Human Carrying Capacity Is Determined by Food Availability

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Simple mathematical models have illustrated the relationship between human carrying capacity and population growth. In this study, food supply is proposed as the variable which best accounts for the human carrying capacity. The logistic equation, using food supply data as a variable carrying capacity, yields population estimates which are in accord with actual population numbers. That food supply data adequately fits the logistic model of human population dynamics provides evidence that, consistent with ecological notions typically applied only to nonhuman species, human population increases are a function of increased food availability.

KEY WORDS: agriculture; ecology; growth; logistic; population.

INTRODUCTION

As human population numbers surpass six billion, and many projections of future population size exceed 12 billion (Lutz et al., 1997), the need to understand and model global human carrying capacity becomes more and more pressing. Although models of human carrying capacity exist, they are typically tied to theoretical constructs rather than biologic data. Also, the use of mathematical models in analyzing human carrying capacity is complicated by the fact that the widely accepted models of population dynamics were developed using laboratory cultures and animal field studies. The present analysis ties known food production data compiled by the Food and Agriculture Organization (FAO) to a previously described model of global human population dynamics (Pearl & Reed, 1920; Cohen, 1995a; Gillman & Hails, 1997; Meyer & Ausubel, 1999).

HUMAN CARRYING CAPACITY MODELS

Ecologists and population biologists have long used the logistic model of population dynamics as a way to understand the cause and effect relationship between carrying capacity and population size (Wilson & Bossert, 1971; Gotelli, 1998). As Malthus (Petersen, 1979) and Darwin (1859) understood, in the absence of limitations on resources, i.e., space and food, populations will grow exponentially. However, if resources are limited, the growth rate begins to decelerate well below the maximum population size that the environmental resources can support. Deceleration continues until a more or less equilibrium level is reached. This equilibrium occurs near the asymptote of environmental limits. When plotted, the resultant growth takes the form of a sigmoidal or S-shaped curve. Typically, in the laboratory and field studies used to test population growth models, the carrying capacity is held constant.

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Unlike these laboratory cultures with a fixed amount of space and resources, the human population can be perceived to exhibit complex growth, with multiple processes occurring sequentially or simultaneously. This seems to be the case, given the complexity of our global society and the diversity of its social, economic and political condition (Arrow, 1995; Daly, 1996). However, as Meyer et al. (1999) explain, "many such (complex) phenomena, it turns out, can be described elegantly with a simple mathematical model."

Several authors (Pearl, R. & Reed, 1920; Cohen, 1995a; Marchetti et al., 1996; Meyer et al., 1999) have demonstrated that simple mathematical models of the relationship between human population and human carrying capacity can account for the growth rate. Cohen (1995a) proposed a human population dynamics model with a variable carrying capacity, in which changes in the carrying capacity is itself a function of population. In this model, shifts in the way the population affects carrying capacity change is dependent on the amount of resources, human potential and cultural attitudes. Similarly, Meyer and Ausubel (1999) proposed a model of bilogistic growth, which allows for a sigmoidally increasing carrying capacity. They stated that "new technologies affect how resources are consumed," thus changing the carrying capacity. The conclusion drawn from these studies is that models that employ a dynamic carrying capacity are more reflective of the human condition.

THE PROBLEM

It has been suggested that explicitly identified and quantified variables responsible for human population growth are unknown or, even worse, possibly unknowable (Cohen, 1995b; Marchetti et al., 1996; Meyer & Ausubel, 1999). The unstated perspective seems to be that population growth is an intrinsic feature of the human species regardless of resources and, therefore, the causes are seldom sought (Meritt, 2001). Further obfuscating the understanding of human population dynamics is the emphasis of the fact that the carrying capacity provides the upper limit to population size. That the carrying capacity of any species, including the human, is, in effect, an ecological magnet that draws population numbers to it is notably de-emphasized in the literature. The existence of human population models that accurately portray growth as a function of carrying capacity indicates that the causes of human population growth are indeed knowable. The difficulty seems to have been one of moving from a theoretically derived carrying capacity to an identifiable and quantifiable one.

Several authors (Cohen, 1995a; Meyer & Ausubel, 1999) have attempted to illustrate human carrying capacity in order to provide a more robust model with which to accurately estimate the size of the human population that the earth can support. As pointed out by Cohen (1995a), there is not much agreement regarding appropriate models of human carrying capacity. Attention has been paid to changes in technology, culture, economics and other factors posited as variables that are part and parcel of the human carrying capacity. However, none of these factors have been operationally defined although some examples are mentioned.

Specifically cited as examples of new technologies and resources are those that have allowed for increasing crop yields as well as other innovations which have ultimately served to increase human food availability (Cohen, 1995a; Meyer & Ausubel, 1999). That these studies highlight food availability as an important factor affecting human population growth is consistent with repeated findings that the level of food availability, along with other density dependent limiting factors, defines the carrying capacity or absolute upper limit for the population of any species, and all species will increase their number until approaching this limit (Pimentel, 1966; Quinn, 1992; Hopfenberg & Pimentel, 2001).

