# Should Population Projections Consider "Limiting Factors"—and If So, How?

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POPULATION QUESTIONS HAVE dimensions, scales, and purposes. Dimensions of population questions include economics, the environment, and culture in addition to demographic and social aspects (Demeny 1988, 1991; Cohen 1995). Population questions are also framed, explicitly or implicitly, at one or more temporal and spatial scales. Typical time scales are less than a generation, one or several generations, and millennia. Typical spatial scales are a small locality, an extended region, and the globe (Lutz 1994: 25–27; Rogers 1995). Population questions are usually asked with a purpose: for example, to identify, warn against, or prevent an undesirable state of affairs; to envision, promote, or give a path to a desirable state of affairs; or to analyze consequences of past trends or hypothetical mechanisms (Luten 1991).

The main points of this chapter can be summarized as follows. Whether and how population projections should consider limiting factors depend on the dimensions, scales, and purposes of the projections. For example, a projection with a five-year future horizon intended solely to illustrate the potential effect on the number of births in the United States that would result from a hypothetical 50 percent reduction in pregnancies among teenagers can safely neglect to consider possible constraints of water or fossil fuels. On the other hand, an illustrative projection of global population to the year 2150 (such as that prepared by the United Nations 1992) that assumes regional levels of fertility are constant at 1990 levels, while life expectancy continues to increase, might usefully comment that the calculated population of 694 billion in 2150 could not be fed with present-day conventional agriculture and conventional water sources because not enough water falls from the sky annually to grow the required crops.

Possible constraints of food and water are likely to be mediated through economic and political systems, rather than acting directly on rates of birth, death, and migration. Hence they should be taken into account in future population projections by means of models that explicitly represent economic and (where possible) behavioral, cultural, and political responses. Such models and the projections they yield depend on the continuation in the future of specified relationships among model variables. No one seems to know quantitatively how future rates of birth, death, and migration will respond to future population sizes, economies, environments, and cultures. No one seems to know how to project future economies, environments, and cultures with great reliability.

The plan of this chapter is to recall some early theory of limiting factors in relation to human population; to review a few concrete examples of population projections that argue in favor of considering limiting factors; to present arguments against considering limiting factors; and to make some practical suggestions that are differentiated by the dimensions, scales, and purposes of population projections.

## Some early theory

In 1798 Thomas Robert Malthus conjectured that human populations tend to increase exponentially with time and that food supplies increase at best linearly with time. When a population grows to the maximum size that can be sustained by the food available, he supposed, population growth ceases as a result of rising death rates. Malthus later allowed for the possibility that populations could also cease to grow because of reduced fertility, not only because of increased death rates.

In 1838 Pierre-François Verhulst noted that population can grow exponentially only in the absence of obstacles (Verhulst 1838 [1977]: 334): "The growth of the population necessarily has a limit, if only in the extent of the soil indispensable for the lodging of this population." By an analogy with physics, Lambert Adolphe Jacques Quételet had published in 1835 the suggestion that the obstacles to population growth were "proportional to the square of the speed with which the population tends to increase." Following this suggestion, Verhulst supposed that the rate of population increase equals the natural tendency to increase (which is proportional to population size) minus the resistance to population increase (which is proportional to the square of population size). Assuming that both time $t$ and population size $P(t)$ at time $t$ are continuous variables, Verhulst's differential equation for population growth can be written in the form $dP(t)/dt = rP(t)[K-P(t)]$, which he later named the logistic equation. This equation is not an exact translation of Malthus's ideas because here the $K$, which is the maximum possible population size, is assumed to be constant. (Malthus assumed that $K$ increased at most linearly with time.) Verhulst solved the differential equation to find the population size as a function of time. The function is the so-called logistic or S-shaped curve.

Raymond Pearl and Lowell Reed (1920) independently rediscovered the logistic equation, which Pearl regarded as analogous to Newton's laws of planetary motion. Pearl and his colleagues fitted the logistic curve to national and global historical population sizes (Pearl 1924; Pearl and Gould 1936). They apparently did not recognize that if individual countries grow logistically, then the global population (being the sum of logistic curves) would not be expected to grow logistically.

When Verhulst fitted the logistic curve to Belgian population data, he predicted a maximum population size of 9.4 million, not far from the mid-1998 estimated population of Belgium of 10.2 million. Pearl and Reed (1920), ignoring changes in the territory of the United States since the first census in 1790, predicted a maximum size for the US population of 197 million, well below the mid-1998 estimated population of 270 million. Pearl's 1924 estimate that the maximum population of the world would be 2 billion people was well below the 6 billion or so expected at the end of the twentieth century. Logistic population projection based on population size and a single limiting factor has fallen into disrepute among professional demographers.

Today population projections prepared by virtually all governmental and most academic demographers rely on the cohort-component method proposed by the English economist Edwin Cannan (1895). The cohort-component method rests on the rates of birth, death, and migration without explicit regard to any dimensions external to demography such as agriculture, ecology, economics, politics, and culture, among others. P. H. Leslie (1945) and others restated Cannan's projection method in the mathematical language of matrices. The population projection matrix is now often called the Leslie matrix, though Leslie later recognized that he was not the first to propose it.

