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. The element of human choice is not captured by ecological notions of carrying capacity that are appropriate for nonhuman populations.

Scientific uncertainty about whether and how the 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]

The Past and Some Possible Futures

Over the past two thousand years, the annual rate of increase of global population has grown about fifty-fold from an average of 0.04 percent

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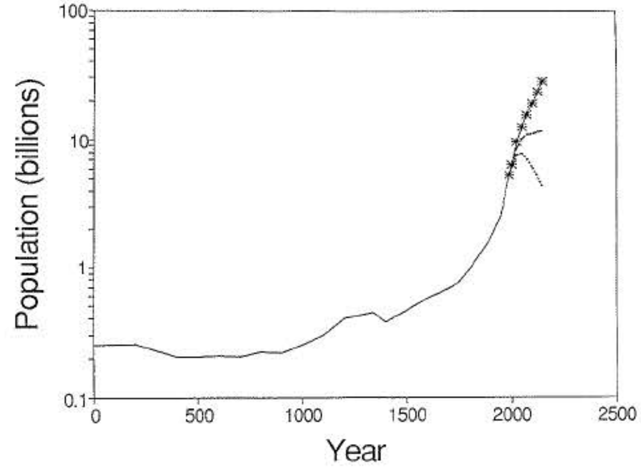

Figure 1. Recent world population history A.D. 1–1990 (solid line)[37] and 1992 population projections of the United Nations[10] from 1990 to 2150. Population growth was faster than exponential from about 1400 to 1970. Asterisks, dashes, and dots indicate high, medium, and low projections, respectively.

per year between A.D. 1 and 1650 to its all-time peak of 2.1 percent per year around 1965–70.[2] The growth rate has since declined haltingly to about 1.4 percent per year (figure 1).[3]

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 1 billion megawatt-hours per year to 93 billion megawatt-hours per year (figure 2). In the minds of many, human action is linked to an unprecedented litany of environmental problems, some of which affect human well-being directly.[4] As more humans contract the viruses and other pathogens of previously remote forests and grasslands, dense urban populations and global travel increase opportunities for infections to spread.[5] 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.[6] In 1992, 15 percent of people in the world's richest countries enjoyed 79 percent of the world's income.[7] Economic contrasts are compounded by cultural ones. 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.[8] The resulting frictions are evident in all parts of the world.

As of 1999, the world has about 6 billion people. The population would double in forty-nine years if it continued to grow at its present 1.4 percent per year, though that is not likely. The population of less developed regions is growing at 1.7 percent per year, while that of more developed regions is growing at 0.1 percent per year.[9]

The future of the human population, like the future of its economies, environments, and cultures, is highly unpredictable. The United Nations regularly publishes projections with a range from high to low (figure 2). In 1992, its high projection assumed that the worldwide average number of children born to a woman during her lifetime at current birth rates (the total fertility rate, or TFR) would fall to 2.5 children per woman in the twenty-first century; in that scenario, the population would grow to 12.5 billion by 2050.[10] Its 1992 low projection assumed that the worldwide average TFR would fall to 1.7 children per woman; in that 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.[11] At the high end, the TFR in the less developed countries today, excluding China, is about 3.8 children per woman; that region includes 3.5 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 Germany now has about 1.3 children, and in Italy and Spain

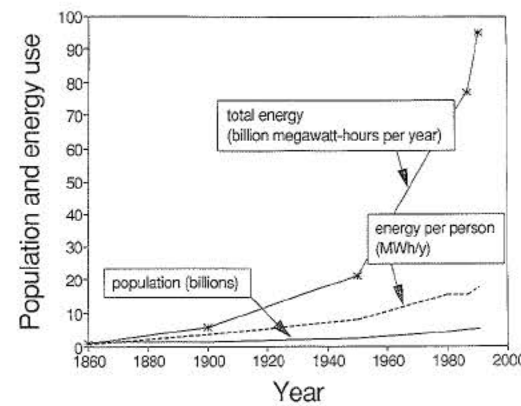

Figure 2. Inanimate energy use from all sources from 1860 to 1991: aggregate (solid line with asterisks)[38] and per person (dashed line). Global population size is indicated by the solid line.

