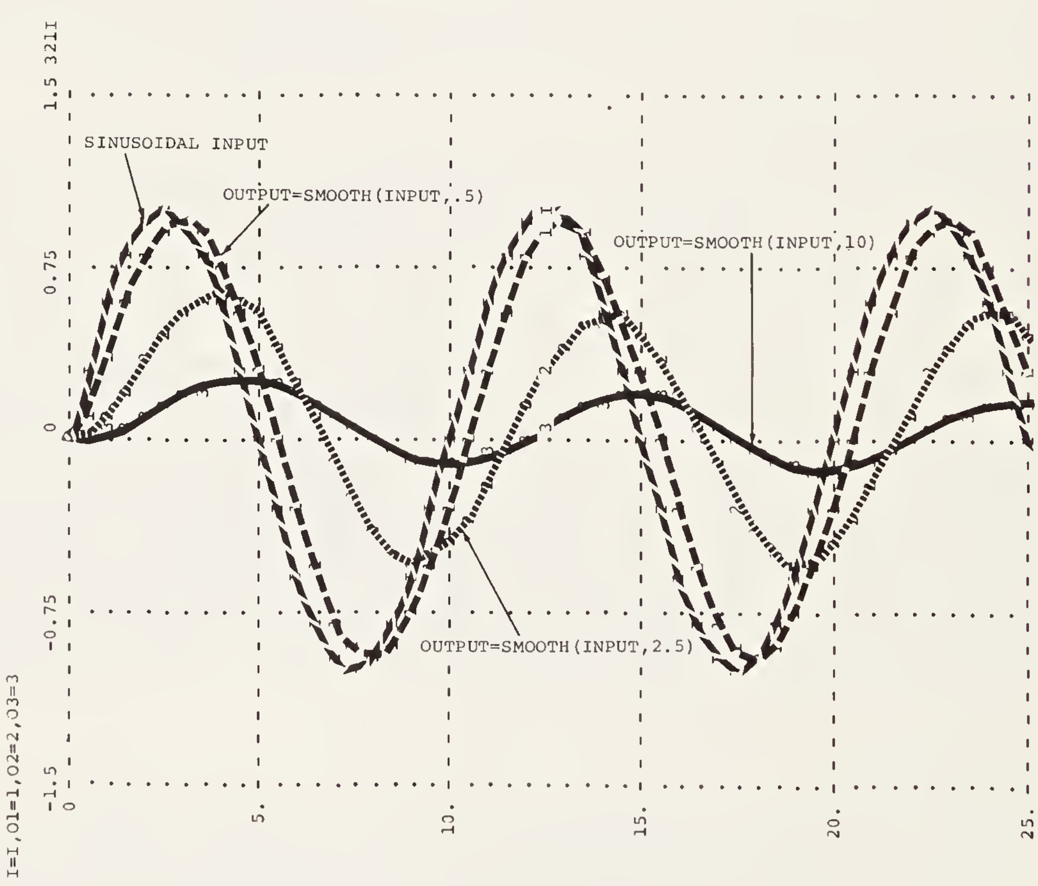


Figure F-1 Response of a first-order information delay to a sinusoidal input

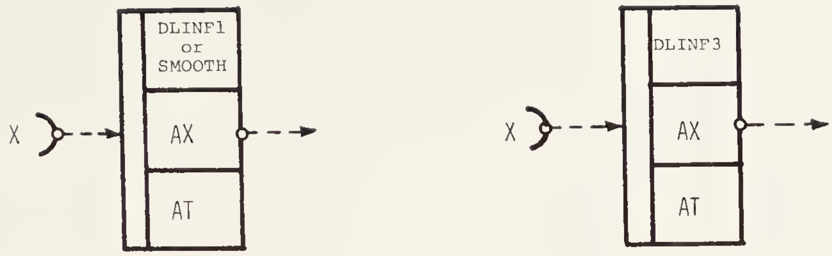


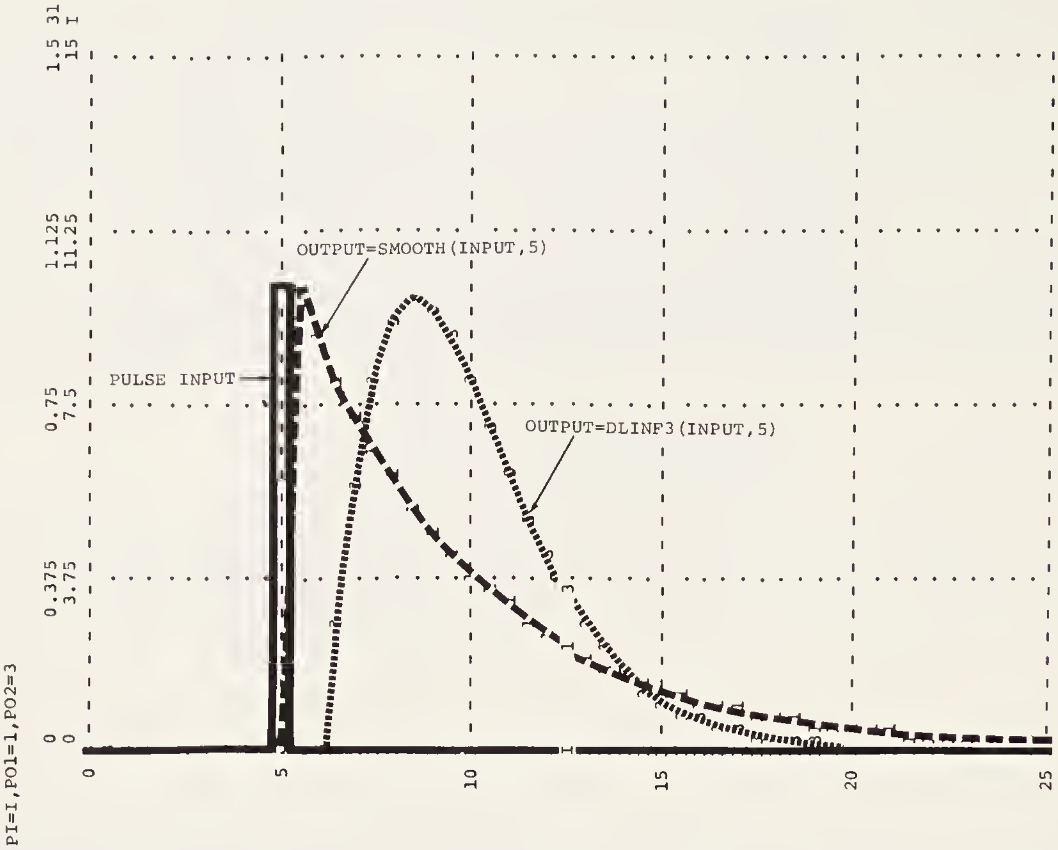
Figure F-2 DYNAMO flow diagram representation of first- and third-order information delays

The time response of first- and third-order delays to a given input signal is qualitatively different, although there is no difference between the time response of information or material delays of the same order with the same constant delay time. Their responses to pulse, step, and ramp inputs are shown in Figure F-3. Note that a first-order delay gives a finite response in the next DT after the change in input, whereas a third-order delay does not respond immediately but ultimately adjusts more rapidly to the same input change. A third-order delay is a series of three first-order delays. Higher-order delays can be created similarly by using first- and third-order delays in series.

It can be seen from Figure F-3 that the outputs of the delay functions have almost fully adjusted to the changed inputs after a time of about 3AT. Thus, loosely speaking, 3AT is the delay between a change in the input and the completed response to that change. AT is the average response time of the output to the change in the input.

