Population Growth and Earth's Human Carrying Capacity

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Earth's capacity to support people is determined both by natural constraints and by human choices concerning economics, environment, culture (including values and politics), and demography. Human carrying capacity is therefore dynamic and uncertain. Human choice is not captured by ecological notions of carrying capacity that are appropriate for nonhuman populations. Simple mathematical models of the relation between human population growth and human carrying capacity can account for faster-than-exponential population growth followed by a slowing population growth rate, as observed in recent human history.

Scientific uncertainty about whether and how Earth will support its projected human population has led to public controversy: will humankind live amid scarcity or abundance or a mixture of both (1, 2)? This article surveys the past, the present, and some possible futures of the global human population; compares plausible United Nations population projections with numerical estimates of how many people Earth can support; presents simplified models of the interaction of human population size and human carrying capacity; and identifies some issues for the future.

The Past and Some Possible Futures

Over the last 2000 years, the annual rate of increase of global population grew by 50-fold from an average of 0.04% per year between A.D. 1 and 1650 to its all-time peak of 2.1% per year around 1965 to 1970 (3). The growth rate has since declined haltingly to about 1.6% per year (4) (Fig. 1). Human influence on the planet has increased faster than the human population. For example, while the human population more than quadrupled from 1860 to 1991, human use of inanimate energy increased from \(10^6\) (1 billion) megawatt-hours/year (MW·hours/year) to 93 billion MW·hours/year (Fig. 2). For many people, human action is linked to an unprecedented litany of environmental problems (5), some of which affect human well-being directly. As more humans contact the viruses and other pathogens of previously remote forests and grasslands, dense urban populations and global travel increase opportunities for infections to spread (6): The wild beasts of this century and the next are microbial, not carnivorous.

Along with human population, the inequality in the distribution of global income has grown in recent decades (7). In 1992, 15% of people in the world's richest countries enjoyed 79% of the world's income (8). In every continent, in giant city systems, people increasingly come into direct contact with others who vary in culture, language, religion, values, ethnicity, and socially defined race and who share the same space for social, political, and economic activities (9). The resulting frictions are evident in all parts of the world.

Today, the world has about 5.7 billion people. The population would double in 43 years if it continued to grow at its present rate of 1.6% per year, though that is not likely. The population of less developed regions is growing at 1.9% per year, while that of more developed regions grows at 0.3 to 0.4% per year (10). The future of the human population, like the futures of its economies, environments, and cultures, is highly unpredictable. The United Nations (UN) regularly publishes projections that range from high to low (Fig. 1). A high projection published in 1992 assumed that the worldwide average number of children born to a woman during her lifetime at current birthrates (the total fertility rate, or TFR) would fall to 2.5 children per woman in the 21st century; in this scenario, the population would grow to 12.5 billion by

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There is much more uncertainty about the demographic future than such projections suggest (12). At the high end, the TFR in less developed countries today, excluding China, is about 4.2 children per woman; that region includes 3.25 billion people. Unless fertility in the less developed countries falls substantially, global fertility could exceed that assumed in the UN’s high projection. At the low end, the average woman in Italy and Germany has about 1.3 children, and in Spain, 1.2. Fertility could fall well below that assumed in the UN’s low projection.

Can Earth support the people projected for 2050? If so, at what levels of living? In 1679, Antoni van Leeuwenhoek (1632–1723) estimated that the maximum number of people Earth can support is 13.4 billion (13). Many more estimates of how many people Earth could support followed (14) (Fig. 3). The estimates have varied from <1 billion to >1000 billion. Estimates published in 1994 alone ranged from <3 billion to 44 billion (15). Since 1679, there has been no clear increasing or decreasing trend in the estimated upper bounds. The scatter among the estimates increased with the passage of time. This growing divergence is the opposite of the progressive convergence that would ideally occur when a constant of nature is measured. Such estimates deserve the same profound skepticism as population projections. They depend sensitively on assumptions about future natural constraints and human choices.

