THE LIMITS TO growth

Donella H. Meadows
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William W. Behrens III

A Report for THE CLUB OF ROME'S Project on the Predicament of Mankind

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To Dr. Aurelio Peccei, whose profound concern for humanity has inspired us and many others to think about the world's long-term problems

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FOREWORD

IN APRIL 1968, a group of thirty individuals from ten countries—scientists, educators, economists, humanists, industrialists, and national and international civil servants—gathered in the Accademia dei Lincei in Rome. They met at the instigation of Dr. Aurelio Peccei, an Italian industrial manager, economist, and man of vision, to discuss a subject of staggering scope—the present and future predicament of man.

THE CLUB OF ROME

Out of this meeting grew The Club of Rome, an informal organization that has been aptly described as an "invisible college." Its purposes are to foster understanding of the varied but interdependent components—economic, political, natural, and social—that make up the global system in which we all live; to bring that new understanding to the attention of policy-makers and the public worldwide; and in this way to promote new policy initiatives and action.

The Club of Rome remains an informal international association, with a membership that has now grown to approximately seventy persons of twenty-five nationalities. None of its members holds public office, nor does the group seek to express any single ideological, political, or national point of view. All are united, however, by their overriding conviction that the major problems facing mankind are of such complexity and are so interrelated that traditional institutions and policies are no longer able to cope with them, nor even to come to grips with their full content.

The members of The Club of Rome have backgrounds as varied as their nationalities. Dr. Peccei, still the prime moving force within the group, is affiliated with Fiat and Olivetti and manages a consulting firm for economic and engineering development, Italconsult, one of the largest of its kind in Europe. Other leaders of The Club of Rome include: Hugo Thiemann, head of the Battelle Institute in Geneva; Alexander King, scientific director of the Organization for Economic Cooperation and Development; Saburo Okita, head of the Japan Economic Research Center in Tokyo; Eduard Pestel of the Technical University of Hannover, Germany; and Carroll Wilson of the Massachusetts Institute of Technology. Although membership in The Club of Rome is limited, and will not exceed one hundred, it is being expanded to include representatives of an ever greater variety of cultures, nationalities, and value systems.

THE PROJECT ON THE PREDICAMENT OF MANKIND

A series of early meetings of The Club of Rome culminated in the decision to initiate a remarkably ambitious undertaking —the Project on the Predicament of Mankind.

The intent of the project is to examine the complex of problems troubling men of all nations: poverty in the midst of plenty; degradation of the environment; loss of faith in institutions; uncontrolled urban spread; insecurity of employment; alienation of youth; rejection of traditional values; and inflation and other monetary and economic disruptions. These seemingly divergent parts of the "world problematique," as The Club of Rome calls it, have three characteristics in common: they occur to some degree in all societies; they contain technical, social, economic, and political elements; and, most important of all, they interact.

It is the predicament of mankind that man can perceive the problematique, yet, despite his considerable knowledge and skills, he does not understand the origins, significance, and interrelationships of its many components and thus is unable to devise effective responses. This failure occurs in large part because we continue to examine single items in the problematique without understanding that the whole is more than the sum of its parts, that change in one element means change in the others.

Phase One of the Project on the Predicament of Mankind took definite shape at meetings held in the summer of 1970 in Bern, Switzerland, and Cambridge, Massachusetts. At a two-week conference in Cambridge, Professor Jay Forrester of the Massachusetts Institute of Technology (MIT) presented a global model that permitted clear identification of many specific components of the problematique and suggested a technique for analyzing the behavior and relationships of the most important of those components. This presentation led to initiation of Phase One at MIT, where the pioneering work of Professor Forrester and others in the field of System Dynamics had created a body of expertise uniquely suited to the research demands.

The Phase One study was conducted by an international team, under the direction of Professor Dennis Meadows, with financial support from the Volkswagen Foundation. The team examined the five basic factors that determine, and therefore, ultimately limit, growth on this planet—population, agricultural production, natural resources, industrial production, and pollution. The research has now been completed. This book is the first account of the findings published for general readership.

A GLOBAL CHALLENGE

It is with genuine pride and pleasure that Potomac Associates joins with The Club of Rome and the MIT research team in the publication of *The Limits to Growth.*

We, like The Club of Rome, are a young organization, and we believe the Club's goals are very close to our own. Our purpose is to bring new ideas, new analyses, and new approaches to persistent problems—both national and international—to the attention of all those who care about and help determine the quality and direction of our life. We are delighted therefore to be able to make this bold and impressive work available through our book program.

We hope that *The Limits to Growth* will command critical attention and spark debate in all societies. We hope that it will encourage each reader to think through the consequences of continuing to equate growth with progress. And we hope that it will lead thoughtful men and women in all fields of endeavor to consider the need for concerted action now if we are to preserve the habitability of this planet for ourselves and our children.

William Watts, *President*
POTOMAC ASSOCIATES

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INTRODUCTION

I do not wish to seem overdramatic, but I can only conclude from the information that is available to me as Secretary-General, that the Members of the United Nations have perhaps ten years left in which to subordinate their ancient quarrels and launch a global partnership to curb the arms race, to improve the human environment, to defuse the population explosion, and to supply the required momentum to development efforts. If such a global partnership is not forged within the next decade, then I very much fear that the problems I have mentioned will have reached such staggering proportions that they will be beyond our capacity to control.