Leslie (1948) suggested that external factors, dependent on population size, could alter the birth and death rates represented by elements of the Leslie matrix. He considered in detail two cases: an increase in mortality by a factor independent of age (and linear in population size), while fertility remains constant; and a decrease in fertility by a factor independent of age (and linear in population size), while mortality remains constant. Although he discussed experiments with caged insect populations, Leslie did not address how his density-dependent matrix models would be applied to projections of human populations.

In the 150 years between Malthus's First Essay on population and Leslie's logistic growth in matrix language, little progress was made in identifying reliable empirical connections between putative external factors like food supply and specific components of demographic changes like birth, death, or migration. The connections between external factors and demographic rates are sure to be complex, as they depend on behavioral, institutional, and cultural factors that vary in time and space.

## Agriculture and population in Bangladesh

Robert Chandler, the founding director of the International Rice Research Institute in Manila, the Philippines, criticized the World Bank's cohort-component projections for Asia because they neglected constraints like population density and grain yields that were external to the projections:

> In my view it seems extremely unlikely that average Asian rice yields will ever exceed 6 [metric tons per hectare], which is double the current level. Yet [some] demographers estimate that world population will at least double before it becomes stabilized, and some predictions even place the ultimate population at twelve to fifteen billion. If such projections prove correct, global food production resources will be strained to the limit and . . . the environment will be severely damaged. . . . Bangladesh . . . now [ca. 1990] has an estimated population of 113 million, which is increasing at the rate of about 2.4 percent annually. The density is 2,028 people per square mile [783 per square kilometer], 80 percent of whom live in rural areas. The land area is about 55,000 square miles [142,000 square kilometers], roughly that of the state of Georgia [United States], which, by contrast, has a population of 6.2 million and a density of 106 per square mile [41 per square kilometer]. . . . More than half the rural population [of Bangladesh] is landless and is severely underemployed. Over 70 percent of the farms are less than one hectare in size. I cannot conceive of Bangladesh supporting the 342 million people predicted by the World Bank. (see Kotler 1990: 175–177)

Chandler objected that the World Bank's use of the cohort-component method neglected certain agricultural and social constraints that he assumed would apply in the future. Chandler's criticism of the Bank's projection as being too narrowly based is itself subject to the same criticism. An economist looking at Chandler's comment might object that Bangladesh need not necessarily grow enough to feed its people if it can produce something else of value and trade for food with areas that have an agricultural surplus. Places that do so include Hong Kong, Singapore, and, increasingly, Israel.

An ecologist might suggest that both Chandler and the World Bank neglect the threats to maintaining the current level of agricultural production from increasing deforestation upstream and beyond the territory of Bangladesh (Brown and Kane 1994) and from possibly rising sea levels downstream, both of which may flood the land of Bangladesh.

An anthropologist might note that even if Bangladesh's current population density tripled to 6,000 per square mile, as the World Bank's projection implied, that density would be less than half of Hong Kong's population density of nearly 16,000 per square mile (Population Reference Bureau 1995). Whether Bangladeshis can make a stable transition to such densities may be constrained (or favored) by behavioral patterns, class differences, cultural norms, and politics long before agricultural, ecological, or economic factors intervene.

It seems plausible to argue that the World Bank's population projections should have considered some of these factors, but the half-century of research since Leslie's 1948 paper has provided little empirical guidance about how best to do so.

## Fresh water as a limiting factor for irrigated cultivation

Of the roughly 113,000 cubic kilometers of fresh water that fall every year on Earth's land (Engelman and LeRoy 1993: 11), about 72,000 cubic kilometers evaporate or are transpired back to the atmosphere, leaving about 41,000 cubic kilometers to replenish aquifers or return to the ocean as runoff. People can capture for use only a fraction of those 41,000 cubic kilometers per year. About 28,000 cubic kilometers run off as flood waters while the renewable infiltration of stable underground flow into rivers is about 13,000 cubic kilometers (World Resources Institute 1992: 160).

Of the 28,000 cubic kilometers per year of flood runoff, the usable portion depends on the capacity of human-made dams and lakes and on how often the water in such reservoirs is turned over. Of the roughly 13,000 cubic kilometers per year of water that infiltrates the soil, about 4,000–5,000 cubic kilometers per year fall on uninhabited areas; how much of this water can be used depends on technology for capturing and transporting it. This leaves about 9,000 cubic kilometers of infiltrated water or stable underground flow in regions where people live. The world's *available* renewable fresh water lies somewhere between the 9,000 cubic kilometers per year of stable underground flow in inhabited regions (World Resources Institute 1992: 160) and the 14,000 cubic kilometers per year that would be available if the stable underground flow in uninhabited regions could be used, plus the usable capacity of human-made dams and reservoirs (also see Postel, Daily, and Ehrlich 1996).

