provide global change scenarios for economic models. Policy options for mitigation and adaptation can be investigated with the use of integrated assessment techniques. For further details and many additional references see N. Nakićenović in (20); E. A. Parsons, Energy Policy, in press; and J. Alcamo, Ed., IMAGE 2.0: Integrated Modeling of Global Climate Change (Kluwer Academic, Dordrecht, Netherlands, 1994).

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Population Growth and Earth's Human Carrying Capacity

Joel E. Cohen

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 about 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

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from 10^9 (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.
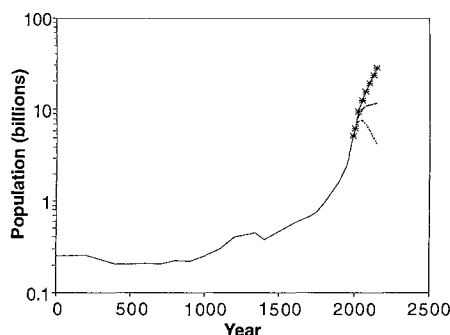

Fig. 1. Recent world population history A.D. 1 to 1990 (solid line) (53) and 1992 population projections of the UN (11) from 1990 to 2150: high (solid line with asterisks); medium (dashed line); and low (dotted line). Population growth was faster than exponential from about 1400 to 1970.

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
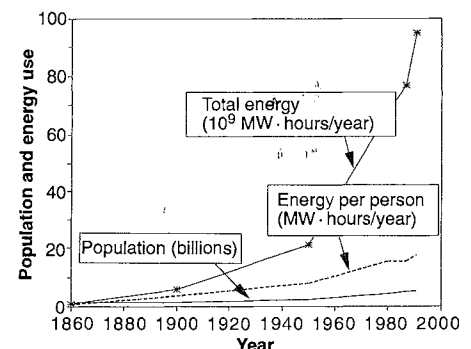

Fig. 2. Inanimate energy use from all sources from 1860 to 1991: aggregate (solid line with asterisks) (54) and per person (dashed line). Global population size is indicated by the solid line.

2050 (*11*). The UN's 1992 low projection assumed that the worldwide average TFR would fall to 1.7 children per woman; in this case, the population would peak at 7.8 billion in 2050 before beginning to decline.

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.

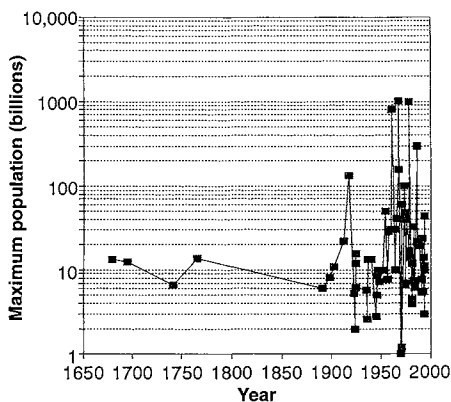Many authors gave both a low estimate and a high estimate. Considering only the highest number given when an author stated a range, and including all single or point estimates, the median of 65 upper bounds on human population was 12 billion. If the lowest number given is used when an author stated a 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 maximal 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*):

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 Eyre 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

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

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 Freiherr von 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

Fig. 3. Estimates of how many people Earth can support, by the date at which the estimate was made. When an author gave a range of estimates or indicated only an upper bound, the highest number stated is plotted here (*55*).