U THANT, 1969

The problems U Thant mentions—the arms race, environmental deterioration, the population explosion, and economic stagnation—are often cited as the central, long-term problems of modern man. Many people believe that the future course of human society, perhaps even the survival of human society, depends on the speed and effectiveness with which the world responds to these issues. And yet only a small fraction of the world's population is actively concerned with understanding these problems or seeking their solutions.

HUMAN PERSPECTIVES

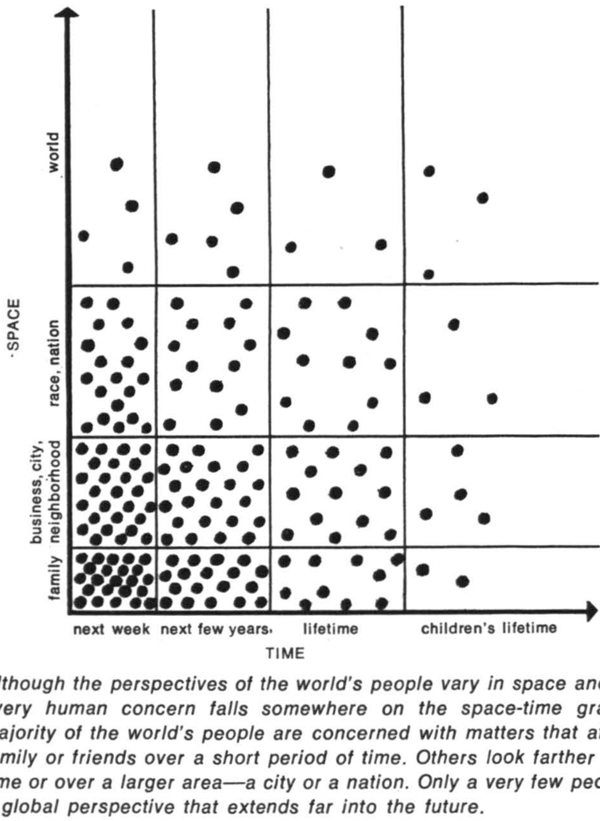
Every person in the world faces a series of pressures and problems that require his attention and action. These problems affect him at many different levels. He may spend much of his time trying to find tomorrow's food for himself and his family. He may be concerned about personal power or the power of the nation in which he lives. He may worry about a world war during his lifetime, or a war next week with a rival clan in his neighborhood.

These very different levels of human concern can be represented on a graph like that in figure 1. The graph has two dimensions, space and time. Every human concern can be located at some point on the graph, depending on how much geographical space it includes and how far it extends in time. Most people's worries are concentrated in the lower left-hand corner of the graph. Life for these people is difficult, and they must devote nearly all of their efforts to providing for themselves and their families, day by day. Other people think about and act on problems farther out on the space or time axes. The pressures they perceive involve not only themselves, but the community with which they identify. The actions they take extend not only days, but weeks or years into the future.

A person's time and space perspectives depend on his culture, his past experience, and the immediacy of the problems confronting him on each level. Most people must have successfully solved the problems in a smaller area before they move their concerns to a larger one. In general the larger the space and the longer the time associated with a problem, the smaller the number of people who are actually concerned with its solution.

There can be disappointments and dangers in limiting one's view to an area that is too small. There are many examples of a person striving with all his might to solve some immediate, local problem, only to find his efforts defeated by events occurring in a larger context. A farmer's carefully maintained

Figure 1 HUMAN PERSPECTIVES



Although the perspectives of the world's people vary in space and in time, every human concern falls somewhere on the space-time graph. The majority of the world's people are concerned with matters that affect only family or friends over a short period of time. Others look farther ahead in time or over a larger area—a city or a nation. Only a very few people have a global perspective that extends far into the future.

fields can be destroyed by an international war. Local officials' plans can be overturned by a national policy. A country's economic development can be thwarted by a lack of world demand for its products. Indeed there is increasing concern today that most personal and national objectives may ultimately be frustrated by long-term, global trends such as those mentioned by U Thant.

Are the implications of these global trends actually so threatening that their resolution should take precedence over local, short-term concerns?

Is it true, as U Thant suggested, that there remains less than a decade to bring these trends under control?

If they are not brought under control, what will the consequences be?

What methods does mankind have for solving global problems, and what will be the results and the costs of employing each of them?

These are the questions that we have been investigating in the first phase of The Club of Rome's Project on the Predicament of Mankind. Our concerns thus fall in the upper right-hand corner of the space-time graph.

PROBLEMS AND MODELS

Every person approaches his problems, wherever they occur on the space-time graph, with the help of models. A model is simply an ordered set of assumptions about a complex system. It is an attempt to understand some aspect of the infinitely varied world by selecting from perceptions and past experience a set of general observations applicable to the problem at hand. A farmer uses a mental model of his land, his assets, market prospects, and past weather conditions to decide which crops to plant each year. A surveyor constructs a physical model—a map—to help in planning a road. An economist uses mathematical models to understand and predict the flow of international trade.

Decision-makers at every level unconsciously use mental models to choose among policies that will shape our future world. These mental models are, of necessity, very simple when compared with the reality from which they are abstracted. The human brain, remarkable as it is, can only keep track of a limited number of the complicated, simultaneous interactions that determine the nature of the real world.

We, too, have used a model. Ours is a formal, written model of the world.* It constitutes a preliminary attempt to improve our mental models of long-term, global problems by combining the large amount of information that is already in human minds and in written records with the new information-processing tools that mankind's increasing knowledge has produced—the scientific method, systems analysis, and the modern computer.