Expert estimates of the volume of water in human-made dams and reservoirs vary surprisingly widely: World Resources Institute (1992: 160) gave 3,000 cubic kilometers; Shiklomanov (in Gleick 1993: 14) gave 5,000 cubic kilometers; Chao (1995) gave more than 10,000 cubic kilometers. Numerous other estimates fall between these extremes. The variation among estimates is probably not attributable to real changes between the dates of the publications. The useful capacity of reservoirs is estimated at less than two-thirds of their total capacity (L'vovich 1987: 831–839). Estimates of other water volumes also vary widely. Cohen (1995: Chapter 14) gives a fuller picture of the significant uncertainty behind estimates of water stocks and flows.

Overall, in 1990, when the world's population was about 5.3 billion and the renewable supply of fresh water totaled 41,000 cubic kilometers per year, the average renewable fresh water per person per year totaled about 7,700 cubic meters. However, renewable water supplies vary widely by region. The United States has about 9,900 cubic meters of renewable fresh water per person per year. The average person in Djibouti, the most water-scarce country in the world, has available some 23 cubic meters of fresh water per year. The average person in Iceland has available about 29,000 times as much (Engelman and LeRoy 1993: 44). These are the extremes. Israel, with 461 cubic meters per person, has half the available fresh water of Somalia, with 980 cubic meters per person, although Israel's 1989 gross national product per person was roughly 57 times Somalia's (World Resources Institute 1992: 236–237).

Renewable water supplies also vary sharply over time. The El Niño Southern Oscillation in the surface-water temperature of the equatorial Pacific Ocean drives a major surge every three or four years in the rainfall and flooding of many regions of the globe. Because rare floods carry large volumes of water, the streamflow that is available 95 years in 100 is sometimes less than half the century-averaged streamflow.

How many people the Earth's renewable water supply can support at a given level of wellbeing cannot be calculated without knowing how much water is required to maintain viable ecosystems; how much water future industry will buy under future arrangements for the delivery and sale of water; how much flood runoff can be captured; how much fresh water can be recycled; how efficient water piping systems will be; and a host of other factors equally difficult to predict.

Despite these difficulties, I can estimate a number such that more people cannot possibly be supplied with enough water for domestic use and for food grown by conventional irrigated—I emphasize *irrigated*—agriculture. In dividing the Earth's terrestrial renewable water supply—rivers and aquifers only—into a maximal number of equal portions, I am assuming that the people who, by accidents of geography, have more such water will share it evenly (at some price) with those who have less; that there are no obstacles of technology, economics, or politics to transporting the water to the people and farms where and when it is wanted, or equivalently no obstacles to transporting the food produced where water and soil are abundant to the people who want it; that variations from year to year in this water supply can be smoothed so that the average and not the minimum or the 95-years-in-100 water supply constrains population size; and that fertile soil is available in excess to grow as much as this water supply will support.

These assumptions are not credible. For example, the assumption of excess available fertile soil is false in most of central and western Africa, where sandy, relatively infertile soils derived from granite erode severely when cleared of forest. Large areas of Africa cannot be economically irrigated because of topography and geology (Robert F. Chandler, Jr., in Kotler 1990: 178). Why make assumptions known to be false? I make these assumptions so that I can do some arithmetic and learn something from the result. An estimate of maximum supportable population made on these assumptions is an extreme upper bound on the additional population that could be supported by irrigated agriculture alone, using present wheat cultivars without recycling of transpired water. Other forms of food production, such as the growth of fish in brackish ponds, are not considered here.

Because wheat plants transpire about 500 tons of water for every ton of wheat plants at the end of the growing season, and roughly half the plant is grain, and there are roughly 4 kilocalories of food energy per gram of grain, a simple calculation yields a rule of thumb that 1,000 daily kilocalories of food energy from wheat require about 100 yearly metric tons of water from precipitation or irrigation, at a minimum. Wheat is used here for illustration, though perhaps two-thirds of the world relies on rice as the staple grain.

I calculated freshwater requirements under two extreme assumptions about the fraction of available water (defined as river runoff plus infiltration to aquifers) that can be captured for use (20 percent and 100 percent), two extreme assumptions about the average dietary calories of plant food that consumers might demand (2,350 kilocalories per day and 10,000 kilocalories per day—the latter for a diet with a high proportion of calories from domesticated animals raised on feed grains), and two extreme assumptions about losses during plant growth, processing, and distribution (10 percent and 40 percent). With all possible combinations of extreme assumptions, I considered 2 x 2 x 2 = 8 scenarios. Each is summarized in one row of Table 1. I assumed for illustration three levels of available fresh water: 41,000, 14,000, and 9,000 cubic kilometers per year (as shown in the last three columns of Table 1).

If 100 percent of available water is assumed to be used for domestic purposes and agriculture, then no water is set aside for industry or ecosystem services, and no groundwater or runoff reaches the sea or evaporates without passing through human households or agriculture. I regard such scenarios as illustrative, not as remotely realistic.

