HUMAN POPULATION NUMBERS AS A FUNCTION OF FOOD SUPPLY

RUSSELL HOPFENBERG[1,*] and DAVID PIMENTEL[2]
[1]*Duke University, Durham, NC, USA;* [2]*Cornell University, Ithaca, NY, USA*
*(*author for correspondence, 105 Autumn Drive, Chapel Hill, NC, USA 27516-7744; e-mail: RussH100@aol.com; tel.: (919) 431 0085)*

(Received 11 January 2000; accepted 6 March 2001)

Abstract. Human population growth has typically been seen as the primary causative factor of other ecologically destructive phenomena. Current human disease epidemics are explored as a function of population size. That human population growth is itself a phenomenon with clearly identifiable ecological/biological causes has been overlooked. Here, human population growth is discussed as being subject to the same dynamic processes as the population growth of other species. Contrary to the widely held belief that food production must be increased to feed the growing population, experimental and correlational data indicate that human population growth varies as a function of food availability. By increasing food production for humans, at the expense of other species, the biologically determined effect has been, and continues to be, an increase in the human population. Understanding the relationship between food increases and population increases is proposed as a necessary first step in addressing this global problem. Resistance to this perspective is briefly discussed in terms of cultural bias in science.

Key words: disease(s), food, food availability, food production, human, population, population growth.

1. Introduction

Of all environmental problems, rapid human population growth is arguably the most detrimental. In fact, escalating human population is fueling the acceleration of all environmental problems (Brown and Nielsen, 2000; Plant et al., 2000; Jayne, 1999; Lelieveld et al., 1999; Carpenter and Watson, 1994; Bartiaux and van Ypersele, 1993; Alper, 1991; Brinckman, 1985). The increase in the number of humans is responsible for amounts of pollutants dumped into land, water, and atmosphere. The consumption of land resources has also increased, and at an accelerating rate. Given the fact that the world population is growing (Marchetti et al., 1996; Pimentel and Pimentel, 1997), the population size is also seen as the major determinant of the amount of resources used. The World Health Organization (WHO, 1996a) reports that more than three billion people are now malnourished – the largest number and proportion ever. In other words, in many places the number of humans exceeds the carrying capacity of the area in which they live. With the world population surpassing six billion, the issue of population growth warrants the most serious attention.

Given the numerous effects of increased population on the planet, human population growth is seen as the main cause of other biologically and ecologically

Environment, Development and Sustainability **3:** 1–15, 2001.

destructive phenomena. In this context, these destructive phenomena are seen as the dependent variables on one side of an ecological equation and population size is seen as the independent variable on the other.

Conceptualizing human population growth as an independent variable has led to an unforeseen consequence. That is, human population has been seen as independent of other identifiable ecological, biological, and behavioral variables. Some have proposed that, while natural resources, ecological concerns, and other biological and behavioral variables can limit human population growth, these same variables, when increased, do not serve to escalate population growth (Marchetti et al., 1996). Thus, the causes of human population growth have been left inadequately addressed. Our position is that population growth, the prime environmental problem affecting all ecological, biological, and non-living systems, is a function of increasing food production (Quinn, 1992, 1996, 1998a; Pimentel, 1966, 1996).

2. The current perspective

It is the current perspective in both the scientific and lay communities that food production must be increased in order to support a growing human population (Postel, 2001; Bongaarts, 1994; Waggoner, 1994; Brundtland, 1993; Baron, 1992; Anifowoshe, 1990; Brown, 1989; Robson, 1981). For example, Young (1999) noted that current UN population projections predict that the population of developing countries will rise to about eight billion by 2025 and nine billion by 2050. He then asserted, "It is widely recognized that massive agricultural development will be needed to feed this added population."

Some contend that fertility is under cultural and economic control (Marchetti et al., 1996) and that science and technology will solve all future food problems (Ausubel, 1996). For example, the ADM Corporation advertises that they are increasing food production to feed a growing world population. Crop yields in the US and other countries were significantly increased from 1950 to 1980 (USDA, 1998; Pimentel and Pimentel, 1996). Ausubel (1996) also reported that US wheat yields tripled from 1940 and corn yields have quintupled. He further indicated that increased food demand is due to growth in world population. However, as Farb (1978, p. 121) has pointed out, "intensification of production to feed an increased population leads to a still greater increase in population." That is to say that as more food has been made available ostensibly to alleviate food shortages caused by the increased number of people, the biologically determined response has been an increase in the population.

P. Waggoner (personal communication, April 1, 1998) stated that "Because people stabilize and even shrink their numbers in wealthy, well-fed countries and multiply in poor, hungry African ones, food supply seems not to determine human population." Abernethy's (1995) investigations and data contradict these opinions. Additional data from the US also contradicts Waggoner's point about where population growth is occurring. The US population doubled from 1935 to 1995 and is now about 270 million. The US population is projected to double again in about 75 years to 540 million, based on the current rate of the population increase in the US (USBC, 1998). These data and projections include immigration numbers. In fact, Bouvier and Grant (1994) have predicted that immigrants and their decedents will comprise approximately 90% of all US population growth between 1993 and 2050. Although these projections might be seen as more reflective of the growth rate in other countries, it is important to remember that the non-native population of the US has grown from zero to over 270 million in only 510 years. In other words, almost all of the prodigious population growth on this continent is the result of increases in the number of immigrants and their descendants. Viewed in this way it becomes apparent that focusing on the question of where population growth is taking place may be a distraction from addressing the question of why it is taking place on a global level.