Our world model was built specifically to investigate five major trends of global concern—accelerating industrialization, rapid population growth, widespread malnutrition, depletion of nonrenewable resources, and a deteriorating environment. These trends are all interconnected in many ways, and their development is measured in decades or centuries, rather than in months or years. With the model we are seeking to understand the causes of these trends, their interrelationships, and their implications as much as one hundred years in the future.

The model we have constructed is, like every other model, imperfect, oversimplified, and unfinished. We are well aware of its shortcomings, but we believe that it is the most useful model now available for dealing with problems far out on the space-time graph. To our knowledge it is the only formal model in existence that is truly global in scope, that has a

* The prototype model on which we have based our work was designed by Professor Jay W. Forrester of the Massachusetts Institute of Technology. A description of that model has been published in his book *World Dynamics* (Cambridge, Mass.: Wright-Allen Press, 1971).

time horizon longer than thirty years, and that includes important variables such as population, food production, and pollution, not as independent entities, but as dynamically interacting elements, as they are in the real world.

Since ours is a formal, or mathematical, model it also has two important advantages over mental models. First, every assumption we make is written in a precise form so that it is open to inspection and criticism by all. Second, after the assumptions have been scrutinized, discussed, and revised to agree with our best current knowledge, their implications for the future behavior of the world system can be traced without error by a computer, no matter how complicated they become.

We feel that the advantages listed above make this model unique among all mathematical and mental world models available to us today. But there is no reason to be satisfied with it in its present form. We intend to alter, expand, and improve it as our own knowledge and the world data base gradually improve.

In spite of the preliminary state of our work, we believe it is important to publish the model and our findings now. Decisions are being made every day, in every part of the world, that will affect the physical, economic, and social conditions of the world system for decades to come. These decisions cannot wait for perfect models and total understanding. They will be made on the basis of some model, mental or written, in any case. We feel that the model described here is already sufficiently developed to be of some use to decision-makers. Furthermore, the basic behavior modes we have already observed in this model appear to be so fundamental and general that we do not expect our broad conclusions to be substantially altered by further revisions.

It is not the purpose of this book to give a complete, scientific description of all the data and mathematical equations included in the world model. Such a description can be found in the final technical report of our project. Rather, in *The Limits to Growth* we summarize the main features of the model and our findings in a brief, nontechnical way. The emphasis is meant to be not on the equations or the intricacies of the model, but on what it tells us about the world. We have used a computer as a tool to aid our own understanding of the causes and consequences of the accelerating trends that characterize the modern world, but familiarity with computers is by no means necessary to comprehend or to discuss our conclusions. The implications of those accelerating trends raise issues that go far beyond the proper domain of a purely scientific document. They must be debated by a wider community than that of scientists alone. Our purpose here is to open that debate.

The following conclusions have emerged from our work so far. We are by no means the first group to have stated them. For the past several decades, people who have looked at the world with a global, long-term perspective have reached similar conclusions. Nevertheless, the vast majority of policy-makers seems to be actively pursuing goals that are inconsistent with these results.

Our conclusions are:

1. If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity.

2. It is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future. The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his individual human potential.

3. If the world's people decide to strive for this second outcome rather than the first, the sooner they begin working to attain it, the greater will be their chances of success.

These conclusions are so far-reaching and raise so many questions for further study that we are quite frankly overwhelmed by the enormity of the job that must be done. We hope that this book will serve to interest other people, in many fields of study and in many countries of the world, to raise the space and time horizons of their concerns and to join us in understanding and preparing for a period of great transition—the transition from growth to global equilibrium.

GROWTH IN THE WORLD SYSTEM

In the circumference of a circle the beginning and end are common.

HERACLITUS, 500 B.C.

We have discussed food, nonrenewable resources, and pollution absorption as separate factors necessary for the growth and maintenance of population and industry. We have looked at the rate of growth in the demand for each of these factors and at the possible upper limits to the supply. By making simple extrapolations of the demand growth curves, we have attempted to estimate, roughly, how much longer growth of each of these factors might continue at its present rate of increase. Our conclusion from these extrapolations is one that many perceptive people have already realized—that the short doubling times of many of man's activities, combined with the immense quantities being doubled, will bring us close to the limits to growth of those activities surprisingly soon.

Extrapolation of present trends is a time-honored way of looking into the future, especially the very near future, and especially if the quantity being considered is not much influenced by other trends that are occurring elsewhere in the system. Of course, none of the five factors we are examining here is independent. Each interacts constantly with all the others. We have already mentioned some of these interactions. Population cannot grow without food, food production is increased by growth of capital, more capital requires more resources, discarded resources become pollution, pollution interferes with the growth of both population and food.

Furthermore, over long time periods each of these factors also feeds back to influence itself. The rate at which food production increases in the 1970's, for example, will have some effect on the size of the population in the 1980's, which will in turn determine the rate at which food production must increase for many years thereafter. Similarly, the rate of resource consumption in the next few years will influence both the size of the capital base that must be maintained and the amount of resources left in the earth. Existing capital and available resources will then interact to determine future resource supply and demand.

The five basic quantities, or levels—population, capital, food, nonrenewable resources, and pollution—are joined by still other interrelationships and feedback loops that we have not yet discussed. Clearly it is not possible to assess the long-term future of any of these levels without taking all the others into account. Yet even this relatively simple system has such a complicated structure that one cannot intuitively understand how it will behave in the future, or how a change in one variable might ultimately affect each of the others. To achieve such understanding, we must extend our intuitive capabilities so that we can follow the complex, interrelated behavior of many variables simultaneously.