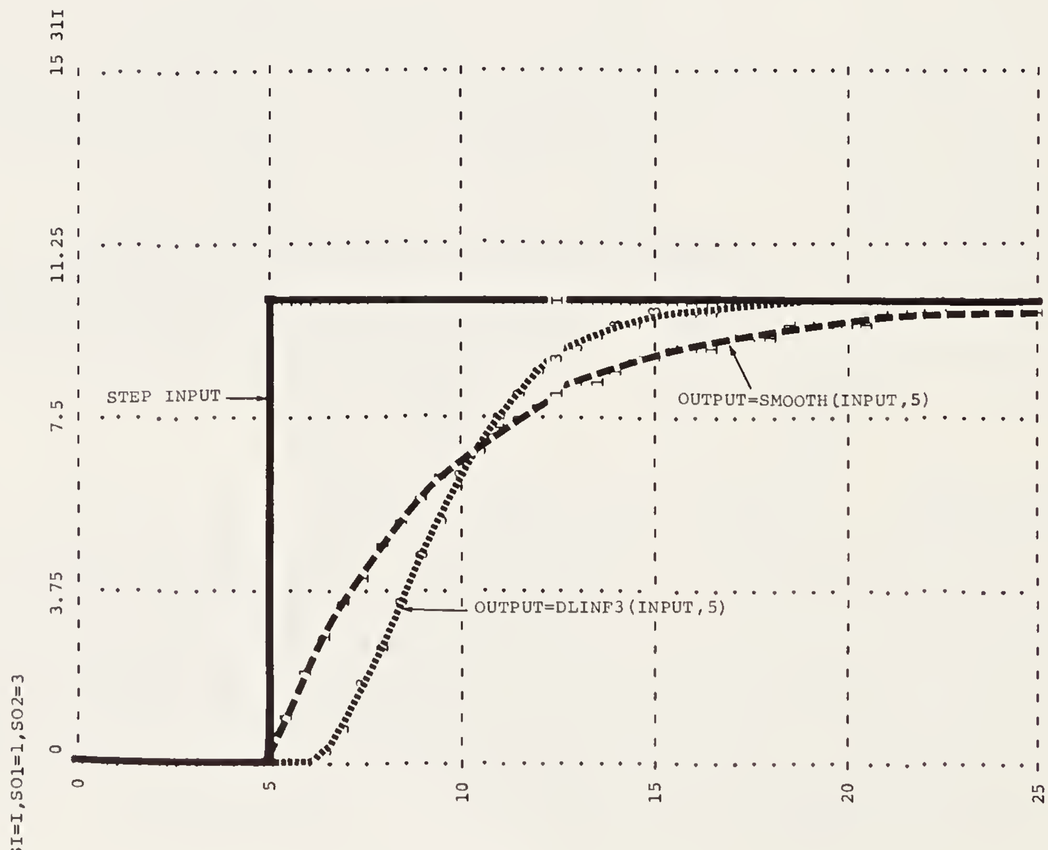
Material Delays

Material delays change the time shape of material flows. The input to a material delay is always a material flow rate, such as the persistent pollution generation rate PPGR. The output is also a rate. Two material delay macros available in DYNAMO are DELAY1 and DELAY3. The former is a first-order delay; the latter is a third-order delay. The DYNAMO flow diagram representations of these delay functions are shown in Figure F-4. The input rates in both diagrams are X. The output rates are the delayed values of X, XD. The adjustment time in both cases is AT, which may be a constant or a variable.



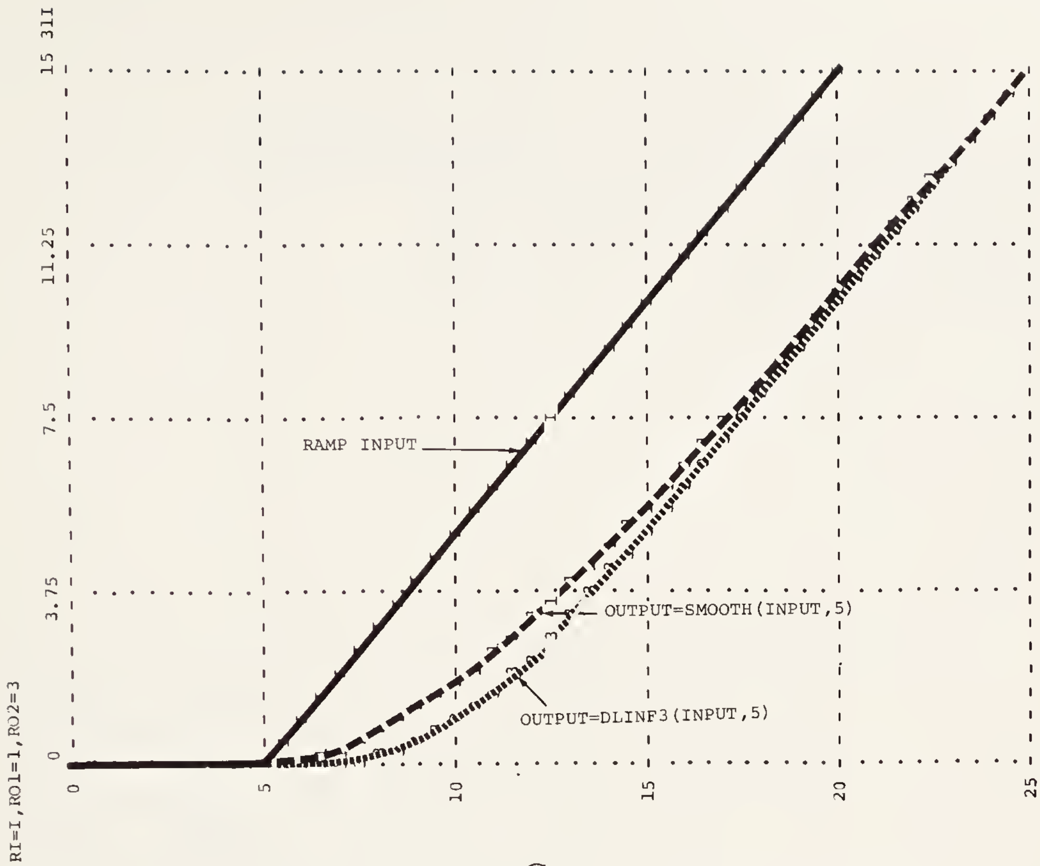
OUTPUT=SMOOTH(INPUT,5)
PULSE INPUT
OUTPUT=DLINF3(INPUT,5)
PI=I,PO1=1,PO2=3
0 0
0.375 3.75
0.75 7.5
1.125 11.25
1.5 15
31 I
0
5
10
15
20
25