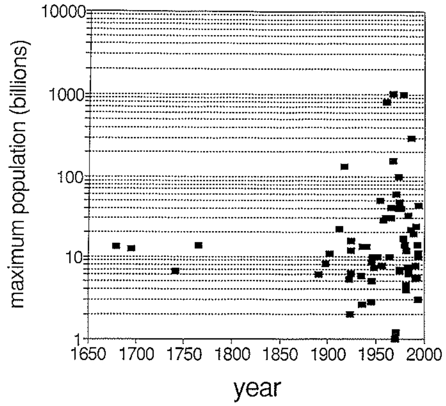

Figure 3. Estimates of how many people earth can support, by the data at which the estimate was made. When an author gave range of estimates or indicated only an upper bound, the highest number is plotted here.[39]

1.2. Fertility could fall well below that assumed in the UN's low projection.

Can the earth support the people projected for 2050? If so, at what levels of living? In 1679, Antony van Leeuwenhoek (1632–1723) estimated that the maximum number of people the earth can support is 13.4 billion.[12] Many more estimates of how many people the earth can support followed (figure 3).[13] The estimates have varied from < 1 billion to >1,000 billion. Estimates published in 1994 alone ranged from < 3 billion to 44 billion.[14] Since 1679, there has been no clear increasing or decreasing trend in the estimated upper bounds. The scatter among the estimates has 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 give 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 sixty-five 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 was 7.7 billion. This range of low to high medians, 7.7–12 billion, is very close to the range of low and high UN projections for the population in 2050: 7.8–12.5 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

Estimates of earth's maximum supportable human population are made with 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.[15] As the causal factors responsible for changes in birth rates 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 is food.[16] In 1925, the German geographer Albrecht Penck stated a simple formula that has been widely used:[17]

$$\text{population that can be fed} = \text{food supply / individual food requirement.} \quad [1]$$

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.[18] 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.[19] 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.[20] Constraints from multiple independent resources are easily combined formally. For example, if one assumes, in addition to a food constraint, a water constraint

$$\text{population that can be watered} = \text{water supply} / \text{individual water requirement} \quad [2]$$

and if both constraints [1] and [2] must be satisfied independently, then

$$\text{population that can be fed and watered} = \text{minimum of } \{\text{food supply} / \text{individual food requirement or water supply} / \text{individual water requirement}\}. \quad [3]$$

This formula is an example of the law of the minimum proposed by the German agricultural chemist Justus Freiherr von Liebig (1803–73).[21] 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.[22] Liebig's 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 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.[23] Liebig's law assumes no interactions among the inputs; independence among limiting factors is not generally observed. (For example, equation [3] neglects the possibility that changes in the water supply may affect the food supply through irrigation.) Liebig's law assumes that adaptive responses will not alter requirements or resources during the time span of interest; 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 treated population size as constrained by multiple interdependent factors and described the 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 relationships and assumptions that were neither mechanistically derived nor quantitatively tested.[24]

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. While a probabilistic measure of human carrying capacity has been developed for local populations in the Amazon,[25] no probabilistic approach to global human 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, such as: conditional on all the assumptions that go into any measure of human carrying capacity, what level of population could be maintained ninety-five years in one hundred in spite of anticipated variability?[26]

Some have urged that individual nations or regions estimate their human carrying capacity separately.[27] While 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.

Some ecologists and others claim that the ecological concept of carrying capacity provides special insight into the question of how many people the earth can support. In basic and applied ecology, the capacity for carrying nonhuman species has been defined in at least nine significantly different ways, none adequate for humans.[28] Human carrying capacity depends both on natural constraints, which are not fully understood, and on individual and collective choices. How many people the 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 the earth can support.

The deceptively simple question "How many people can the earth support?" hides a host of thorny issues: How many people with what fashions, tastes, and values? How many people at what average level of material well-being? With what distribution of material well-being? With what technology? With what domestic and international political institutions? With what domestic and international economic and demographic arrangements? In what physical, chemical, and biological environments? With what variability or stability? With what risk or robustness? What standards of personal liberty will people choose?

How many people for how long? Human carrying capacity depends strongly on the time horizon people choose for planning. The population that the earth can support at a given level of well-being for twenty years may differ substantially from the population that can be supported for one hundred or one thousand years.