In this chapter we describe the formal world model that we have used as a first step toward comprehending this complex world system. The model is simply an attempt to bring together the large body of knowledge that already exists about cause-and-effect relationships among the five levels listed above and to express that knowledge in terms of interlocking feedback loops. Since the world model is so important in understanding the causes of and limits to growth in the world system, we shall explain the model-building process in some detail.

In constructing the model, we followed four main steps:

1. We first listed the important causal relationships among the five levels and traced the feedback loop structure. To do so we consulted literature and professionals in many fields of study dealing with the areas of concern—demography, economics, agronomy, nutrition, geology, and ecology, for example. Our goal in this first step was to find the most basic structure that would reflect the major interactions between the five levels. We reasoned that elaborations on this basic structure, reflecting more detailed knowledge, could be added after the simple system was understood.
2. We then quantified each relationship as accurately as possible, using global data where it was available and characteristic local data where global measurements had not been made.
3. With the computer, we calculated the simultaneous operation of all these relationships over time. We then tested the effect of numerical changes in the basic assumptions to find the most critical determinants of the system's behavior.
4. Finally, we tested the effect on our global system of the

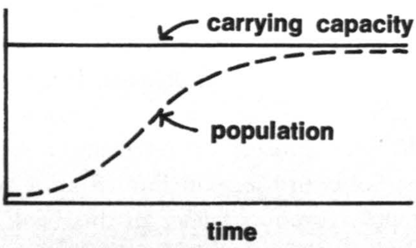
various policies that are currently being proposed to enhance or change the behavior of the system.

These steps were not necessarily followed serially, because often new information coming from a later step would lead us back to alter the basic feedback loop structure. There is not one inflexible world model; there is instead an evolving model that is continuously criticized and updated as our own understanding increases.

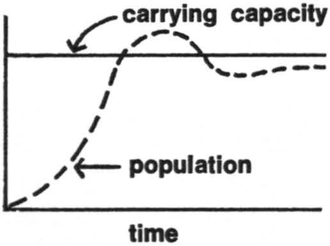
A summary of the present model, its purpose and limitations, the most important feedback loops it contains, and our general procedure for quantifying causal relationships follows.

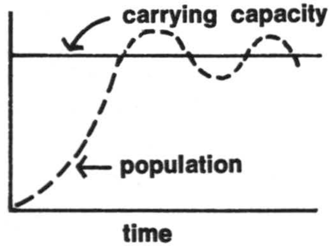
THE PURPOSE OF THE WORLD MODEL

In this first simple world model, we are interested only in the broad behavior modes of the population-capital system. By *behavior modes* we mean the tendencies of the variables in the system (population or pollution, for example) to change as time progresses. A variable may increase, decrease, remain constant, oscillate, or combine several of these characteristic modes. For example, a population growing in a limited environment can approach the ultimate carrying capacity of that environment in several possible ways. It can adjust smoothly to an equilibrium below the environmental limit by means of a gradual decrease in growth rate, as shown below. It can over-

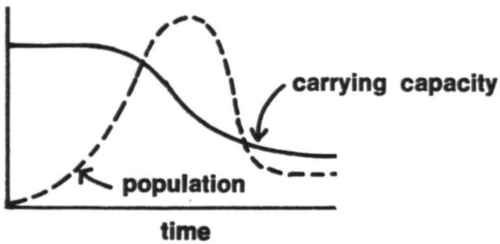


shoot the limit and then die back again in either a smooth or an oscillatory way, also as shown below. Or it can overshoot





the limit and in the process decrease the ultimate carrying capacity by consuming some necessary nonrenewable resource, as diagramed below. This behavior has been noted in many natural systems. For instance, deer or goats, when natural enemies are absent, often overgraze their range and cause erosion or destruction of the vegetation.[28]



A major purpose in constructing the world model has been to determine which, if any, of these behavior modes will be most characteristic of the world system as it reaches the limits to growth. This process of determining behavior modes is "prediction" only in the most limited sense of the word. The output graphs reproduced later in this book show values for world population, capital, and other variables on a time scale that begins in the year 1900 and continues until 2100. These graphs are *not* exact predictions of the values of the variables at any particular year in the future. They are indications of the system's behavioral tendencies only.

The difference between the various degrees of "prediction" might be best illustrated by a simple example. If you throw a ball straight up into the air, you can predict with certainty what its general behavior will be. It will rise with decreasing velocity, then reverse direction and fall down with increasing velocity until it hits the ground. You know that it will not continue rising forever, nor begin to orbit the earth, nor loop three times before landing. It is this sort of elemental understanding of behavior modes that we are seeking with the present world model. If one wanted to predict exactly how high a thrown ball would rise or exactly where and when it would hit the ground, it would be necessary to make a detailed calculation based on precise information about the ball, the altitude, the wind, and the force of the initial throw. Similarly, if we wanted to predict the size of the earth's population in 1993 within a few percent, we would need a very much more complicated model than the one described here. We would also need information about the world system more precise and comprehensive than is currently available.