A.



STEP INPUT
OUTPUT=SMOOTH(INPUT,5)
OUTPUT=DLINF3(INPUT,5)
SI=I,SO1=1,SO2=3
0
3.75
7.5
11.25
15
31I
0
5
10
15
20
25

B.



C.

Figure F-3 Response of first- and third-order delays to pulse, step, and ramp inputs

The DYNAMO equations for the delays shown in Figure F-4 are:

A XD.KL = DELAY1(X.JK,AT)

A XD.KL = DELAY3(X.JK,AT)

The time response of material delays to different inputs is the same as that for information delays (Figure F-3) when the adjustment time AT is constant. Further details about the internal structure of the macros generated by the DYNAMO compiler to produce these delays can be found in Forrester (1961, 1968) and Pugh (1970).

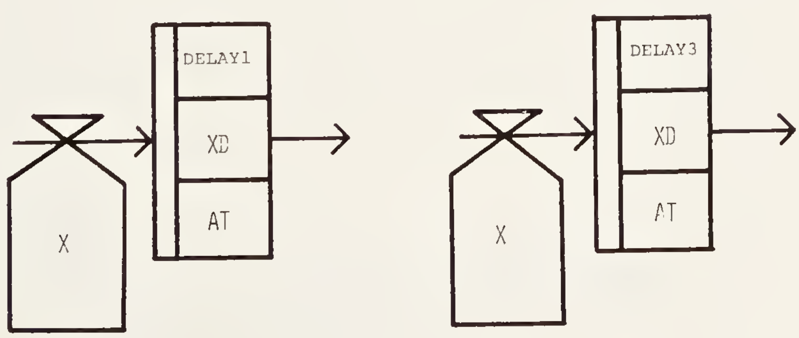


Figure F-4 DYNAMO flow diagram representation of first- and third-order material delays

Appendix G: Parameter and Structural Changes for *Limits to Growth* Runs

```
NOTE   PARAMETER AND STRUCTURAL CHANGES FOR LIMITS TO GROWTH RUNS
NOTE
NOTE   STRUCTURAL CHANGES
NOTE
NOTE   ** THE FOLLOWING CHANGES MUST BE MADE IN EDIT MODE:
NOTE   ** CHANGE:
NOTE   ** R ICIR.KL=CLIP(ICIR2.K,(IO.K*FIOAI.K),TIME.K,ICET)
NOTE   ** INSERT:
NOTE   ** A ICIR2.K=CLIP(MIN(ICDR.JK,IO.K*FIOAI.K),
NOTE   ** X IO.K*FIOAI.K,DIOPC.K-DIOP.K,0)
NOTE   ** C ICET=4000
NOTE   ** A DIOP.K=SAMPLE(IOPC.K,DIST.K,0)
NOTE   ** A DIST.K=STEP(4000,DISI+1905)+DISI
NOTE   ** C DISI=4000
NOTE
NOTE   PARAMETER CHANGES
NOTE
PLOT   NRFR=R(0,1)/IOPC=I,SOPC=S,FPC=F(0,1000)/POP=P(0,15E9)/PPOLX=X(0,32)
X      /CBR=B,CDR=D(0,50)
RUN    FIG. 35: STANDARD RUN
C      PET=1975
RUN    FIG. 44: WORLD MODEL WITH STABILIZED POPULATION
C      PET=1975
C      ICET=1985
RUN    FIG. 45: WORLD MODEL WITH STABILIZED POP. AND CAP.
CP     NRI=2E12
RUN    FIG. 36: DOUBLED RESOURCES
CP     NRUF2=.25
RUN    FIG. 37: "UNLIMITED" RESOURCES
CP     PPGF2=.25
RUN    FIG. 39: "UNLIMITED" RESOURCES & POLLUTION CONTROLS
C      LYF2=2
RUN    FIG. 40: "UNLIM." RES.,POL. CON., & INCR. AG. PRODUCTIVITY
C      FCEST=1975
RUN    FIG. 41: RESOURCE & POLLUTION POLICIES & BIRTH CONTROL
C      LYF2=2
C      FCEST=1975
RUN    FIG. 42: LAND YIELD GAINS ADDED TO THE POLICIES OF FIG. 41
C      NRI=1E12
C      LYF2=1
C      FCEST=4000
C      PET=1975
C      ICET=1990
CP     ALIC2=18
TP     ISOPC2T=80/450/1000/1500/1800/2100/2400/2700/3000
TP     IFPC2T=250/600/900/1100/1200/1275/1350/1375/1375
TP     FALMT=0/.045/.08/.1/.105
RUN    FIG. 46: STABILIZED WORLD MODEL I
C      FCEST=1975
C      ZPGT=1975
C      DISI=75
C      ICET=1975
```

```
RUN    FIG. 47: STABILIZED WORLD MODEL II
C      FCEST=2000
C      ZPGT=2000
C      DISI=100
C      ICET=2000
C      PYEAR=2000
RUN    FIG. 48: STABILIZATION POLICIES IN THE YEAR 2000
```