Many authors gave both a low estimate and a high estimate. Considering only the highest number given when an author stated a range of estimates, the median of 65 upper bounds on human population was 12 billion. If the lowest number given is used when an author stated a range of estimates, and all point estimates are included otherwise, the median of 65 estimated bounds on human population was 7.7 billion. This range of low to high medians, 7.7 to 12 billion, is very close to the range of low and high UN projections for 2050: 7.8 to 12.5 billion. A historical survey of estimated limits is no proof that limits lie in this range. It is merely a warning that the human population is entering a zone where limits on the human carrying capacity of Earth have been anticipated and may be encountered.

Methods of Estimating Human Carrying Capacity

Calculations of estimates of Earth’s maximum supportable human population use one of six methods, apart from those that are categorical assertions without data. First, several geographers divided Earth’s land into regions, assumed a maximum supportable population density in each region, multiplied each assumed maximum population density by the area of the corresponding region, and summed over all regions to get a maximum supportable population of Earth. The assumed maximum regional population densities were treated as static and were not selected by an objective procedure. Second, some analysts fitted mathematical curves to historical population sizes and extrapolated them into the future (16). As the causal factors responsible for changes in birthrates and death rates were, and are, not well understood, there has been little scientific basis for the selection of the fitted curves.

Third, many studies focused on a single assumed constraint on population size, without checking whether some other factors might intervene before the assumed constraint comes into play. The single factor most often selected as a likely constraint was food (17). In 1925, the German geographer Albrecht Penck stated a simple formula that has been widely used (18):

\[
\text{Population that can be fed} = \frac{\text{food supply}}{\text{individual food requirement}} \quad (1)
\]

This apparently objective formula can lead to extremely different estimates of maximum supportable population because it depends on estimates of the food supply and of individual requirements. The food supply depends on areas to be planted and watered, choice of cultivars, yields, losses to pests and waste, cultural definitions of what constitutes acceptable food, and random fluctuations of weather. Individual requirements depend on the calories and protein consumed directly as well as on nutrients used as animal fodder (19). Besides food, other factors proposed as sole constraints on human numbers include energy, biologically accessible nitrogen, phosphorus, fresh water, light, soil, space, diseases, waste disposal, nonfuel minerals, forests, biological diversity, and climatic change.

Fourth, several authors reduced multiple requirements to the amount of some single factor. For example, in 1978 Bryd reduced requirements for food, paper, timber, and other forest products to the area of land required to grow them (20). Other factors that cannot be reduced to an area of land, such as water or energy, are sometimes recognized indirectly as constraints on the extent or productivity of cultivable land. The authors who combined different constraints into a single resource assumed that their chosen resource intervened as a constraint before any other factor.

Fifth, several authors treated population size as constrained by multiple independent factors. For example, Westing in 1981 estimated the constraints on population imposed independently by total land area, cultivated land area, forest land area, cereals, and wood (21). Constraints from multiple independent resources are easily combined formally. For example, if one assumes, in addition to a food constraint, a water constraint

\[
\text{Population that can be watered} = \frac{\text{water supply}}{\text{individual water requirement}} \quad (2)
\]

and if both constraints (1) and (2) must be satisfied independently, then

\[
\text{Population that can be fed and watered} = \text{minimum of} \left\{ \frac{\text{food supply}}{\text{individual food requirement}}, \frac{\text{water supply}}{\text{individual water requirement}} \right\} \quad (3)
\]

This formula is an example of the law of the minimum proposed by the German agricultural chemist Justus Liebig (1803–1873) (22). Liebig’s law of the minimum asserts that under steady-state conditions, the population size of a species is constrained by whatever resource is in shortest supply (23). This law has serious limitations when it is used to estimate the carrying capacity of any population. If different components of a population have heterogeneous requirements, aggregated estimates of carrying capacity based on a single formula will not be
accurate; different portions of the global human population are likely to have heterogeneous requirements. In addition, Liebig's law does not apply when limiting factors fluctuate, because different factors may be constraining at different times—an average over time may be misleading. Liebig's law assumes no interactions among the inputs; independence among limiting factors is not generally observed. (For example, Eq. 3 neglects the possibility that changes in the water supply may affect the food supply through irrigation.) Liebig's law also assumes that adaptive responses will not alter requirements or resources during the time span of interest. But economic history (including the inventions of agriculture and industry) and biological history (including the rise of mutant infections and the evolution of resistance to pesticides and drugs) are full of such adaptive responses.