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."[29] Malthus opposed the optimism of the Marquis de Condorcet (1743–94), 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.[30]

These models illuminate the 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 the 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 tradeoffs 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.

The "bigger pie" school says: develop more technology.[31] The "fewer forks" school says: slow or stop population growth.[32] 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. 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 separate effects.[33] Some unanswered questions are: how soon will global fertility fall? by what means? at whose expense?

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).[34] 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"[35]; that individuals neglect negative externalities when they have children has been called "the second tragedy of the commons."[36] 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.

Notes

1. L. R. Brown and H. Kane, *Full House: Reassessing the Earth's Population Carrying Capacity* (New York: W.W. Norton, 1994); F. Duchin and G. Lange, *The Future of the Environment: Ecological Economics and Technological Change* (New York: Oxford University Press, 1994); N. Myers and J. L. Simon, *Scarcity or Abundance? A Debate on the Environment* (New York: W.W. Norton, 1994).
2. M. Livi-Bacci, *A Concise History of World Population,* trans. Carl Ipsen (Oxford, England: Blackwell, 1992). Estimates of global population size at A.D. 1 vary from 133 million (E. S. Deevey, Jr., *Scientific American* 203,

no. 9 [September 1960]: 195–204) to 330 million (J. Durand, *Population and Development Review* 3, no. 3 [1977]: 253–96).
3. *1998 World Population Data Sheet* (Washington, D.C.: Population Reference Bureau, 1998).
4. P. Demeny in *Resources, Environment, and Population: Present Knowledge, Future Options* K. Davis and M. S. Bernstam, eds. (New York: Oxford University Press, 1991), p. 416, gives a grim list of such environmental problems: "loss of topsoil, desertification, deforestation, toxic poisoning of drinking water, oceanic pollution, shrinking wetlands, overgrazing, species loss, shortage of firewood, exhaustion of oil reserves and of various mineral resources, siltation in rivers and estuaries, encroachment of human habitat on arable land, dropping water tables, erosion of the ozone layer, loss of wilderness areas, global warming, rising sea levels, nuclear wastes, acid rain."
5. J. Lederberg, *Journal of the American Medical Association* 260, no. 5 (1988): 684–85; S. S. Morse, ed., *Emerging Viruses* (New York: Oxford University Press, 1993); R. M. Anderson and R. M. May, *Infectious Diseases of Humans: Dynamics and Control* (Oxford, England: Oxford University Press, 1991), chap. 23.
6. In 1960, the richest countries, with 20 percent of world population, earned 70.2 percent of global income, while the poorest countries, with 20 percent of world population, earned 2.3 percent of global income. Thus, the ratio of income per person between the top fifth and the bottom fifth was 31:1. In 1970, that ratio was 32:1; in 1980, 45:1; in 1991, 61:1. In U.S. dollars, the absolute gap between the top fifth and the bottom fifth rose from $1,864 in 1960 to $15,149 in 1989 (United Nations Development Programme, *Human Development Report 1992* [New York: Oxford University Press, 1992], p. 36, *Human Development Report 1994,* p. 63).
7. P. Demeny, *Population and Development, International Conference on Population and Development 1994* (Liège, Belgium: International Union for the Scientific Study of Population, 1994); these numbers are based on World Bank estimates.
8. From 1950 to 1995, the world's urban population increased more than 3.5-fold, from 0.74 billion to 2.6 billion, and from 29 percent to 45 percent of the total population (United Nations, *World Urbanization Prospects: The 1992 Revision,* ST/ESA/SER.A/136 [New York: United Nations, 1993), pp. 74–75, 82–83.
9. *1998 World Population Data Sheet; World Population 1994* (New York: United Nations, 1994).
10. United Nations, Department of International Economic and Social Affairs, *Long-Range World Population Projections: Two Centuries of Population Growth 1950–2150,* ST/ESA/SER.A/125 (New York: United Nations, 1992).
11. Systematic retrospective analyses of past population projections indicate that more confidence has been attached to projections than was justified

by their eventual predictive accuracy; M. A. Stoto, *Journal of the American Statistical Association* 78 (1983): 13–20; N. Keyfitz, *Population Change and Social Policy* (Cambridge, Mass.: Abt Books, 1982), chap. 13.