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 that the carrying capacity is strictly proportional to the limiting factor (within the range where that factor is limiting); strictly linear responses are not generally observed (24). 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 Niño 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 anticipated 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 polyester; on how many will eat meat and how many bean sprouts; 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 dynamic 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 system 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

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

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 is directly proportional to the rate of change in population size. Call Eq. 5 the equation of Condorcet:

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

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, and logistically (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 logistically, even though

$K(t)$ will change if $c \neq 0$. 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 $[P(t + \Delta t) - P(t)]/\Delta t$ and $[K(t + \Delta t) - K(t)]/\Delta t$. This model can display exponential ($c = 1$) and faster-than-exponential ($c > 1$) growth as well as all the dynamic behaviors 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.

$$\frac{dK(t)}{dt} = \frac{L}{P(t)} \frac{dP(t)}{dt} \qquad (6)$$

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 $t = 1970$, 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
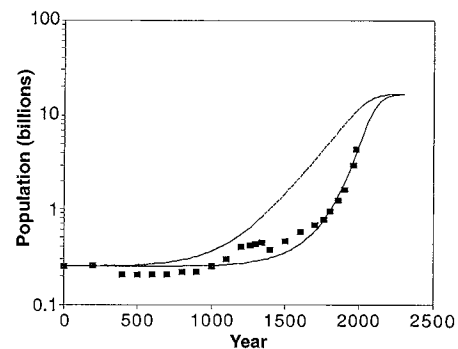

Fig. 4. Numerical illustration of the equations of Malthus and Condorcet-Mill: human carrying capacity $K(t)$ is shown by the dashed line and model population size $P(t)$ by the solid line; for comparison, estimated actual human population (solid rectangles) is shown. Equations: $P(t + \Delta t) - P(t) =$ $rP(t) [K(t) - P(t)]\Delta t$, $K(t + \Delta t) - K(t) = Lr[K(t) - P(t)]\Delta t$. Initial conditions and parameters: $\Delta t = 20$ years, $P(0) = 0.252$, $K(0) = 0.252789$, $r = 0.0014829$, and $L = 3.7$. $P(0)$, $K(0)$, and L are measured in billions (10^9).

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 believable information to show which approach will lower a country's fertility rate the most, now or 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 sepa-

rate effects (43). 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 source 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 negative 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.