METHOD

Models of human population growth are typically an extension of the widely used logistic equation (Lotka, 1925):

$$\frac{dP(t)}{dt} = rP(t)\left(1 - \frac{P(t)}{\mathrm{K}(t)}\right) \tag{1}$$

Here P is the population, t is time and K is the carrying capacity. The constant $r > 0$ is the Malthusian parameter and represents the rate of population growth, which is the net effect of reproduction and mortality, and is expressed as a percentage. As previously mentioned, a static carrying capacity does not accurately reflect the current human condition. Therefore, a carrying capacity that changes with time t is substituted and takes the form K(t). The analytic solution to equation (1) takes the following form:

$$P(t + \Delta t) = \frac{\mathrm{K}(t)}{1 + \left(\frac{\mathrm{K}(t)}{P(t)} - 1\right)e^{-r\Delta t}} \tag{2}$$

Positing human food availability as the variable which best accounts for human carrying capacity requires quantification of food production data converted to “maximum population” values, i.e., the number of individuals that the resources can support. In identifying human food as the resource that accounts for human carrying capacity, a measure of global food availability must be calculated. The FAO obtains data from official and semiofficial reports of crop yields, area under production, and livestock numbers (World Development Indicators, 2002). If data are not available, the FAO makes estimates. The food production index covers food crops that are considered edible and that contain nutrients. The FAO determined these numbers relative to the average food production for the years 1989 to 1991, and set the average for these three years equal to 100. The FAO calculated livestock numbers separately and these were normalized independent of food production data. Similar to food production calculations, the FAO presented livestock numbers for all years relative to the average for the years 1989 to 1991, which was set at 100.

Increases in livestock production and food production show similar trends over the same time period (See figure 1). However, no conversion factor from food production to livestock production was provided. As livestock and food production data have similar values, use of food production or livestock data alone will suffice to estimate carrying capacity values. Since more years of food production data are available, these are used as the carrying capacity estimate for the present analysis. Therefore, although livestock are indeed a human food resource, these data are omitted.

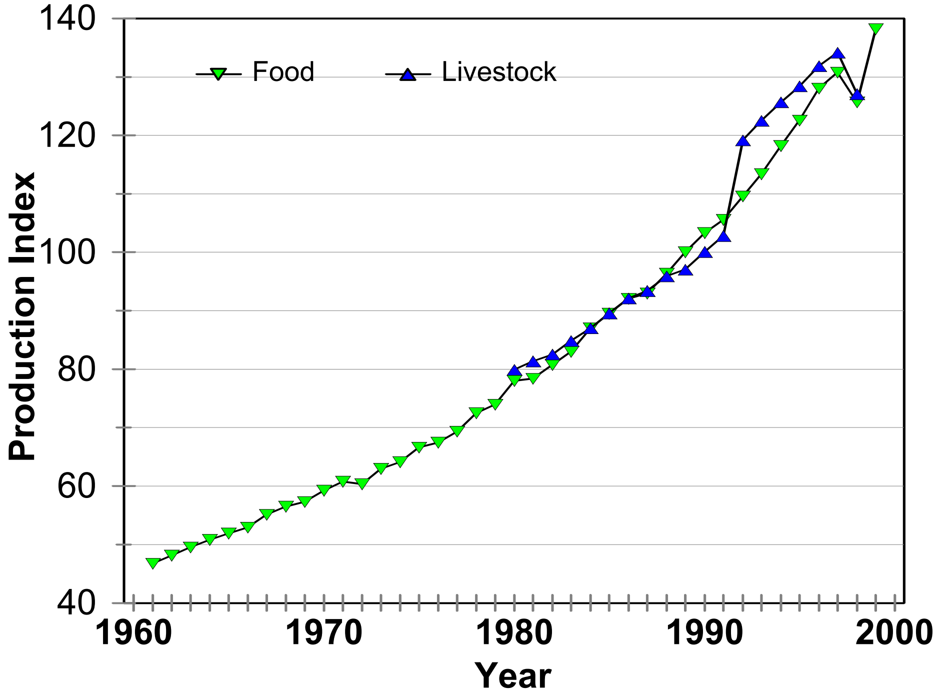

Figure 1. Food production index (WDI, 2002) (green) are three-year averages and normalized to the average for 1989–1991 = 100. Livestock production index (blue) were compiled independently and similarly normalized.