Because we are interested at this point only in broad behavior modes, this first world model need not be extremely detailed. We thus consider only one general population, a population that statistically reflects the average characteristics of the global population. We include only one class of pollutants—the long-lived, globally distributed family of pollutants, such as lead, mercury, asbestos, and stable pesticides and radioisotopes—

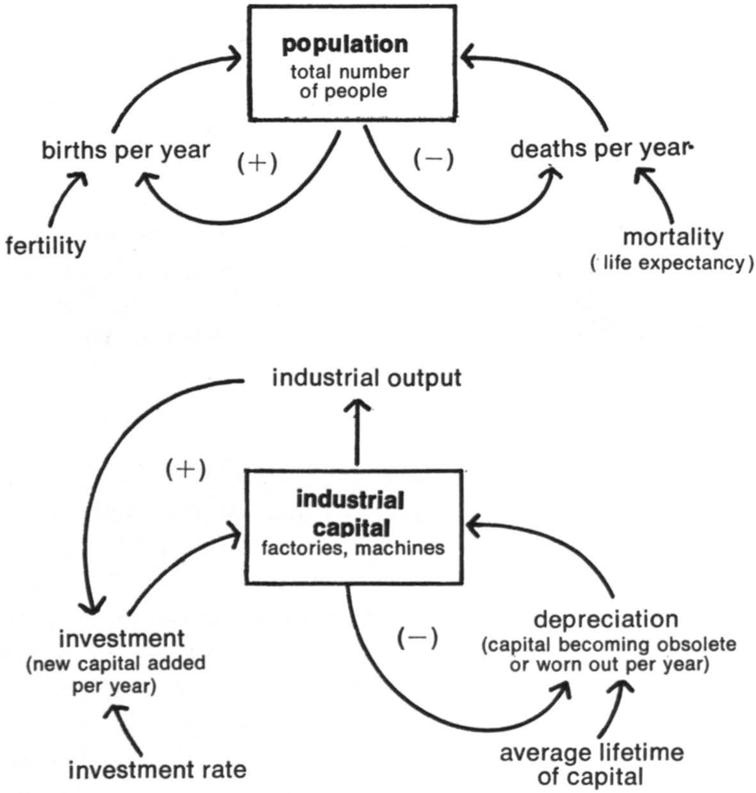
whose dynamic behavior in the ecosystem we are beginning to understand. We plot one generalized resource that represents the combined reserves of all nonrenewable resources, although we know that each separate resource will follow the general dynamic pattern at its own specific level and rate.

This high level of aggregation is necessary at this point to keep the model understandable. At the same time it limits the information we can expect to gain from the model. Questions of detail cannot be answered because the model simply does not yet contain much detail. National boundaries are not recognized. Distribution inequalities of food, resources, and capital are included implicitly in the data but they are not calculated explicitly nor graphed in the output. World trade balances, migration patterns, climatic determinants, and political processes are not specifically treated. Other models can, and we hope will, be built to clarify the behavior of these important subsystems.*

Can anything be learned from such a highly aggregated model? Can its output be considered meaningful? In terms of exact predictions, the output is not meaningful. We cannot forecast the precise population of the United States nor the GNP of Brazil nor even the total world food production for the year 2015. The data we have to work with are certainly not sufficient for such forecasts, even if it were our purpose to make them. On the other hand, it is vitally important to gain some understanding of the causes of growth in human society, the limits to growth, and the behavior of our socio-economic systems when the limits are reached. Man's knowledge of the

* We have built numerous submodels ourselves in the course of this study to investigate the detailed dynamics underlying each sector of the world model. A list of those studies is included in the appendix.

Figure 23 POPULATION GROWTH AND CAPITAL GROWTH FEEDBACK LOOPS



The central feedback loops of the world model govern the growth of population and of industrial capital. The two positive feedback loops involving births and investment generate the exponential growth behavior of population and capital. The two negative feedback loops involving deaths and depreciation tend to regulate this exponential growth. The relative strengths of the various loops depend on many other factors in the world system.

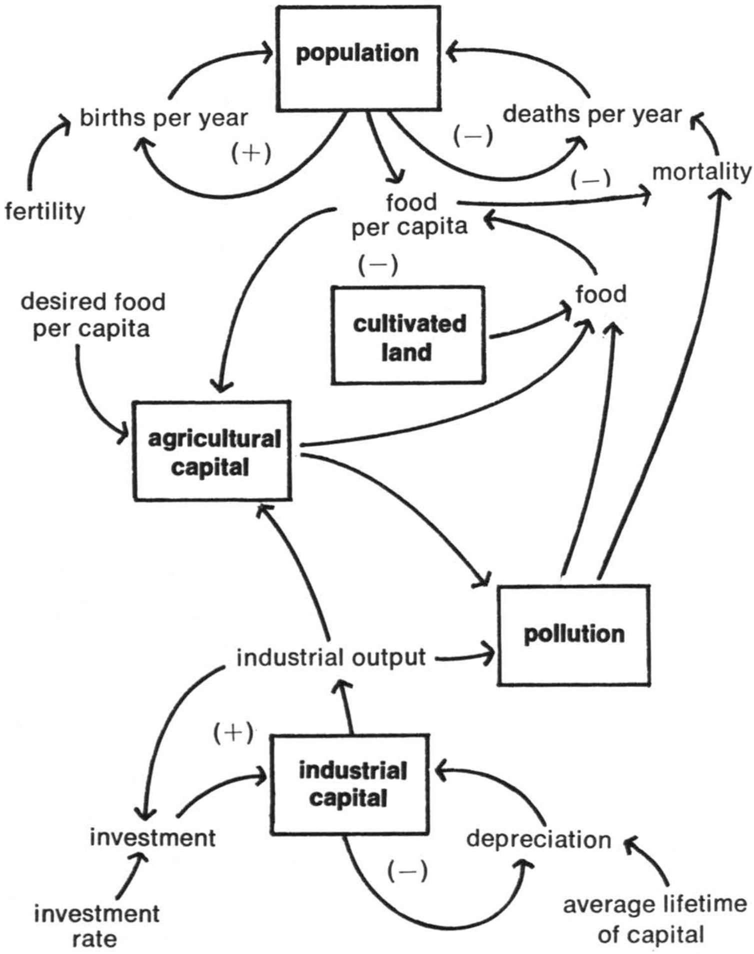
behavior modes of these systems is very incomplete. It is currently not known, for example, whether the human population will continue growing, or gradually level off, or oscillate around some upper limit, or collapse. We believe that the aggregated world model is one way to approach such questions. The model utilizes the most basic relationships among people, food, investment, depreciation, resources, output—relationships that are the same the world over, the same in any part of human society or in society as a whole. In fact, as we indicated at the beginning of this book, there are advantages to considering such questions with as broad a space-time horizon as possible. Questions of detail, of individual nations, and of short-term pressures can be asked much more sensibly when the overall limits and behavior modes are understood.