12. A. van Leeuwenhoek, *Collected Letters* (Amsterdam: Swets and Zeitlinger, 1948), Letter 43, April 25, 1679, vol. 3, pp. 4–35. Leeuwenhoek multiplied his estimate of the population of Holland (1 million people) by his estimate of the ratio of the earth's habitable land area to Holland's area (13,385).
13. J. E. Cohen, *How Many People Can the Earth Support?* (New York: W.W. Norton, 1995).
14. V. Smil, *Population and Development Review* 20 (June 1994): 255–92, estimated 10–11 billion; D. Pimentel, R. Harman, M. Pacenza, J. Pecarsky, and M. Pimentel, *Population and Environment* 15, no. 5 (May 1994): 347–69, estimated < 3 billion; P. E. Waggoner "How Much Land Can Ten Billion People Spare for Nature?" in *Task Force Report No. 121* (Ames, Iowa: Council for Agricultural Science and Technology, February 1994) estimated at least 10 billion; Brown and Kane, *Full House,* p. 202, 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 kilograms per year per person, or just over 10 billion people at the Indian level of consumption of 200 kilograms per year per person; Wetenschappelijke Raad voor het Regeringsbeleid [Scientific Council for the Dutch Government], *Duurzame risicos: een blijvend gegeven* [*Sustainable risks: an enduring given*] (Den Haag, The Netherlands: Sdu Uitgeverij Plantijnstraat, 1994), p. 9, estimated 11–44 billion people, depending on the scenario.
15. For example, R. Pearl and L. J. Reed, in R. Pearl, ed., *Studies in Human Biology* (Baltimore: Williams and Wilkins, 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, *Human Biology* 8, no. 3 (1936): 399–419, again used the logistic curve to project 2.645 billion people as an ultimate limit to be nearly approached by the end of the twenty-first 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 Alfred J. Lotka's theory of population growth and age-composition (*Théorie analytique des associations biologiques, II Analyse démographique avec application particulière à l'espèce humaine* [Paris, Hermann: 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 the earth's human carrying capacity have been published almost exclusively by nondemographers. Demography, like economics, still lacks a working theory of scale. In another example of curve fitting, A. L. Austin and J. W. Brewer, *Technological Forecasting and Social Change* 3, no. 1

(1971): 23–49, 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.

16. H. Brown, *The Challenge of Man's Future: An Inquiry Concerning the Condition of Man During the Years That Lie Ahead* (New York: Viking, 1954); H. Brown, J. Bonner, and J. Weir, *The Next Hundred Years: Man's Natural and Technological Resources* (New York: Viking, 1957); C. Clark in *Nature* 181 (May 3, 1958): 1235–36, reprinted in W. Y. Davis, ed., *Readings in Human Population Ecology* (Englewood Cliffs, N.J.: Prentice-Hall, 1971), pp. 101–06; M. Cépède, F. Houtart, and L. Grond, *Population and Food* (New York: Sheed & Ward, 1964); W. R. Schmitt in *Annals of the New York Academy of Science* 118, no. 17 (1965): 645–718; H. Lieth in *Human Ecology* 1, no. 4 (1973): 303–32; K. Blaxter, *People, Food and Resources* (Cambridge, England: Cambridge University Press, 1986); P. Buringh, H. D. J. van Heemst, and G. J. Staring, *Computation of the Absolute Maximum Food Production of the World* (Wageningen, The Netherlands: Agricultural Press, 1975); P. Buringh and H. D. J. van Heemst, *An Estimation of World Food Production Based on Labour-Oriented Agriculture* (Wageningen, The Netherlands: Agricultural Press, 1977); G. M. Higgins, A. H. L. Kassam, L. Naiken, G. Fischer, and 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 (Rome: Food and Agricultural Organization of the United Nations, 1983); Robert S. Chen et al., eds., *The Hunger Report: 1990* (HR-90-1, Alan Shawn Feinstein World Hunger Program, Brown University, June 1990); S. R. Millman et al., *The Hunger Report: Update 1991* (HR-91-1, Alan Shawn Feinstein World Hunger Program, Brown University, April 1991); Brown and Kane, *Full House,* 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* 93:3 (1964): 830–44.
17. A. Penck, *Zeitschrift für Geopolitik* 2 (1925): 330–48; *Sitzungsberichte der Preussischen Akademie der Wissenschaften* 22 (1924): 242–57. The formula was used but not stated explicitly in 1917 by G. H. Knibbs, *The Mathematical Theory of Population, of Its Character and Fluctuations, and of the Factors Which Influence Them,* Appendix A (Melbourne: Census of the Commonwealth of Australia, Minister of State for Home and Territories; McCarron, Bird & Co.), vol. 1, p. 455.
18. In 1972, domestic animals were fed 41 percent of all grain consumed; in 1992, 37 percent (Brown and Kane) *Full House,* p. 67; World Resources Institute, *World Resources 1994–95* [New York: Oxford University Press, 1994], p. 296).
19. S. R. Eyre, *The Real Wealth of Nations* (New York: St. Martin's Press; London: Edward Arnold, 1978).