To organize the food production data for use in the logistic equation, the food production index was converted to carrying capacity values. The carrying capacity is defined here as the number of individuals that the resources can support. First, each year of food production was assigned a t value of the year of harvest plus one. For example, food production data for the year 1961 were assigned a year value of 1962 and was then used to calculate P for the year 1962 using equation (2). Changing the *t* value allows the time required for human gestation. Second, as food production data are reported based upon setting the average to 100 for the years 1989 to 1991, all values were multiplied by the constant 0.06710779. This constant was derived by dividing the PRB (2000) population data by the FAO Food Production data for t = 1962 thus setting food data equal to P for t = 1962 (P expressed in billions). The resultant converted food indices were then multiplied by 2.487 to generate a good fit with actual population data using equation (2) for the first available data point, t = 1962. Third, the Malthusian Parameter for Equation 2 was held constant at r = 0.03.

RESULTS AND DISCUSSION

Positing FAO food production data as the sole variable in the logistic equation that accounts for human carrying capacity yields population estimates that closely approximate actual population numbers as illustrated in Figure 2. Population estimates derived from the FAO food production data show an increasing trajectory, as do the actual population numbers. Of particular note is the difference between K and P values for all years. For example, at t = 2000, K = 23.06 billion, 3.79 times the value of P. These numbers are consistent with findings from the FAO and other sources (Lappé et al., 1998; Rahnema, 2002). Given these data, it is clear that issues of starvation and malnutrition are not a function of worldwide food production but a function of distribution complexities (Hinrichsen, 1997), which seem to increase as a function of the size of the global population (Calhoun, 1962; Hopfenberg & Pimentel, 2001).

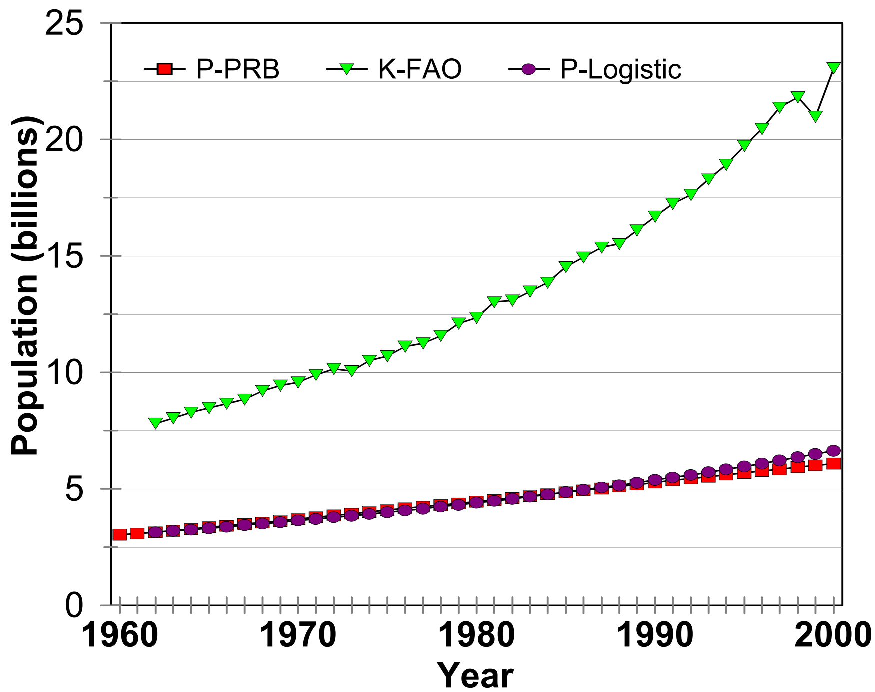

FIGURE 2. Food production data (K-FAO) indicates the carrying capacity or maximum number of people that can be sustained at this level of food availability; logistically derived population numbers using Equation (2), (PLogistic); and actual human population numbers (P-PRB).

Increasing food production is a phenomenon that is not limited to the past 40 years. Although more precise data have been kept for this period, the prodigious increase in food production has its roots in the beginning of the agricultural revolution 10,000 years ago. As Cohen (1995b) stated, "The ability to produce food allowed human numbers to increase greatly and made it possible, eventually, for civilizations to arise." Meritt (2001) expanded on this notion. He asserted, "With a genuinely ecological understanding of how humanity fits in with the rest of nature, the filters through which we see our 'increase culture' can finally be removed. The result is the uncovering of a complex of cultural traits, including total reliance on agriculture, the ultracompetitive interspecies practices that surround that reliance and the institutionalized ownership of food as a means (to perpetuate civilization)."

An indication of our ultracompetitive cultural stance toward increasing food production is the FAO's project during the 1970's to map the productive capabilities of soil the world over, including estimates of the kinds of crops that might be grown in the various soil types (Higgins et al., 1983). The implication is that all soil on the planet that is cultivable, has freshwater accessibility and contains the nutrients necessary for crop growth is ultimately available for human food production. Again, the data presented here indicate that population will continue to increase as long as food production continues to increase.