THE FEEDBACK LOOP STRUCTURE

In chapter I we drew a schematic representation of the feedback loops that generate population growth and capital growth. They are reproduced together in figure 23.

A review of the relationships diagramed in figure 23 may be helpful. Each year the population is increased by the total number of births and decreased by the total number of deaths that have taken place during that year. The absolute number of births per year is a function of the average fertility of the population and of the size of the population. The number of deaths is related to the average mortality and the total population size. As long as births exceed deaths, the population grows. Similarly, a given amount of industrial capital, operating at constant efficiency, will be able to produce a certain amount of output each year. Some of that output will be more factories, machines, etc., which are investments to increase the stock of capital goods. At the same time some capital equipment will depreciate or be discarded each year. To keep industrial capital growing, the investment rate must exceed the

Figure 24 FEEDBACK LOOPS OF POPULATION, CAPITAL, AGRICULTURE, AND POLLUTION



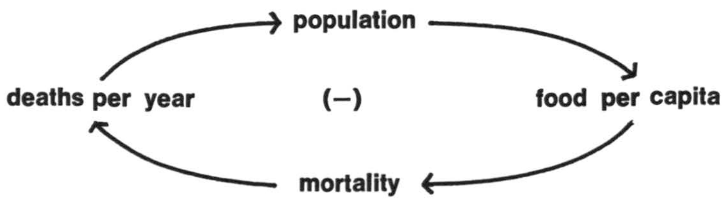
Some of the interconnections between population and industrial capital operate through agricultural capital, cultivated land, and pollution. Each arrow indicates a causal relationship, which may be immediate or delayed, large or small, positive or negative, depending on the assumptions included in each model run.

depreciation rate.

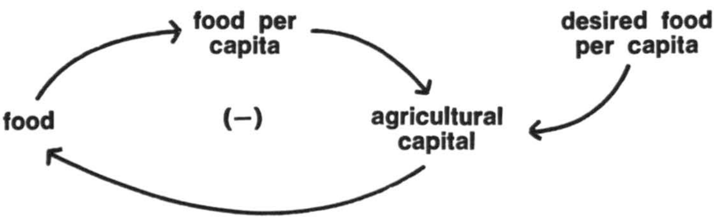
In all our flow diagrams, such as figure 23, the arrows simply indicate that one variable has some influence on another. The *nature* and *degree* of influence are not specified, although of course they must be quantified in the model equations. For simplicity, we often omit noting in the flow diagrams that several of the causal interactions occur only after a delay. The delays are included explicitly in the model calculations.

Population and capital influence each other in many ways, some of which are shown in figure 24. Some of the output of industrial capital is agricultural capital—tractors, irrigation ditches, and fertilizers, for example. The amount of agricultural capital and land area under cultivation strongly influences the amount of food produced. The food per capita (food produced divided by the population) influences the mortality of the population. Both industrial and agricultural activity can cause pollution. (In the case of agriculture, the pollution consists largely of pesticide residues, fertilizers that cause eutrophication, and salt deposits from improper irrigation.) Pollution may affect the mortality of the population directly and also indirectly by decreasing agricultural output.[29]

There are several important feedback loops in figure 24. If everything else in the system remained the same, a population *increase* would decrease food per capita, and thus increase mortality, increase the number of deaths, and eventually lead to a population decrease. This negative feedback loop is diagramed below.