The choices among these scenarios are likely to be determined by relative prices and by cultural factors that are even more difficult to predict than prices. I am unable to construct a plausible model to project all the relevant prices in response to changes in the fraction of available water

**TABLE 1 Renewable freshwater requirements per person for irrigated agriculture, and the maximum population that can be provided with domestic water and food produced entirely from irrigated agriculture, under various assumptions**

| If the fraction of available renewable fresh water in rivers and aquifers that can be used is (percent) | and the average diet requires the growth of wheat that yields (kilocalories per day) | and the fraction of calories lost is (percent) | then the amount of renewable fresh water that must be available for irrigated food crops alone is (cubic meters per year per person) | If 41,000 cubic kilometers per year of water are available, then the maximum population is (billions) | If 14,000 cubic kilometers per year of water are available, then the maximum population is (billions) | If 9,000 cubic kilometers per year of water are available, then the maximum population is (billions) |
|---|---|---|---|---|---|---|
| 20 | 2,350 | 10 | 1,306 | 30.5 | 10.4 | 6.7 |
| 20 | 2,350 | 40 | 1,958 | 20.5 | 7.0 | 4.5 |
| 20 | 10,000 | 10 | 5,556 | 7.3 | 2.5 | 1.6 |
| 20 | 10,000 | 40 | 8,333 | 4.9 | 1.7 | 1.1 |
| 100 | 2,350 | 10 | 261 | 137.5 | 47.0 | 30.2 |
| 100 | 2,350 | 40 | 392 | 95.6 | 32.7 | 21.0 |
| 100 | 10,000 | 10 | 1,111 | 35.7 | 12.2 | 7.8 |
| 100 | 10,000 | 40 | 1,667 | 24.1 | 8.2 | 5.3 |

NOTE: Calculations assume that 1,000 kilocalories per day of humanly edible wheat require 100 cubic meters per year of usable fresh irrigation water. (Actual use of water in the United States is about four times this minimal amount.) The amount of renewable fresh water that must be available (in cubic meters per year per person) = (kilocalories per day)/[10 x fraction of water used x (1 – fraction of calories lost)]. Example: 2,350/(10 x 0.2 x 0.9) = 1,306. The maximum population supportable with 37 cubic meters of water for domestic use plus food from irrigated agriculture (in billions) = 41,000/(37 + cubic meters per year per person for food). Example: 41,000/(37 + 1,306) = 30.5.
SOURCE: Cohen (1995: 316). Copyright©1995 by Joel E. Cohen.

that is used, the global demand for calories from animal products, the fraction of food lost before people eat it, capital investments in water infrastructure, energy prices, and other factors that affect the amount of available renewable fresh water. Consequently, Table 1 describes alternative water scenarios without mention of prices.

The estimated agricultural water requirements in Table 1 range from 261 cubic meters per year per person (with 100 percent use of the available water, low dietary requirements, and low food losses) to 8,333 cubic meters per year (with the opposite assumptions). If (unrealistically) all 41,000 cubic kilometers of renewable water are available, the upper bounds on the size of the population that could be fed from irrigated agriculture range from 137.5 billion with the lowest water requirements to 4.9 billion with the highest water requirements. If only 20 percent of renewable fresh water from runoff and infiltration is available for domestic and agricultural use, and if people want a diet that requires the equivalent of 10,000 kilocalories per day of wheat, and if losses of food are reduced to only 10 percent, then the maximum population supportable by irrigated agriculture is 7.3 billion (under all the above idyllic assumptions about sharing and distribution of water and availability of fertile land). The upper bounds range from 30.2 billion people to 1.1 billion people if only 9,000 cubic kilometers of renewable fresh water are available.

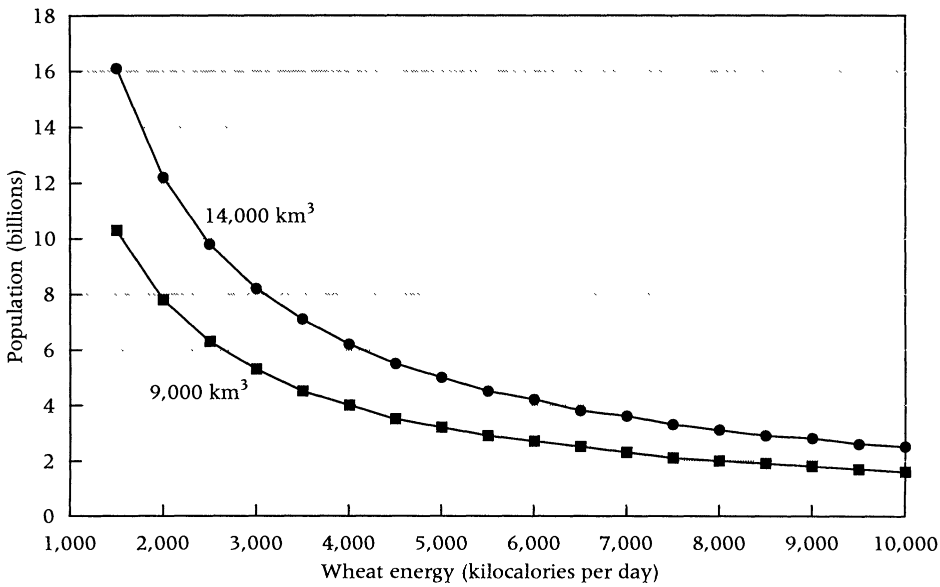
The assumptions required to obtain these figures are numerous and doubtful. Rainfed agriculture is not included, for example. Nevertheless, it is instructive to observe that the hydrological cycle does not supply enough river water and groundwater to irrigate food grown by conventional agriculture for the populations at the upper extremes estimated by Clark (1977) (157 billion) and De Wit (1967) (1,022 billion). Unless there is a revolution in the productivity of rainfed agriculture, the Earth's production of human food is likely to be limited by renewable fresh water for irrigation before it is limited by photosynthesis, as in De Wit's (1967) calculation.