Sixth and finally, several authors have treated population size as constrained by multiple interdependent factors and have described this interdependence in system models. System models are large sets of difference equations (deterministic or stochastic), which are usually solved numerically on a computer. System models of human population and other variables have often embodied relations and assumptions that were neither mechanistically derived nor quantitatively tested (25).

The first five methods are deterministic and static. They make no allowances for changes in exogenous or endogenous variables or in functional relations among variables. Although a probabilistic measure of human carrying capacity has been developed for local populations in the Amazon (26), no probabilistic approach to global human population carrying capacity has been developed. Yet, stochastic variability affects local and global human populations through weather, epidemics, accidents, crop diseases and pests, volcanic eruptions, the El Nifio Southern Oscillation in the Pacific Ocean, genetic variability in viruses and other microbes, and international financial and political arrangements. Stochastic models of human carrying capacity would make it possible to address questions that deterministic models cannot, including (conditional on all assumptions that go into any measure of human carrying capacity) what level of population could be maintained 95 years in 100 in spite of anticipat ed variability (27).

Some ecologists and others claim that the ecological concept of carrying capacity provides special insight into the question of how many people Earth can support. In basic and applied ecology, the carrying capacity of nonhuman species has been defined in at least nine different ways, none of which is adequate for humans (28). Human carrying capacity depends both on natural constraints, which are not fully understood, and on individual and collective choices concerning the average level and distribution of material well-being, technology, political institutions, economic arrangements, family structure, migration and other demographic arrangements, physical, chemical, and biological environments, variability and risk, the time horizon, and values, tastes, and fashions. How many people Earth can support depends in part on how many will wear cotton and how many will wear polyester; on how many will eat meat and how many will sprout; on how many will want parks and how many will want parking lots. These choices will change in time and so will the number of people Earth can support.

Some have urged that individual nations or regions estimate their human carrying capacity separately (29). Although specific resources such as mineral deposits can be defined region by region, the knowledge, energy, and technology required to exploit local resources often depend on other regions; the positive and negative effects of resource development commonly cross national borders. Human carrying capacity cannot be defined for a nation independently of other regions if that nation trades with others and shares the global resources of the atmosphere, oceans, climate, and biodiversity.

Mathematical Cartoons
If a current global human carrying capacity could be defined as a statistical indicator, there would be no reason to expect that indicator to be static. In 1798, Thomas Robert Malthus (1766–1834) described a logistic relation between human population size and human carrying capacity: “The happiness of a country does not depend, absolutely, upon its poverty or its riches, upon its youth or its age, upon its being thinly or fully inhabited, but upon the rapidity with which it is increasing, upon the degree in which the yearly increase of food approaches to the yearly increase of an unrestricted population” (30). Malthus opposed the optimism of the Marquis de Condorcet (1743–1794), who saw the human mind as capable of removing all obstacles to human progress. Malthus predicted wrongly that the population growth rate would always promptly win a race against the rate of growth of food. Malthus has been wrong for nearly two centuries because he did not foresee how much people can expand the human carrying capacity of Earth, including but not limited to food production. To examine whether Malthus will continue to be wrong, economists, demographers, and systems analysts have constructed models in which population growth drives technological change, which permits further population growth (31).

I describe here idealized mathematical models for the race between the human population and human carrying capacity (32). Suppose that it is possible to define a current human carrying capacity $K(t)$ as a numerical quantity measured in numbers of individuals. Suppose also that $P(t)$ is the total number of individuals in the population at time $t$ and that

$$\frac{dP(t)}{dt} = rP(t)[K(t)-P(t)] \quad (4)$$

The constant $r > 0$ is called the Malthusian parameter (33). I will call Eq. 4 the equation of Malthus. It is the same as the logistic equation except that the constant $K$ in the logistic equation is replaced by variable carrying capacity $K(t)$ here.