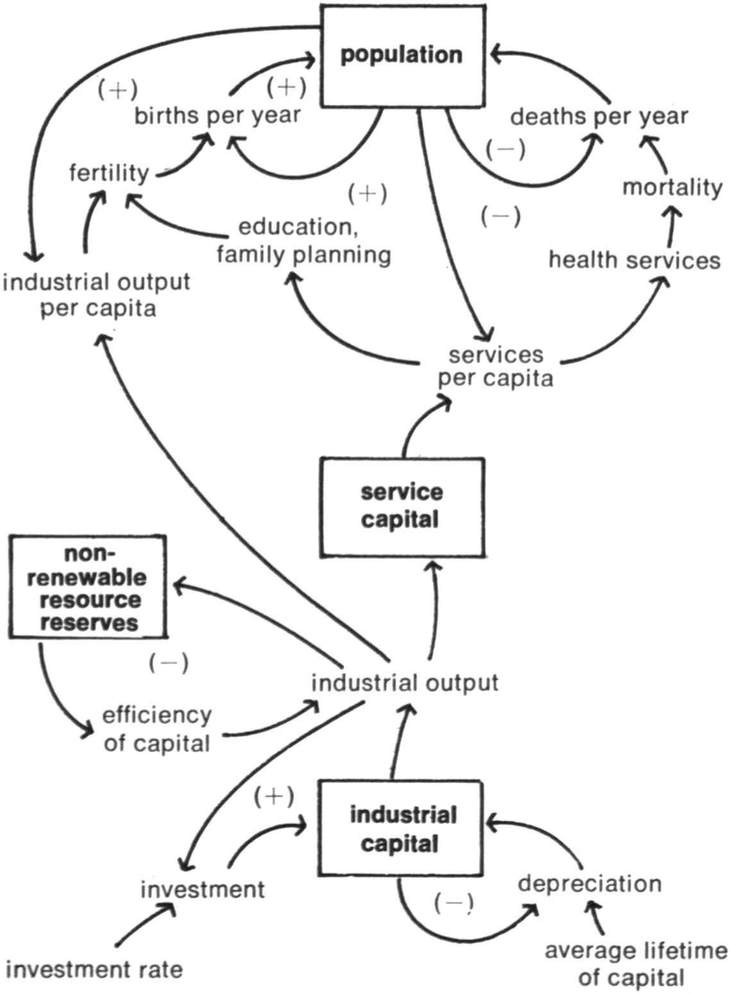
Another negative feedback loop (shown below) tends to counterbalance the one shown above. If the food per capita *decreases* to a value lower than that desired by the population, there will be a tendency to increase agricultural capital, so that future food production and food per capita can *increase.*



Other important relationships in the world model are illustrated in figure 25. These relationships deal with population, industrial capital, service capital, and resources.

Industrial output includes goods that are allocated to service capital—houses, schools, hospitals, banks, and the equipment they contain. The output from this service capital divided by the population gives the average value of services per capita. Services per capita influence the level of health services and thus the mortality of the population. Services also include education and research into birth control methods as well as distribution of birth control information and devices. Services per capita are thus related to fertility.

Figure 25 FEEDBACK LOOPS OF POPULATION, CAPITAL, SERVICES, AND RESOURCES

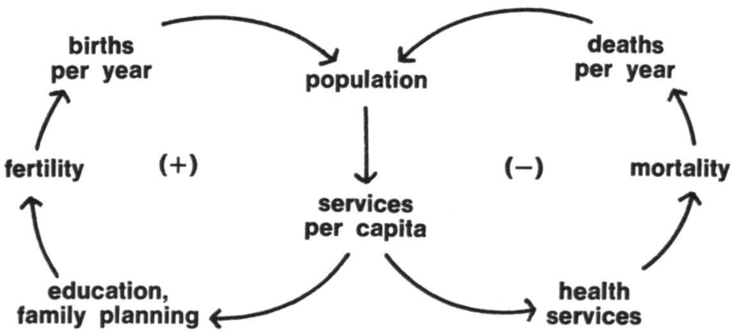


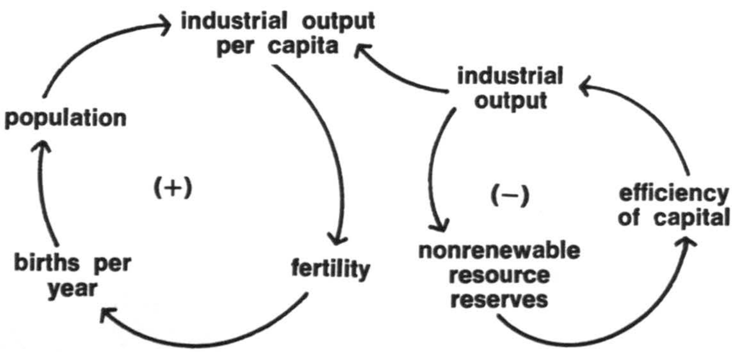
Population and industrial capital are also influenced by the levels of service capital (such as health and education services) and of nonrenewable resource reserves.

A changing industrial output per capita also has an observable effect (though typically after a long delay) on many social factors that influence fertility.

Each unit of industrial output consumes some nonrenewable resource reserves. As the reserves gradually diminish, more capital is necessary to extract the same amount of resource from the earth, and thus the efficiency of capital decreases (that is, more capital is required to produce a given amount of finished goods).

The important feedback loops in figure 25 are shown below.