For the year 2150, the United Nations (1992) low, medium, and high projected populations are 4.3 billion, 11.5 billion, and 28.0 billion. The projection with fertility at replacement level from 1990 onward gives 8.4 billion and the projection with constant 1990 fertility rates gives 694.2 billion. The limited renewable freshwater supply of the Earth is too small for the constant-fertility projection to come true. If every drop of the 110,000 cubic kilometers of water that fall on land were used domestically and for rainfed or irrigated agriculture, and if people ate only 2,350 kilocalories per day and lost only 10 percent of food before consumption, the maximum possible population would be 369 billion; if people captured only 20 percent of the total precipitation over land for domestic use and agriculture (rainfed or irrigated), the maximum population would be 82 billion.

Rising incomes in some developing countries are permitting people in those countries to eat more meat and other animal products. As the fraction of daily calories in the human diet derived from animals increases, the required primary energy supplies (the plant calories required to feed humans and their domestic animals) increase. As the required daily primary energy supplies increase, the population that can be supported by conventional irrigated agriculture decreases (Figure 1). The special assumptions underlying the two curves shown in Figure 1 (namely, 20 percent use of all available water for domestic purposes and agricultural irrigation, and 10 percent loss of food between growth and consumption) are no more plausible than various other assumptions that could have been chosen. The larger the desired daily food energy, the smaller the difference between the curves for annual water supplies of 14,000 cubic kilometers and 9,000 cubic kilometers. As daily calories rise from very low levels, the supportable population drops rapidly at first, then more slowly.

It would be desirable to carry out such calculations for individual countries (Engelman and LeRoy 1993), because these global calculations have

**FIGURE 1 Upper limits on world population set by requirements of water for domestic use and irrigated agriculture of wheat, assuming 20 percent use of available water and 10 percent loss of food between growth and consumption. The upper curve assumes available renewable annual water supplies in rivers and aquifers of 14,000 cubic kilometers per year; the lower curve assumes 9,000 cubic kilometers per year. Important additional assumptions are set out in the text**

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little relevance to humid, temperate regions like Sweden or the eastern United States, where the growth of plants is limited more by light and temperature than by water.

## Ten thousand years: A glance backward and forward

Around 10,000 years ago, there were roughly 6 million people on Earth. (A plausible range is from 2 million to 20 million.) Today there are about 6 billion people. (This figure is probably reliable to within a quarter billion.) The human population increased by a factor of about 1,000 in 10,000 years. An increase by a factor of 1,000 represents fewer than ten doublings in population size. On the average, the human population doubled no more often than once per millennium.

Now look to the future. If humans exist after another ten millennia, the average population growth rate from now until then cannot exceed the average growth rate over the past ten millennia. Why not? If the population as much as doubled for each of the next ten millennia, it would increase by another 1,000-fold, from roughly 6 billion now to 6 trillion ($6 \times 10^{12}$) people. The total surface area of the Earth, including oceans, lakes, streams, icecaps, swamps, volcanoes, forests, highways, reservoirs, and football fields, is 510 million square kilometers. With a population of 6 trillion, each person would be allotted a square area less than 10 meters on a side. This area may be commodious as a jail cell, but seems very unlikely to be capable, on average over the oceans and continents of the Earth, of supporting a person with the food, water, clothing, fuel, and physical and psychological amenities that distinguish people from ants or bacteria. Certainly not enough water falls from the sky to grow the plants required to nourish that number of people by conventional agriculture, according to the calculations in the preceding section. No optimist, if that is the right word, has suggested that people would choose, individually and collectively, a world in which 6 trillion people occupy the Earth, even if such a world were ecologically and technologically possible. It follows that, for the next ten millennia, the average future population growth rate cannot exceed a doubling every millennium, or an average growth rate of 0.069 percent per year.

The same argument applies to the estimated 1995 population growth rate of 1.6 percent per year. If growth of 1.6 percent per year persists for 436 years, the population will have increased at least 1,000-fold. If a world of 6 trillion people in the distant future is not humanly acceptable (whether or not it is ecologically and technologically possible), it seems even less likely to be acceptable 436 years from now, given plausible changes in human values, institutions, knowledge, technologies, and capital assets. If people and the planet will not tolerate a tenfold, rather than a 1,000-fold, increase in population size to 60 billion, then the present global growth rate cannot continue even another 150 years.

While these calculations are uncontroversial, I believe they are also uninformative about the possible trajectories of, and possible constraints on, human population sizes, globally and locally, in the coming century and a half.