To describe changes in the carrying capacity $K(t)$, let us recognize, in the phrase of former U.S. president George H. Bush Jr., that “every human being represents hands to work, and not just another mouth to feed” (34). Additional people clear rocks from fields, build irrigation canals, discover ore deposits and antibiotics, and invent steam engines; they also clear-cut primary forests, contribute to the erosion of topsoil, and manufacture chlorofluorocarbons and plutonium. Additional people may increase savings or dilute and deplete capital; they may increase or decrease the human carrying capacity.

Suppose that the rate of change of carrying capacity $K(t)$ is directly proportional to the rate of change in population size. Call Eq. 5 the equation of Condorcet:

$$\frac{dK(t)}{dt} = c\frac{dP(t)}{dt} \quad (5)$$

The Condorcet parameter $c$ can be negative, zero, or positive.

In this model, population size changes in one of three distinct ways: faster than exponentially, exponentially, or logarithmically (35). When $c > 1$, each additional person increases the human carrying capacity enough for her own wants plus something extra. Then $K(t) - P(t)$ increases with time $t$, population growth accelerates faster than exponentially, and finally, after some finite period of time, $P(t)$ explodes to infinity. When $c = 1$, each additional person adds to carrying capacity just as much as he consumes. Thus, $K(t) - P(t) = K(0) - P(0)$ for any $t$ and $P(t)$ grows exponentially. When $c < 1$, $P(t)$ grows logarithmically, even though
K(t) will change if c ≠ 0. The population growth rate falls smoothly toward zero. When c < 1, the net effect on population size of changes in K(t) is equivalent to having a "virtual" constant carrying capacity K'. The virtual K' equals the initial carrying capacity K(0) if and only if c = 0, when changes in P(t) do not alter K(t). K' > K(0) if 0 < c < 1: in this case, each additional person increases the carrying capacity, but not by as much as the person consumes. When c < 0, population growth diminishes K(t), as in situations of congestion, pollution, and overgrazing, and K' < K(0). The Malthus-Condorcet model integrates the exponential growth model of Euler in the 18th century, the logistic growth model of Verhulst in the 19th century, and the doomsday (faster-than-exponential) growth model of von Foerster et al. in the 20th (36).

The discrete-time equations of Malthus and Condorcet replace the derivatives dP/dt and dK/dt by the corresponding finite differences [P(t + Δt) - P(t)]/Δt and [K(t + Δt) - K(t)]/Δt. This model can display exponential (c = 1) and faster-than-exponential (c > 1) growth as well as all the dynamic behavior of the discrete-time logistic equation (logistic growth, overshoot and damped oscillations, and periodic oscillations with various periods, chaotic behavior, and overshoot and collapse) (37). Overshoots become possible in discrete time because population and carrying capacity respond to current conditions with a time lag.

If an additional person can increase human carrying capacity by an amount that depends on the resources available to make her hands productive, and if these resources must be shared among more people as the population increases, then the constant c should be replaced by a variable c(t) that declines as population size increases. Suppose, for example, that there is a constant L > 0 such that c(t) = L/P(t). The assumption that c(t) = L/P(t) is positive, no matter how big P(t) is, models the dilution of resources, but not their depletion or degradation. Replacing c by L/P(t) gives the Condorcet-Mill equation (6), which I name after the British philosopher John Stuart Mill (1806–1873), who foresaw a stationary population as both inevitable and desirable (38); L is the Mill parameter.

\[
\frac{dK(t)}{dt} = \frac{L}{P(t)} \frac{dP(t)}{dt}
\]  

(6)

Assume further that c(0) = L/P(0) > 1. Then the population initially grows faster than exponentially. As P(t) increases past L, c(t) passes through 1 and the population experiences a brief instant of exponential growth. Then c(t) falls below 1 and the population size thereafter grows sigmoidally.

The overall trajectory looks sigmoidal on a logarithmic scale of population (Fig. 4). Population size rises to approach a unique stationary level, which is independent of r. The bigger K(0) and L are, the bigger the stationary level is, other things being equal. Figure 4 shows a trajectory of human carrying capacity K(t) above and population size P(t) below according to the Malthus-Condorcet-Mill model. P(t) is compared with the estimated human population history over the past 2000 years (39). Values of P(t) beyond t = 1995 are intended only to illustrate the qualitative behavior of the model, not to predict future human population; nothing guarantees that the actual human population will reach or remain at the high plateau shown. For example, the model neglects the possibilities that people could increasingly choose to divide the available material resources among fewer offspring, trading numbers for wealth, and that pollution or exogenous climatic changes could diminish human carrying capacity.