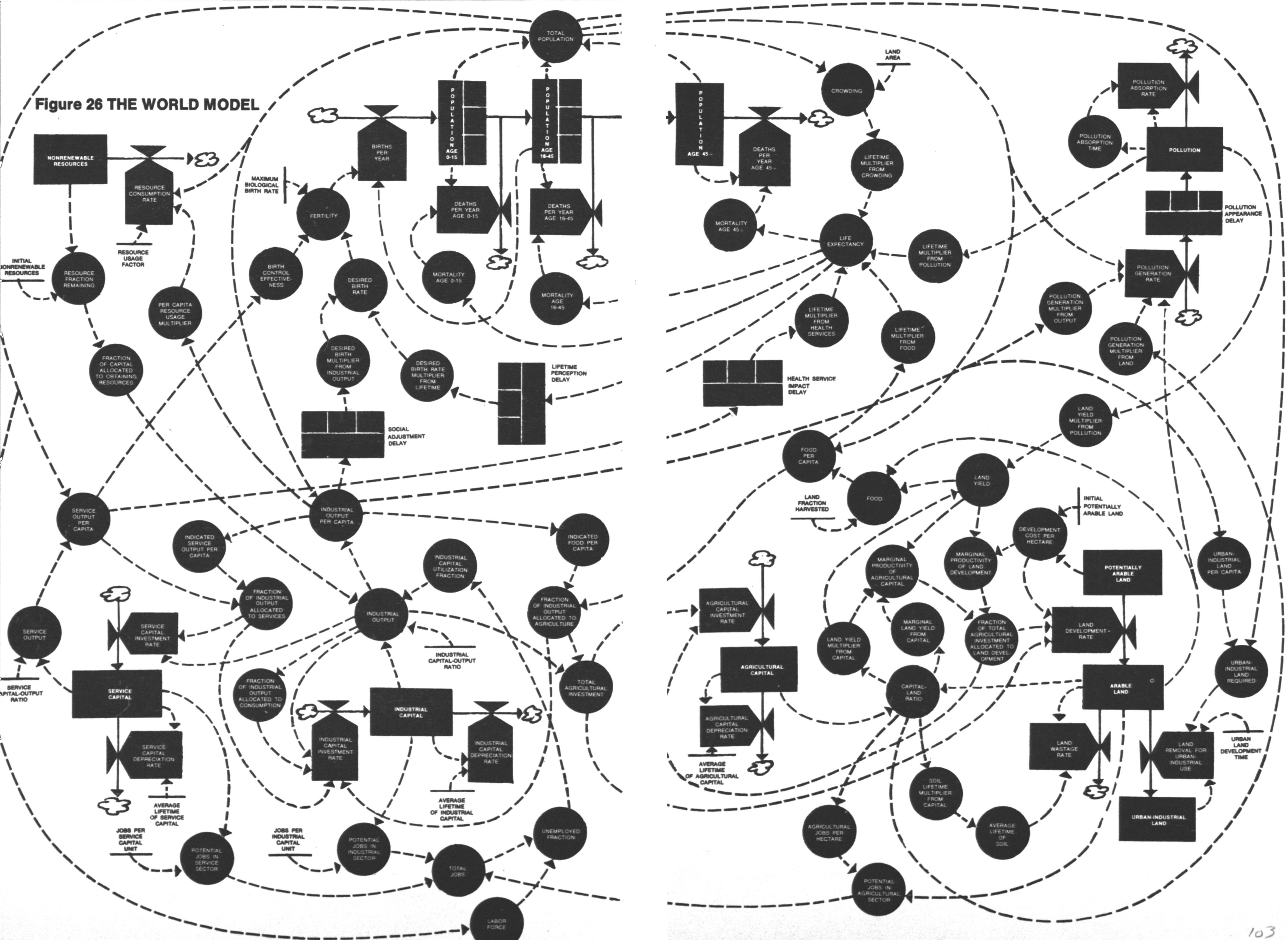


Figure 26 THE WORLD MODEL

Figure 26 THE WORLD MODEL

The entire world model is represented here by a flow diagram in formal System Dynamics notation. Levels, or physical quantities that can be measured directly, are indicated by rectangles ■, rates that influence those levels by valves, and auxiliary variables that influence the rate equations by circles ●. Time delays are indicated by sections within rectangles. Real flows of people, goods, money, etc. are shown by solid arrows → and causal relationships by broken arrows - - - - - ▸ Clouds represent sources or sinks that are not important to the model behavior.

The relationships shown in figures 24 and 25 are typical of the many interlocking feedback loops in the world model. Other loops include such factors as the area of cultivated land and the rate at which it is developed or eroded, the rate at which pollution is generated and rendered harmless by the environment, and the balance between the labor force and the number of jobs available. The complete flow diagram for the world model, incorporating all these factors and more, is shown in figure 26.

QUANTITATIVE ASSUMPTIONS

Each of the arrows in figure 26 represents a general relationship that we know is important or potentially important in the population-capital system. The structure is, in fact, sufficiently general that it might also represent a single nation or even a single city (with the addition of migration and trade flows across boundaries). To apply the model structure of figure 26 to a nation, we would quantify each relationship in the structure with numbers characteristic of that nation. To represent the world, the data would have to reflect average characteristics of the whole world.

Most of the causal influences in the real world are nonlinear.

That is, a certain change in a causal variable (such as an increase of 10 percent in food per capita) may affect another variable (life expectancy, for example) differently, depending on the point within the possible range of the second variable at which the change takes place. For instance, if an increase in food per capita of 10 percent has been shown to increase life expectancy by 10 years, it may not follow that an increase of food per capita by 20 percent will increase life expectancy by 20 years. Figure 27 shows the nonlinearity of the relationship between food per capita and life expectancy. If there is little food, a small increase may bring about a large increase in life expectancy of a population. If there is already sufficient food, a further increase will have little or no effect. Nonlinear relationships of this sort have been incorporated directly into the world model.*

The current state of knowledge about causal relationships in the world ranges from complete ignorance to extreme accuracy. The relationships in the world model generally fall in the middle ground of certainty. We do know something about the direction and magnitude of the causal effects, but we rarely have fully accurate information about them. To illustrate how we operate on this intermediate ground of knowledge, we present here three examples of quantitative relationships from the world model. One is a relationship between economic variables that is relatively well understood; another involves sociopsychological variables that are well studied but difficult to quantify; and the third one relates biological variables that

* The data in figure 27 have not been corrected for variations in other factors, such as health care. Further information on statistical treatment of such a relationship and on its incorporation into the model equations will be presented in the technical report.