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14. J. E. Cohen, *How Many People Can the Earth Support?* (Norton, New York, in press).
15. V. Smil [*Popul. Dev. Rev.* **20**, 255 (1994)] estimated 10 to 11 billion; D. Pimentel, R. Harman, M. Pacenza, J. Pecarsky, and M. Pimentel [*Popul. Environ.* **15**, 347 (May 1994)] estimated <3 billion; P. E. Waggoner (48) 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 2.5 billion people at the U.S. consumption level of 800 kg/year per person or just over 10 billion people at the Indian level of consumption of 200 kg/year per person; and the Wetenschappelijke Raad voor het Regeringsbeleid [(Scientific Council for the Dutch Government), *Duurzame risicos: een blijvend gegeven* (Sustainable risks: An enduring given) (Sdu Uitgeverij Plantijnstraat, Den Haag, Netherlands, 1994), p. 9] estimated 11 to 44 billion people, depending on the scenario.
16. For example, R. Pearl and L. J. Reed [in *Studies in Human Biology*, R. Pearl, Ed. (Williams and Wilkins, Baltimore, MD, 1924), chap. 25, p. 632] fitted a logistic curve to past world population sizes and confidently estimated a maximum world population of 2 billion. The world's population passed 2 billion around 1930. Undeterred, R. Pearl and S. Gould [*Hum. Biol.* **8**, 399 (1936)] again used the logistic curve to project 2.645 billion people as an ultimate limit to be nearly approached by the end of the 21st century. That population size was surpassed before 1955. On a logarithmic scale of population, the logistic curve is concave while the observed trajectory of global population size was convex until about 1970. The failures of Pearl's logistic projections and the usefulness of A. J. Lotka's theory of population growth and age-compositon [*Théorie analytique des associations biologiques, II Analyse démographique*
avec application particulière à l'espèce humaine (Hermann, Paris, 1939)] led demographers to abandon studying the absolute size of populations in favor of studying population structure and change. Since World War II, estimates of Earth's human carrying capacity have been published almost exclusively by non-demographers. Demography, like economics, still lacks a working theory of scale. In another example of curve-fitting, A. L. Austin and J. W. Brewer (49) modified the logistic curve to allow for faster-than-exponential growth followed by leveling off; they fitted their curve to past global population sizes and predicted an asymptote around 50 billion people.
17. H. Brown, *The Challenge of Man's Future: An Inquiry Concerning the Condition of Man During the Years That Lie Ahead* (Viking, New York, 1954); H. Brown, J. Bonner, J. Weir, *The Next Hundred Years: Man's Natural and Technological Resources* (Viking, New York, 1957); C. Clark, *Nature* **181**, 1235 (1958), reprinted in *Readings in Human Population Ecology*, W. Y. Davis, Ed. (Prentice-Hall, Englewood Cliffs, NJ, 1971), pp. 101–106; M. Cépède, F. Houtart, L. Grond, *Population and Food* (Sheed & Ward, New York, 1964); W. R. Schmitt, *Ann. N.Y. Acad. Sci.* **118**, 645 (1965); H. Lieth, *Hum. Ecol.* **1**, 303 (1973); K. Blaxter, *People, Food and Resources* (Cambridge Univ. Press, Cambridge, 1986); P. Buringh, H. D. J. van Heemst, G. J. Staring, *Computation of the Absolute Maximum Food Production of the World* (Agricultural Press, Wageningen, Netherlands, 1975); P. Buringh and H. D. J. van Heemst, *An Estimation of World Food Production Based on Labour-Oriented Agriculture* (Agricultural Press, Wageningen, Netherlands, 1977); G. M. Higgins, A. H. Kassam, L. Naiken, G. Fischer, M. M. Shah, "Potential population supporting capacities of lands in the developing world," technical report of project INT/75/P13, "Land resources for populations of the future," FPA/INT/513 (Food and Agricultural Organization of the United Nations, Rome, 1983); R. S. Chen *et al.*, Eds., *The Hunger Report: 1990* (HR-90-1, Alan Shawn Feinstein World Hunger Program, Brown University, Providence, RI, June 1990); S. R. Millman *et al.*, *The Hunger Report: Update 1991* (HR-91-1, Alan Shawn Feinstein World Hunger Program, Brown University, Rhode Island, April 1991). See also (1), p. 31. It is remarkable that food continues to be viewed as a limiting constraint on population size even though, globally, the countries with the lowest fertility and the lowest population growth rates are among those where food is most abundant [J. Mayer, *Daedalus* **93**, 830 (1964)].
18. A. Penck, *Z. Geopolitik* **2**, 330 (1925); *Sitzungsberichte der Preußischen Akademie der Wissenschaften* **22**, 242 (1924). The formula was used in 1917 but not stated explicitly by G. H. Knibbs [*The Mathematical Theory of Population, of Its Character and Fluctuations, and of the Factors Which Influence Them*, appendix A (Census of the Commonwealth of Australia, Minister of State for Home and Territories, Melbourne; McCarron, Bird & Co., Melbourne, 1917], vol. 1, p. 455.
19. In 1972, domestic animals were fed 41% of all grain consumed; in 1992, 37%. See (50), p. 296; (1), p. 67.
20. S. R. Eyre, *The Real Wealth of Nations* (St. Martin's, New York, 1978).
21. A. H. Westing, *Environ. Conserv.* **8**, 177 (1981).
22. J. F. von Liebig, *Principles of Agricultural Chemistry* (Wiley, New York, 1855), German edition: *Die Grundsätze der Agriculturchemie* (Vieweg und Sohn, Braunscheweig, 1855). Also see D. L. DeAngelis, *Dynamics of Nutrient Cycling and Food Webs* (Chapman and Hall, London, 1992), pp. 38–45, 228.
23. 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 economic theory as the Walras-Leontief-Harrod-Domar production function.
24. V. Smil [*Popul. Dev. Rev.* **17**, 569 (1991), pp. 586 and 597] reported that in the 1980s, nitrogen applied in the Zhejiang and Shandong provinces of China increased rice yields by amounts that were only 50 to 60% as large as the increments from an additional kilogram per hectare applied in the 1960s.
25. Examples of system models are J. W. Forrester,