20. A. H. Westing, *Environmental Conservation* 8, no. 3 (1981): 177–83.
21. J. F. von Liebig, *Principles of Agricultural Chemistry* (New York: John Wiley, 1855); German edition: *Die Grundsätze der Agriculturchemie* (Braunschweig: F. Vieweg und Sohn). Also see D. L. DeAngelis, *Dynamics of Nutrient Cycling and Food Webs* (London: Chapman and Hall, 1992), pp. 38–45, 228.
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 economic theory as the Walras-Leontief-Harrod-Domar production function.
23. V. Smil, *Population and Development Review* 17, no. 4 (1991): 569–601, pp. 586, 597, reported that in the 1980s, nitrogen applied in Zhejiang and Shandong provinces of China increased rice yields by amounts that were only 50–60 percent as large as the increments from an additional kg/ha applied in the 1960s.
24. Examples of system models are: J. W. Forrester, *World Dynamics* (Cambridge, MA: Wright-Allen Press, 1971); D. Meadows, D. L. Meadows, J. Randers, and William W. Behrens III, *The Limits to Growth* (New York: New American Library, 1972); M. Mesarovic and E. Pestel, *Mankind at the Turning Point* (New York: E. P. Dutton and Reader's Digest Press, 1974); P. House and E. R. Williams, *The Carrying Capacity of a Nation: Growth and the Quality of Life* (Lexington, Mass.: D. C. Heath, 1975); J. Gever, R. Kaufmann, D. Skole, and C. Vörösmarty, *Beyond Oil: The Threat to Food and Fuel in the Coming Decades*, 3rd ed. (Niwot: University Press of Colorado, 1991); A. J. Gilbert and L. C. Braat, eds., *Modelling for Population and Sustainable Development* (London: Routledge, 1991); W. Lutz, ed., *Population-Development-Environment: Understanding Their Interactions in Mauritius* (Heidelberg: Springer-Verlag, 1994). Critiques of systems models are: C. Kaysen in *Foreign Affairs* 50, no. 4 (July 1972): 660–68; H. S. D. Cole, C. Freeman, M. Jahoda, and K. L. R. Pavitt, eds., *Models of Doom: A Critique* of *The Limits to Growth,* with a reply by the authors of *The Limits to Growth* (New York: Universe Books, 1973); W. D. Nordhaus, *Economic Journal* 83, 332 (December 1973): 1156–83; E. van de Walle, in *Science* 189 (1975): 1077–78; D. Berlinski, *On Systems Analysis* (Cambridge, Mass.: MIT Press, 1976); P. R. Ehrlich, A. H. Ehrlich, and J. P. Holdren, *Ecoscience: Population, Resources, Environment* (San Francisco: W.H. Freeman, 1977), pp. 730–33.
25. P. M. Fearnside, *Human Carrying Capacity of the Brazilian Rainforest* (New York: Columbia University Press, 1986).
26. In many regions, the average amount of fresh water available annually is more than twice the amount of water that can be counted on ninety-five years in one hundred; (P.P. Rogers in *The Global Possible: Resources, Development, and the New Century,* R. Repetto, ed. (New Haven: Yale University Press, 1985), p. 294.
27. Paragraph 5.23 of *Agenda 21,* final document of the United Nations Conference on Environment and Development, held in Rio de Janeiro in June 1992 (Rio Earth Summit).
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