## System models

During and after World War II, military analysts developed methods, known by the general title of "systems analysis," to track and project very complex situations. After the war, concepts of systems analysis were applied to nonmilitary problems. At the Massachusetts Institute of Technology in the 1950s, Jay Forrester promoted the use of system models to simulate industrial and urban problems. In recent decades, numerous system models have tried to describe human populations interacting with energy, agriculture, pollution, and other nondemographic phenomena (Forrester 1971; Randers and Meadows 1972; Meadows et al. 1972; Cole et al. 1973; Mesarovic and

Pestel 1974; van de Walle 1975; House and Williams 1975; Gever et al. 1986; Gilbert and Braat 1991; Meadows, Meadows, and Randers 1992; Sanderson 1995; Lee 1986, 1988, 1992, 1993). Some of these are complex computer simulations; some are small, intellectually transparent sets of equations; and some are intermediate in complexity. Of 12 large-scale urban models reviewed by Wegener, only three modeled demographic change and household formation (Wegener 1994: 22; see also the reviews of urban models by Klosterman 1994 and Lee 1994).

In 1972 protégés of Forrester produced what was undoubtedly the best-advertised example at that time. An MIT study team led by Donella Meadows, Dennis Meadows, Jørgen Randers, and William Behrens III published a small book, *The Limits to Growth.* The book predicted dire futures from a continuation of what it represented as current trends.

Meadows and her colleagues constructed a computer model for five variables: population, food, industrialization, nonrenewable resources, and pollution. Their model, called World3, was a refinement of earlier models, World1 and World2, proposed by Forrester. The World2 model was published in full detail in Forrester's (1971) *World Dynamics.* Meadows et al. adjusted World3 to fit values of the five variables estimated from historical or putative data for the years 1900 to 1970. They then computed the consequences of various assumptions about the future. Alternatives included, among others, a continuation of previous trends, a doubling of resources with limitless energy, and a doubling of agricultural yields with a fourfold reduction of pollution per unit of industrialization. These scenarios were presented as conditional predictions, as sketches of what would happen if the growth in human population and industrial output continued according to the authors' model of their past dynamics.

In all the scenarios considered, population and industrialization surged upward and then fell sharply. Meadows et al. concluded that this pattern, which they called "overshoot and collapse," is a fundamental property of World3:

> *The basic behavior mode of the world system is exponential growth of population and capital, followed by collapse. . . .* [T]his behavior mode occurs if we assume no change in the present system or if we assume any number of technological changes in the system.
>
> The unspoken assumption behind all of the model runs we have presented . . . is that population and capital growth should be allowed to continue until they reach some 'natural' limit. (Meadows et al. 1972 [1974 ed.]: 149; emphasis in original)

Meadows et al. inferred that overshoot and collapse are fundamental properties of both their model and the world itself.

*The Limits to Growth* excited a storm of public and scholarly argument (e.g., Kaysen 1972; Cole et al. 1973; Nordhaus 1973; Berlinski 1976; Ehrlich, Ehrlich, and Holdren 1977: 730–733). Even after two decades, there seems to be little consensus about the value of the conclusions of *The Limits to Growth*. (For the controversy over the 1992 reprise by Meadows, Meadows, and Randers, see Lippman 1992.) T. N. Srinivasan (1987: 4), an economist at Yale, dismissed the 1972 study as an example of "simple trend analyses and mechanical models devoid of economic content." By contrast, Kingsley Davis (in Davis and Bernstam 1991: 11–12), a demographer then at the University of Southern California and Stanford University, wrote in 1991 that "one cannot ignore developments in the last two decades that tend to support the study's findings." After giving numerous examples, he concluded, "Thus the grisly truth may turn out to be that *Limits* was more prophetic than its detractors and even some of its defenders thought possible."

In one critique, Cole et al. (1973: 125–134) at the Science Policy Research Unit of the University of Sussex, England, mounted the World2 model of Forrester and the World3 model of Meadows et al. on their own computer. They showed that the models are by no means fated to overshoot and collapse. Meadows et al. considered the possibility of a one-time, large advance in technology; they found that population, industrial output, and food still overshoot and collapse. Cole et al. found, on the contrary, that if a single, large technological advance is replaced by continuous, small incremental improvements in the technology of food production, resource recycling, fertility reduction, and pollution control, then overshoot and collapse can be replaced by more or less steady growth in industrial output per person, population, and food. The alternative assumptions may be more or may be less plausible than the originals, depending on one's prejudices. Either way the exercise casts much doubt on the claim that overshoot and collapse are inevitable properties of the models and of the world.

*Limits* argued that, if the physical relationships of production and consumption assumed in World3 (as an approximation to what happened in the real world from 1900 to 1970) persist unchanged, there will soon be a collision with the finiteness of the world, and therefore those physical relationships will be forced to change. In short, according to *Limits*, the absence of a change of technology implies a catastrophic change (or collapse) of technology. Is there useful news here? Most people are aware that the physical, economic, political, and cultural relationships of production and consumption are constantly shifting in response to changing values, preferences, environmental conditions, technology, and prices. Is it more plausible to posit a rigidly unchanging world system that collapses when it encounters constraints, or a world system that adapts incrementally (albeit sometimes unevenly and inefficiently)?