World Dynamics (Wright-Allen Press, Cambridge, MA, 1971); D. Meadows, D. L. Meadows, J. Randers, W. W. Behrens III, *The Limits to Growth* (Signet, New American Library, New York, 1972, ed. 2, 1974); M. Mesarovic and E. Pestel, *Mankind at the Turning Point* (Dutton and Reader's Digest Press, New York, 1974). See also (*51*); J. Gever, R. Kaufmann, D. Skole, C. Vörösmarty, *Beyond Oil: The Threat to Food and Fuel in the Coming Decades* (Ballinger, Cambridge, MA, 1986); A. J. Gilbert and L. C. Braat, Eds., *Modelling for Population and Sustainable Development* (Routledge, London, 1991). See also (*52*) and W. Lutz, Ed., *Population-Development-Environment: Understanding Their Interactions in Mauritius* (Springer-Verlag, Heidelberg, 1994). Critiques of system models are C. Kaysen, *Foreign Aff.* **50**, 660 (1972); H. S. D. Cole, C. Freeman, M. Jahoda, K. L. R. Pavitt, Eds., *Model of Doom: A Critique of* The Limits to Growth, *With a Reply by the Authors of* The Limits to Growth (Universe Books, New York, 1973); W. D. Nordhaus, *Econ. J.* **83**, 1156 (1973); E. van de Walle, *Science* **189**, 1077 (1975); D. Berlinski, *On Systems Analysis* (MIT Press, Cambridge, MA, 1976); and P. R. Ehrlich, A. H. Ehrlich, J. P. Holdren, *Ecoscience: Population, Resources, Environment* (Freeman, San Francisco, 1977), pp. 730–733.

26. P. M. Fearnside, *Human Carrying Capacity of the Brazilian Rainforest* (Columbia Univ. Press, New York, 1986).

27. In many regions, the average amount of fresh water available annually is more than twice the amount of water that can be counted on 95 years in 100 [P. P. Rogers, in R. Repetto, Ed., *The Global Possible: Resources, Development, and the New Century* (Yale Univ. Press, New Haven, 1985), p. 294].

28. B. Zaba and I. Scoones, in *Environment and Population Change*, B. Zaba and J. Clarke, Eds. (Ordina Editions, Liege, 1994), pp. 197–219; H. R. Pulliam and N. M. Haddad, *Bull. Ecol. Soc. Amer.* **75**, 141 (1994). See also (*14*).

29. Paragraph 5.23 of Agenda 21, final document of the UN Conference on Environment and Development, Rio de Janeiro, June 1992 (Rio Earth Summit).

30. T. R. Malthus, *An Essay on the Principle of Population* [1798; reprint, with part of ed. 7, in *On Population*, Gertrude Himmelfarb, Ed. (Modern Library, New York, 1960), chap. VII, p. 51]. P. Demeny [in *Population and Resources in Western Intellectual Traditions*, M. S. Teitelbaum and J. M. Winter, Eds. (Population Council, New York, 1989), p. 232] generalized Malthus's view to incorporate all aspects of economic output, not just food: "Posed in the simplest terms, the economics of population reduces to a race between two rates of growth: that of population and that of economic output."

31. F. L. Pryor and S. B. Maurer, *J. Dev. Econ.* **10**, 325 (1982); R. D. Lee, in *The State of Population Theory: Forward from Malthus*, D. Coleman and R. Schofield, Eds. (Basil Blackwell, Oxford, 1986), pp. 96–130; *Math. Popul. Studies* **1**, 265 (1988); *Population* **47**, 1533 (1992); *Explor. Econ. Hist.* **30**, 1 (1993); M. Kremer, *Q. J. Econ.* **108**, 681 (1993). See also (*49*, *51*, *52*).