Up to about r = 1970, population sizes (theoretical and actual) are convex on the logarithmic scale; after roughly t = 1970, they are concave. The human carrying capacity K(t), initially only slightly above P(t), began to exceed P(t) substantially at times corresponding to the 9th and 10th centuries and experienced nearly exponential growth (linear increase on the logarithmic scale shown) from the 11th to the mid-20th century. According to the model, the acceleration of population growth in the 17th century was preceded by a long period of increasing human carrying capacity (40).

These models illuminate Earth's human carrying capacity. First, the statement that "every human being represents hands to work, and not just another mouth to feed" does not specify the cultural, environmental, and economic resources available to make additional hands productive and therefore does not specify by how much the additional hands can increase (or decrease) human carrying capacity. Yet, the quantitative relation between an increment in population and an increment in carrying capacity is crucial to the future trajectory of both the population and the carrying capacity. Second, the historical record of faster-than-exponential population growth, accompanied by an immense improvement in average well-being, is logically consistent with many alternative futures, including a continued expansion of population and carrying capacity, or a sigmoidal tapering off of the growth in population size and carrying capacity, or oscillations (damped or periodic), or chaotic fluctuations, or overshoot and collapse. Third, to believe that no ceiling to population size or carrying capacity is imminent entails believing that nothing in the near future will stop people from increasing Earth's ability to satisfy their wants by more than, or at least as much as, they consume. The models focus attention on, and provide a framework in which to interpret, quantitative empirical studies of the relation between rapid population growth and changing human carrying capacity.

**Issues for the Future**

Three valuable approaches have been advocated to ease future trade-offs among population, economic well-being, environmental quality, and cultural values. Each of these approaches is probably necessary, but is not sufficient by itself, to alleviate the economic, environmental, and cultural problems described above. First, the "bigger pie" school says: develop more technology (41). Second, the "fewer forks" school says: slow or stop population growth (42). In September 1994 at the UN population conference in Cairo, several approaches to slowing population growth by lowering fertility were advocated and disputed. They included promoting modern contraceptives; promoting economic development; improving the survival of infants and children; improving the status of women; educating men; and various combinations of these. Unfortunately, there appears to be no reliable information to show which approach will lower a country's fertility rate the most, nor is there a decade from now, per dollar spent. In some developing countries such as Indonesia, family planning programs interact with educational, cultural, and economic improvements to lower fertility by more than the sum of their inferred separa-
rate effects (45). Some unanswered questions are how soon will global fertility fall, by what means, and at whose expense.

Third, the “better manners” school says: improve the terms under which people interact (for example, by defining property rights to open-access resources; by removing economic irrationalities; and by improving governance) (44). When individuals use the environment as a scarce or a sink and when they have additional children, their actions have consequences for others. Economists call “externalities” the consequences that fall on people who are not directly involved in a particular action. That individuals neglect negative externalities when they use the environment has been called “the tragedy of the commons” (45); that individuals neglect positive externalities when they have children has been called “the second tragedy of the commons” (46). The balance of positive and negative externalities in private decisions about fertility and use of the environment depends on circumstances. The balance is most fiercely debated when persuasive scientific evidence is least available. Whatever the balance, the neglect by individuals of the negative externalities of childbearing biases fertility upward compared to the level of aggregate fertility that those same individuals would be likely to choose if they could act in concert or if there were a market in the externalities of childbearing. Voluntary social action could change the incentives to which individuals respond in their choices concerning childbearing and use of the environment.