In World3, the number of births was assumed to be determined by total fertility, which in turn was affected by six factors: population size, the fraction of fertile women in the population (set at a constant 22 percent), the reproductive lifetime (set at a constant 30 years), maximum total fertility or biological fecundity (normally 12 children when life expectancy is 60 years, but changing with life expectancy), average desired total fertility, and birth control effectiveness. The last was assumed to depend on service output per person, including health services. Desired total fertility depended on a "compensating multiplier from the perceived life expectancy" (assuming that, if parents perceive that their children will survive longer, they will bear fewer children to achieve the completed family size they want) and on "desired completed family size" (normally set to four children). Desired completed family size was modified by a "family norm multiplier from income expectations," which in turn depended on income expectation, and by a "family norm multiplier from social structure." Both income expectation and the "family norm multiplier from social structure" depended on industrial output per person. A similarly complex set of relationships was posited to predict deaths per year.

In the 1992 reprise and refinement of World3, called World3/91, Meadows, Meadows, and Randers (1992: 240–241) maintained the structure of World3 but renamed the elements. The 1992 model population had four age groups: 0–14 years old, 15–44, 45–64, and 65 and older. Meadows, Meadows, and Randers found that the old World3 failed to predict the speed of decline in both global birth and death rates since 1972. They therefore adjusted World3/91 to bring it in line with historical experience (Meadows, Meadows, and Randers 1992: 247–249).

A whole academic industry is devoted to elucidating the so-called determinants of fertility by econometric and statistical means. Historical demographers have encountered great difficulty in predicting population change from social and economic variables. One would never know it from *World Dynamics* or *The Limits to Growth*. The real question concerning system models, as Cannan wrote in 1895, is "whether we shall be content with estimates which have been formed without adequate consideration of all the data available. . . ."

In a critique of *World Dynamics*, William Nordhaus, a Yale economist, wrote: "The treatment of empirical relations . . . can be summarised as *measurement without data*. The model contains 43 variables connected by 22 non-linear (and several linear) relationships. *Not a single relationship or variable is drawn from actual data or empirical studies*" (Nordhaus 1973: 1157; emphasis in original).

*World Dynamics* suffers from other omissions as well (Nordhaus 1973: 1158; Kaysen 1972: 665; Cole et al. 1973: 202). The model omits the possibility of devoting resources to reducing the production of pollutants or cleaning them up. It omits technological progress, the discovery of resources, and the invention of substitute materials. The model has no system of prices to reflect scarcities and induce substitutions and shifts in behavior. The model treats all effects as instantaneous: there is no lag in the effects of crowding or pollution on the birth rate, no lag in the effect of any variable on any other. The model ignores differences between poor and rich countries, differences among poor countries, differences among rich countries, and differences within countries. All the system models omit shifts in goals, values, and priorities, as well as the political processes that mediate the conflicts among goals, values, and priorities.

By 1992 Meadows, Meadows, and Randers had come to appreciate the limits of system models. One indication was the chapter in *Beyond the Limits* devoted to statistical data on factors that could limit the growth of population and industrial output. Another indication, relevant to the choice of a method of population projection, was the explicit disclaimer with which Meadows, Meadows, and Randers introduced World3/91: "It is not possible to make accurate 'point [that is, numerically exact] predictions' about the future of the world's population, capital, and environment. No one knows enough to do that. And the future of that system is too dependent on human choice to be precisely predictable" (Meadows, Meadows, and Randers 1992: 108–110).

Although less in the public eye, large-scale urban planning models have passed through a similar evolution in the last quarter-century (Klosterman 1994; Lee 1994; Wegener 1994).

## Arguments against the use of limiting factors in population projections

So far I have given arguments in favor of considering external constraints on population change along with some primitive examples of how to do so. It is not obvious to everyone, however, that it is a good idea to consider external factors in making population projections. External factors must be projected into the future to anticipate how they will affect population, and it may be even more difficult to project the external factors than to project population.

When I raised the question of whether and how limiting factors should be considered in population projections, in a seminar at the Population Studies Center of the University of Michigan in Ann Arbor (11 March 1996), the director of the Center, economist David Lam, and others argued against the use of limiting factors. Lam said he was more confident of demographic projections than of other projections because, in the past, the best projections have been demographic. Technological changes are the most important and least predictable factors that affect the possible sizes of future human populations, he argued.

At the same seminar, Stephen Schneider, an atmospheric scientist, argued that environmental fluctuations affect human carrying capacity: in anticipation of such fluctuations, future human populations may realize the importance of maintaining reserve capacity. To the extent that future humans choose to maintain reserve capacity, the effective carrying capacity of Earth would be reduced, but by how much seems impossible to quantify now.