32. These models assume no migration and ignore the population's age composition, geographical distribution, and 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 stochastic 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 influencing one another's carrying capacity (for example, through transboundary air pollution), additional modes of behavior appear.

33. The dimensions of *r* are $[T^{-1}P^{-1}]$, where *T* is time.

34. Carrying Capacity Network, *Focus: Carrying Capacity Selections* **1**, 57 (1992).

35. At $t = 0$, assume that $K(0) > P(0) > 0$ and $r > 0$. The form of $P(t)$ depends on c.

   Case i: $c < 1$. Because $K(0) > P(0) > cP(0)$,

$$P(t) = \frac{1}{\left(\dfrac{1}{P(0)} + \dfrac{c-1}{K(0) - cP(0)}\right)e^{-r[K(0) - cP(0)]t} - \dfrac{c-1}{K(0) - cP(0)}} \tag{7}$$

The solution $P(t)$ is a logistic curve with the "virtual" Malthusian parameter $r' = r(1 - c) > 0$ and the constant "virtual" carrying capacity $K' = [K(0) - cP(0)]/(1 - c)$. [The special case $c = 0$ reproduces the logistic equation with $r' = r$ and $K' = K(0)$.] $K(t)$ is logistic in shape after possible shifting by $K(0) - cP(0)$ and rescaling by c. $K' > K(0)$, $K' = K(0)$, or $K' < K(0)$ according to whether $1 > c > 0$, $c = 0$, or $0 > c$.

   Case ii: $c = 1$. Then $P(t)$ grows exponentially with "virtual" Malthusian parameter $r[K(0) - P(0)]$.

   Case iii: $c > 1$. For some finite time T (where $0 < T < \infty$), $\lim_{t \uparrow T} P(t) = \infty$. When $K(0) - cP(0) \neq 0$, Eq. 7 describes $P(t)$ and the population size becomes infinite when t rises to

$$T = \frac{1}{r[K(0) - cP(0)]} \times \log\left\{\left[\frac{1}{P(0)} + \frac{c-1}{K(0) - cP(0)}\right] \Big/ \left[\frac{c-1}{K(0) - cP(0)}\right]\right\} \tag{8}$$

When $K(0) - cP(0) = 0$, then $P(t) = P(0)/[1 - r(c - 1)P(0)t]$, which is the solution of the "doomsday equation" of von Foerster *et al.* The population size becomes infinite at time $T = 1/[r(c - 1)P(0)]$.

36. H. von Foerster, P. M. Mora, L. W. Amiot, *Science* **132**, 1291 (1960); J. S. Robertson, V. P. Bond, E. P. Cronkite, *ibid.* **133**, 936 (1961); A. J. Coale, *ibid.*, p. 1931; H. von Foerster, P. M. Mora, L. W. Amiot, *ibid.* **136**, 173 (1962).

37. P. J. Myrberg, *J. Math. Pures Appl.* **41**, 339 (1962); R. M. May, *Science* **186**, 645 (1974); _____, *J. Theor. Biol.* **51**, 511 (1975); _____ and G. F. Oster, *Am. Nat.* **110**, 573 (1976); R. M. May, *Ecology* **67**, 1115 (1986); A. Hastings, C. L. Horn, S. Ellner, P. Turchin, H. C. J. Godfray, *Annu. Rev. Ecol. Syst.* **24**, 1 (1993); J. E. Cohen and I. Barradas, in preparation. These behaviors include all those D. M. Meadows, D. L. Meadows, and J. Randers [(*52*), pp. 108–9] attributed to the system models called World3 and World3/91 in *Beyond the Limits* (*52*), and more.

38. J. S. Mill, *Principles of Political Economy with Some of Their Applications to Social Philosophy* (1848), V. W. Bladen and J. M. Robson, Eds. (Univ. of Toronto Press, Toronto, 1965).