Much attention has been paid to human population growth and concomitant problems. The impact of continued population increases on the extinction rate of other species has been well documented (Hinrichsen, 1994; Hern, 1999). It is also accepted that population growth has had a detrimental impact on the quality of human life itself. The biological, social and psychological well being of people worldwide has been negatively impacted by the prodigious increases in population, and the danger of continued increases is well understood. These dangers include diseases that may ultimately control population growth by means of an increased death rate (Hopfenberg & Pimentel, 2001). Addressing the problem of human population growth must include a shift in cultural attitudes, which may well consist of changes in the social, political, educational and religious mindset. This cultural shift must also include the recognition, as the present study makes clear, that the problem of human population growth can be feasibly addressed only if it is recognized that increases in the population of the human species, like increases in the population of all other species, is a function of increases in food availability. As Quinn (1996) so eloquently stated, "There is no species that dwindles in the midst of abundance, no species that thrives on nothing."

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REFERENCES

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Foilce, C., Holling, C. S., Jansson, B., Levin, S., Maler, K., Perrings, C. & Pimentel D. (1995). Economic Growth, Carrying Capacity, and the Environment. Science 268, 520–521.

Calhoun, J. B. (February, 1962). Population Density and Social Pathology. Scientific American 206, 139–150.

Cohen, J. E. (1995a). Population Growth and the Earth's Human Carrying Capacity. Science 269, 341–346.

Cohen, J. E. (1995b). How Many People Can the Earth Support? New York: Norton.

Daly, H.E. (1996). Beyond growth: The economics of sustainable development. Boston, MA: Beacon.
Darwin, C. (1859). On the Origin of Species By Means of Natural Selection. Random House, USA, Modern Library edn. (1998).
Gillman, M. & Hails, R. (1997). An Introduction to Ecological Modelling. Malden, MA: Blackwell Science.
Gotelli, N. (1998). A Primer of Ecology (2nd ed.). Sunderland, MA: Sinauer Associates.
Hern, W. (1999). How Many Times Has the Human Population Doubled? Comparisons with Cancer. Population and Environment 21 (1), 59–80.
Higgins, G.M., Kassam, A.H. Naiken, L. Fischer, G. & Shah, M.M. (1983). 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.
Hinrichsen, D. (1994). Putting the bite on planet earth. International wildlife 24, 36–46.
Hinrichsen, D. (December, 1997). Winning the Food Race. Population Reports Series M, No. 13, Baltimore, Johns Hopkins School of Public Health, Population Information Program.
Hopfenberg, R. & Pimentel, D. (2001). Human Population Numbers as a Function of Food Supply. Environment, Development and Sustainability 3 (1), 1–15.
Lappé, F. M., Collins, J., & Rosset, P. (1998). World Hunger: 12 Myths (2nd ed.). New York: Grove Press.
Lotka, A. J. (1925). Elements of Physical Biology. Baltimore, MD: Williams and Wilkins.
Lutz, W., Sanderson, W. & Scherbov, S. (1997). Doubling of World Population Unlikely. Nature 387, 803–805.
Marchetti, C., Meyer, P. S. & Ausubel, J. H. (1996). Human population dynamics revisited with the logistic model: How much can be modeled and predicted? Technological Forecasting and Social Change 52 (1), 1–30.
Meritt, M.S. (2001). The unsustainability and origins of socioeconomic increase. Unpublished master's thesis, The City University of New York, New York.
Meyer, P. S. & Ausubel, J. H. (1999). Carrying capacity: A model with logistically varying limits. Technological Forecasting and Social Change 61 (3), 209–214.
Meyer, P.S , Yung, J.W. & Ausubel, J. H. (1999). A primer on logistic growth and substitution: The mathematics of the loglet lab software. Technological Forecasting and Social Change 61 (3), 247–271.
Pearl, R. & Reed L.J. (1920). On the rate of growth of the population of the United States since 1790 and its mathematical representation. Proceedings of the National Academy of Science 6, 275–288.
Petersen, W. (1979). Malthus. Cambridge, MA: Harvard University Press.
Pimentel, D. (1966). Complexity of ecological systems and problems in their study and management. In Watt, K. (Ed.) Systems Analysis in Ecology (pp. 15–35). New York and London: Academic Press.
Population Reference Bureau (PRB): 2000, 2000 World Population Data Sheet, Washington, DC: PRB, Inc.
Quinn, D. (1992). Ishmael. New York: Bantam/Turner.
Quinn, D. (1996). The Story of B. New York: Bantam Books.
Rahnema, M. (2002). A Different Look at the "Population Problem." Population and Environment 24 (1), 97–104.
Wilson, E.O. & Bossert, W.H. (1971). A Primer of Population Biology. Sunderland, MA: Sinauer Associates.
World Development Indicators: 2002, Agricultural Output and Productivity. Washington, DC: The World Bank 2002.