REFERENCES AND NOTES

7. In 1960, the richest countries with 20% of world population earned 70.2% of global income, while the poorest countries with 40% of world population earned 2.3% of global income. Thus, the ratio of income per person between the top fifth and the bottom fifth was 31:1 in 1960. In 1970, that ratio was 39:1. In 1990, 20 U.S. dollars, the absolute gap between the top fifth and the bottom fifth rose from 1964 in 1960 to $15,149 in 1989 [United Nations Development Programme, Human Development Report (Oxford Univ. Press, New York, 1992), p. 36; Human Development Report 1994, p. 63].
9. From 1960 to 1995, the world’s urban population increased from 1.8 billion to 3.6 billion people, or just over 2.5 billion people.
12. Systematic retrospective analyses of past populations and projections have been attached to projections that were justified by their eventual predictive accuracy (M. A. Stoto, J. Am. Stat. Assoc. 73, 13 (1978); N. Keyfitz, Population Change and the Stability of the Human Environment (Abk Books, Cambridge, MA, 1982), chap. 13).
13. A. van Leeuwenhoek, Collected Letters (Swets and Zeitlinger, Amsterdam, 1948), letter 43, 25 April 1779, vol. 3, pp. 87–89. Leeuwenhoek estimated the population of Holland (1 million people) by his estimate of the ratio of the earth’s inhabited land area to Holland’s area (3,185).
15. V. Smi (Popul. Dev. Rev. 20, 255 (1994)) estimated 101 to 111 billion; D. Pimentel, R. Harman, M. Pacenza, J. Peres, and M. Pimentel (Population, 16, 947 (May 1994)); P. E. Wagg­goner (44) estimated at least 10 billion; Brown and Kane (1) estimated that a projected world grain harvest of 2.1 billion tons in 2030 could feed 2.6 billion people (the U.S. Department of Agriculture estimated 560 kg per person or just over 10 billion people at the Indian level of consumption of 200 kg per person, and the Wetenscappelijke Raad voor het Re­glementering der Landbouw voor het Neder­landse (For the Dutch Government)). Dzuurzame risicos: een blijvend probleem (Scientific Reference, Amsterdam, 1973, pp. 91–96) estimated that the earth could support one billion people. "Land resources for populations of the future," FPA INT/513 (Food and Agricultural Organization of the United Nations, Rome, 1989); R.S. Chen et al., Eds., The Hunger Report: 1990 (Food and Agriculture Organization of the United Nations, New York, 1990).
18. F. Smi (Popul. Dev. Rev. 20, 255 (1994)) estimated 101 to 111 billion; D. Pimentel, R. Harman, M. Pacenza, J. Peres, and M. Pimentel (Population, 16, 947 (May 1994)); P. E. Wagg­goner (44) estimated at least 10 billion; Brown and Kane (1) estimated that a projected world grain harvest of 2.1 billion tons in 2030 could feed 2.6 billion people (the U.S. Department of Agriculture estimated 560 kg per person or just over 10 billion people at the Indian level of consumption of 200 kg per person, and the Wetenscappelijke Raad voor het Re­glementering der Landbouw voor het Neder­landse (For the Dutch Government)). Dzuurzame risicos: een blijvend probleem (Scientific Reference, Amsterdam, 1973, pp. 91–96) estimated that the earth could support one billion people. "Land resources for populations of the future," FPA INT/513 (Food and Agricultural Organization of the United Nations, Rome, 1989); R.S. Chen et al., Eds., The Hunger Report: 1990 (Food and Agriculture Organization of the United Nations, New York, 1990).
22. Liebig’s law extends to any number of independent constraints. When population on the left side of the formula is replaced by production, the formula is known in economics as the Quesnay-Walras-Les­ontin-Hamard production function.
23. V. Smi (Popul. Dev. Rev. 17, 569 (1991), p. 567) estimated that in the 1980s, nitrogen applied to the cropland area of China increased four-fold by amounts that were only 50% to 60% as large as the increments from an additional kilogram per hectare applied in the 1960s.
24. Examples of system models are J. W. Forrester,


32. These models assume no migration and ignore the population’s age composition, geographical distribution, or the distribution of well-being. The models also omit any changes in human carrying capacity that depend on the past history of human carrying capacity and population size, rather than on their present magnitudes. The models also ignore eutrophic fluc­tuations in environmental and human factors. When these models are extended to describe two or more regional populations that interact through migration as well as by influenza, one another’s carrying capacity (for example, through transboundary air pollution), ad­