39. I chose $P(0) = 0.252$ billion, the estimated population in A.D. 1, and $L = 3.7$ billion, the estimated population size in 1970, then varied the remaining parameters r and $K(0)$ numerically to obtain a close fit by using "fmins" of MATLAB version 4.1, based on the Nelder-Meade simplex search; see *MATLAB Reference Guide* (Mathworks, Natick, MA, August 1992), pp. 208–10. The criterion of goodness of fit was

$$\sum(\text{observed population} - \text{calculated population})^2 / (\text{observed population})$$

summed over the dates of observation shown in the figure.

40. Europe grew technologically and economically for a millennium before the Industrial Revolution; England developed economically from the 12th century onward. In the 13th century, English forests were cleared, swamps drained, and new lands exploited for cultivation; yields improved as a result of liming, plowing straw ash into the field, and planting new varieties of seeds. At the same time, the mining and smelting of tin, lead, and iron; the manufacture of pottery; and the production of salt and wool all increased. Additional surges of economic development occurred in the 16th century [C. M. Cipolla, *Before the Industrial Revolution: European Society and Economy, 1000–1700* (Norton, New York, ed. 3, 1994), pp. 137–159; R. G. Wilkinson, *Poverty and Progress: An Ecological Perspective on Economic Development* (Praeger, New York, 1973); D. L. Hardesty, *Ecological Anthropology* (Wiley, New York, 1977), pp. 209–10].

41. J. H. Ausubel, *The Sciences* **33**, 14 (1993). See also (*48*).

42. J. Bongaarts, *Science* **263**, 771 (1994).

43. P. J. Gertler and J. W. Molyneaux, *Demogr.* **31**, 33 (1994).

44. R. Repetto, Ed., *The Global Possible: Resources, Development, and the New Century* (Yale Univ. Press, New Haven, 1985); D. W. Pearce and J. J. Warford, *World Without End: Economics, Environment, and Sustainable Development* (Oxford Univ. Press, New York, 1993).

45. G. Hardin, *Science* **162**, 1243 (1968).

46. R. D. Lee, in *Resources, Environment, and Population: Present Knowledge, Future Options*, K. Davis and M. S. Bernstam, Eds. (Oxford Univ. Press, New York, 1991), pp. 315–332. Earlier discussions of the negative externalities of childbearing include H. F. Dorn, *Science* **135**, 283 (1962); P. E. Sorenson, in *Population, Environment and People*, N. Hinrichs, Ed. (McGraw-Hill, New York, 1971), pp. 113–121; and P. Dasgupta and R. J. Willis, in *Population Growth and Economic Development: Issues and Evidence*, D. G. Johnson and R. D. Lee, Eds. (Univ. of Wisconsin Press, Madison, 1987), pp. 631–702.

47. J. Durand, *Popul. Dev. Rev.* **3**, 253 (1977).

48. P. E. Waggoner, "How much land can ten billion people spare for nature?" (Task Force Report 121, Council for Agricultural Science and Technology, Ames, IA, February 1994).

49. A. L. Austin and J. W. Brewer, *Technol. Forecasting Soc. Change* **3**, 23 (1971).

50. World Resources Institute, *World Resources 1994–95* (Oxford Univ. Press, New York, 1994).

51. P. W. House and E. R. Williams, *The Carrying Capacity of a Nation: Growth and the Quality of Life* (Lexington Books, Lexington, MA, 1975).

52. D. H. Meadows, D. L. Meadows, J. Randers, *Beyond the Limits: Global Collapse or a Sustainable Future* (Earthscan Publications, London, 1992).

53. C. McEvedy and R. Jones, *Atlas of World Population History* (Viking Penguin, New York, 1978); J.-N. Biraben, *Population* **34**, 13 (1979). See also (*11*, *47*).

54. C. M. Cipolla, *Economic History of World Population* (Penguin, Harmondsworth, England, ed. 6, 1974), pp. 56–59. See also (*50*), pp. 332–334.

55. Data are from (*14*). The estimate by J. H. Fremlin [*New Sci.* **24**, 285 (1964)] would be off the scale and is omitted.

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