REFERENCES

Forrester 1961	Forrester, Jay W. *Industrial Dynamics.* Cambridge, Mass.: The M.I.T. Press, 1961.
Forrester 1968	Forrester, Jay W. *Principles of Systems.* Cambridge, Mass. Wright-Allen Press, 1968.
Pugh 1970	Pugh, A.L. III. *DYNAMO II User's Manual.* Cambridge, Mass.: The M.I.T. Press, 1970.

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World Dynamics interrelates population, industrialization, natural resources, food, crowding, and pollution to present an exploratory theory of man in the world ecology. The book is the first step toward adapting the principles of system dynamics to the behavior of the forces involved in determining the transition from growth to world equilibrium. It has been adopted in many colleges and universities for teaching courses in such diverse fields as geology, zoology, life sciences, political science, ecology, and cybernetics. A new chapter on the physical and social limits to growth has been added in this second edition.

1973, second edition, 144 pp., ill., $9.75

Principles of Systems
by Jay W. Forrester

Principles of Systems introduces the basic concepts of structure in dynamic systems and leads into the way structure determines behavior. The book serves as a starting point for teaching dynamic systems in multidisciplinary courses on urban, ecological, corporate, and other social systems. It is an excellent study complement to other books treating social systems.

1968, 392 pp., ill., $8.00 paperback

Collected Papers of Jay W. Forrester
edited by Jay W. Forrester

The collection consists of 17 of Professor Forrester's papers written since 1958 on system dynamics and its applications. The papers lead the reader from early applications of system dynamics in industry to present use of the methodology in urban and national policy design. The chronological organization of the papers provides a historical perspective of the development of the field of system dynamics.

Fall 1974, approx. 350 pp., ill., $18.00

Wright-Allen Press, Inc.
238 Main Street
Cambridge, Massachusetts 02142
(617) 491-6826

The Life Cycle of Economic Development
by Nathan B. Forrester

This book presents a system dynamics model of national economic development. It interrelates the five production sectors (agriculture, goods, services, resources, and capital) of a national economy to examine the shifting allocation of labor and capital between these sectors as development progresses. The book analyzes various possible modes of economic development for an industrial economy, and the effects of different development strategies. Complete details of the computer model are included to enable the reader to extend the study. The book also illustrates the use of system dynamics in national policy planning.

1973, second edition, 194 pp., ill., $20.00

Dynamics of Commodity Production Cycles
by Dennis L. Meadows

Professor Meadows finds the classical Cobweb Theorem and its modifications to be inadequate representations of dynamic relationships in actual commodity systems. Employing the system dynamics methodology, he develops a general dynamic model of the economic, biological, technological, and psychological factors which lead to the instability of commodity systems. With appropriate parameter values, the general model explains the hog, cattle, and chicken cycles observed in the real world. Experimental simulations of the model present surprising implications for current stabilization policies.

1970, 104 pp., ill., $14.75

Toward Global Equilibrium: Collected Papers
edited by Dennis L. Meadows and Donella H. Meadows

This volume contains 13 papers which describe individual research on dynamic issues evolving from the Club of Rome project reported in *The Limits to Growth*. It presents detailed analyses of several important global problems, e.g. DDT and mercury pollution, natural resource depletion, solid waste disposal, etc. and provides policy suggestions which may alleviate these problems. It also examines the economic, political, and ethical implications of growth and the transition to equilibrium.

1973, 358 pp., ill., $18.00