Other participants in the seminar also did not favor constraining population projections by external factors. They pointed out that, as difficult as technological and environmental changes are to predict, it is equally difficult to predict energy supplies, socially acceptable standards of living, and governmental policies that influence fertility, mortality, and migration. For example, the government of Singapore, an island state with nearly 13,000 people per square kilometer (Population Reference Bureau 1995), a population density exceeded only by those of Macao and Hong Kong, changed from a fertility policy of "stop at 2" from 1965 to the mid-1980s to a policy of "have 3 or more if you can afford it" for economic and political reasons (Teo 1995). This decision could not readily have been predicted from ecological accounts of the relationship between population size and natural or agricultural resources, and is conceivable only in a world economy where other countries grow food and are reliably willing to trade it. Thus the "limiting factors" that affect one country may depend on the "limiting factors" that affect other countries far away.

## How to recognize limiting factors in population projections

Population projections display the numerical consequences for future population of assumptions about future rates of birth, death, and migration. Projections are thus conditional predictions, given the assumptions. It seems consistent with the conditional nature of population projections to enlarge the set of assumptions where there is a compelling need to do so. However, preparing an informative projection that incorporates economic, environmental, and cultural assumptions will require information and skills that go beyond traditional demographic training. Interdisciplinary self-education or collaboration may be required.

The arguments in the previous section against considering external factors in population projections can be addressed by stating that the economic, environmental, and cultural assumptions underlying a projection, and the assumed linkages to demographic rates, may be just as unreliable as the demographic assumptions.

I will give an example of what might be possible, starting with some background. Faye Duchin and Glenn-Marie Lange (1994) and William Nordhaus (1994) independently developed models of the future of the world economy and future emissions of selected greenhouse gases. They differed widely in methods of economic forecasting, levels of disaggregation, representation of technology, and extent of feedback from the environment to economic activities. However, both studies represented human population growth as exogenous, uninfluenced by economic or environmental conditions. Duchin and Lange (1994: 13–14) used a single United Nations medium-variant population projection for all scenarios. Nordhaus (1994: 12) assumed that the global population growth rate would decline by a constant fraction each year. In a regionally disaggregated extension of Nordhaus's original model, Nordhaus and Yang (1996: 744) apparently used a single United Nations projection. Yet Nordhaus's sensitivity analysis of the original globally aggregated model showed that the outcome variables of interest were more sensitive to the assumed rate of decline in the global population growth rate than to any other parameter (Nordhaus 1994: 142).

These economic-environmental models could be used, in their present form, to explore the economic and environmental consequences of alternative population projections. With minor modifications, the models could be used to compare the costs and benefits of family planning, reproductive health, other public health measures, and public education with the costs and benefits of other policies to affect economic wellbeing and environmental quality. For example, Nancy Birdsall (1992) estimated that industrial nations would reduce global carbon dioxide concentrations more per dollar spent for family planning and girls' education in developing countries than per dollar spent on carbon taxes in industrial countries. Her result could be tested in more comprehensive models than she considered by using cost estimates for family planning and girls' education plus plausible estimates of the association between female education and reduced fertility in developing countries. For example, Yousif, Goujon, and Lutz (1996) gave projections for North Africa by age, sex, and educational status. Associations between indicators of economic wellbeing (such as the level of income and female education) and levels of fertility and mortality could be added to the models to make the population projections endogenous (i.e., determined within the models, rather than fixed externally). The uncertainties of translating associations into assumed causation should be prominently advertised. Sensitivity analyses of assumptions in the models should be carried out to quantify uncertainties.

## Conclusions

The dimensions, scales, and purposes of a population projection must be considered in deciding whether and how to take account of limiting factors in a particular case.

The use of limiting factors or external constraints in population projections is inappropriate if the purpose of a projection is solely to illustrate the demographic consequences of an assumed set of demographic rates (for example, as a counterfactual hypothetical). Two arguments against the use of limiting factors are that the limiting factors or external constraints may be more difficult to project than the population itself; and that external factors, though foreseeable, may not be linked in a predictable way to components of population growth.

Even when external factors do not shape a population projection, however, it often seems illuminating to comment on what a projection implies for external factors such as population density, supplies of inputs such as food and energy, or disposition of outputs and wastes such as greenhouse gases. Especially valuable are observations about the incompatibility between a changed future population and unchanged technology or economics or culture. For example, if the world has 694 billion people in 2150 (as in the United Nations 1992 constant-fertility illustrative projection), they will not be eating grain grown by conventional rainfed or irrigated agriculture. Such comments draw attention to necessary eventual changes in population trends or in technology, economics, the environment, or culture.

Population projections that are influenced by external factors are sometimes appropriate. Projections might assume different governmental policies about immigration and fertility (e.g., Bouvier and Grant 1994). For countries with authoritarian governments, whether relatively rich (Romania under Ceaucescu) or relatively poor (China), governmental prohibitions of contraception (Romania) or reproduction (China) may play a role in population projections. In China, governmental control of the number of births as a function of time has been explicitly modeled in population projections (Song and Yu 1988). For economically less developed countries like Djibouti with few assets that are currently recognized as resources and with limited opportunities for trade, it seems useful to consider water shortages and limited agricultural potential in projecting population. Where an infectious disease like AIDS interacts with culture and politics to produce ravaging, lethal epidemics, these epidemics should be considered in national population projections (United Nations 1994), with explicit attention to the uncertainty in modeling the interaction (United Nations 1991).

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