The prevailing lay and scientific attitudes beg the Malthusian question "how will the US continue to feed its population and still maintain its food exports to needy nations?" In other words, "how are we going to feed all these people?" This indicates a denial of the certainty that increasing the availability of food will further increase the population, thereby increasing the number of starving and malnourished people. Thus, it does not address the Quinnian question "how are we going to stop producing all these people (Quinn, 1997)?" since it is through exports from food-rich to food-poor areas (Allaby, 1984; Pimentel et al., 1999) that the population growth in these food-poor areas is further fueled.

Another problem that appears to cloud the picture is that population growth seems to be slow and gradual. Adding one million to the world population every four days or adding three million to the US population every year is scarcely noticeable. With the passage of years, the world population doubled and the US population also doubled.

3. Animal data

Many field studies have demonstrated that all animals tend to increase and convert as much of their environmental resources as possible into themselves and their progeny. Darwin (1859) in his chapter 'The Struggle For Existence' pointed out that food is a critical factor that limited some animal populations. He also noted the "numerous recorded cases of the astonishingly rapid increase of various animals in a state of nature, when circumstances have been favorable to them during two or three following seasons." Elton (1927) was the first to explicitly state that when animals start struggling for existence, they spend a large part of their lives eating and seeking food. He added that the prime driving force for all animals is finding the right kind of food and finding enough food. Elton (1927, p. 56) in fact pointed out that "the whole structure and activities of the community are dependent upon questions of food-supply."

The finding that the population size of animal species is a function of food availability has been empirically demonstrated. Food energy is partitioned into four compartments viz.: maintenance, growth, stored energy, and reproduction. Scott and Fore (1995) investigated the effects of food availability on reproduction in the marbled salamander. Subjects were assigned to one of three groups. At the end of the experiment, 60% of the high-food females were reproductive. In the medium- and low-food groups, these numbers were 42% and 12% respectively. These results demonstrate that food availability influences the population dynamics of a species. Similarly, Komdeur (1996) demonstrated that the Seychelles warbler prolonged their reproductive season, including increases to year-round breeding, when their natural condition changed to one with high food availability. Conversely, in female musk shrews (whose sexual receptivity is not restricted to the preovulatory period), 48 h of food restriction led to reduced mating behavior compared with ad-lib controls. Thus, small reductions in food availability can inhibit female sexual behavior (Gill and Rissman, 1997). In the *Calanus finmarchicus*, egg production is suppressed when the nutrient pool decreases below a minimal critical value. Thereafter, no eggs are laid. When food is reintroduced, somatic growth resumes until structural body weight is restored, then oogenesis is fueled (Carlotti and Hirche, 1997). Also, Iwamoto (1978) has shown that monkey troop size increases rapidly after artificial provisioning, but the level of consumption efficiency of the troop is always maintained lower than the critical point in both the artificial and natural habitat. Starvation within the troop simply does not occur if the rate of food availability is held relatively constant. Under natural conditions, as the feeder population increases, the food population decreases. This leads to a decrease in the feeder population which is then followed by an increase in the food population. This increase in food availability again produces an increase in the feeder population. In quaternary consumer species, the so-called 'top of the food chain', this occurs primarily through fluctuations in birth rates.

Again, the data overwhelmingly establishes that increasing the amount of food available to the population of any species leads to an increase in the population of that species and a decrease in the amount of food leads to a decrease in the size of the affected population (Caceres et al., 1994; McKillup and McKillup, 1994; Angerbjorn et al., 1991; Wayne et al., 1991; Bomford, 1987).

Some animals, such as rabbits, have evolved the adaptation of increasing their numbers rapidly as predation and/or disease organisms often limit their numbers (Elton, 1927; Pimentel, 1988). Some species self-regulate their number to their food resources by maintaining home ranges. Chitty (1995) reported that excess young voles, for example, are forced to leave the home range of their parents. While traveling to find new homes for themselves the young are heavily preyed on or die of starvation and disease. Possibly more germane is the evidence that a sudden improvement of diet in sheep cause an increased ovulation rate (Schinkel, 1963) and that fasting in mice for relatively short periods of time prior to mating resulted in depression of male libido and reduced conception in females (Christian et al., 1965).

The evidence clearly demonstrates that, although species have evolved different strategies for adjusting to food supply limitations, food availability influences and determines the population size of all species.

4. Human correlational data

The populations of human cultures described as hunter-gatherers were limited to the food resources available (Lee, 1969; Lee and DeVore, 1976; Pimentel and Pimentel, 1996). Where these cultures still exist untouched, this continues to hold true. After one culture of humans started a program of agricultural expansion about 10 000 years ago (Quinn, 1992) they seem to have generally escaped the controls and limits of natural resources. However, this escape is proving illusory. Recent data concerning the increasing malnutrition and diseases in the human population worldwide indicates that human numbers will be limited in other ways (Pimentel et al., 1999). If increases continue, the population will ultimately be controlled through mechanisms such as malnutrition and disease, i.e., by means of accelerated death rates.

Marchetti et al. (1996) have extrapolated human population data back to 10 000 BCE and show a geometrically increasing population. Although humans have been on the planet for over two million years, it is interesting that they chose to extrapolate back to 10 000 BCE as this is the usually agreed upon beginning of the 'agricultural revolution'. The agricultural revolution produced human food surpluses, through a program of expansion and elimination of competing cultures and species (Quinn, 1992; Zinn, 1995). The resultant food surplus is both necessary and sufficient to explain the meteoric rise in the human population in only 500 generations. Based on the experimental evidence, the correlational data and the seeming coincidence of agricultural expansion and the prodigious human population increases, there is overwhelming evidence that food surplus explains, i.e., is causally related to, human population increases. Pimentel and Pimentel (1996) also noted that growth in human population numbers began to escalate about 10 000 years ago, when agriculture was first initiated. Farb (1978, p. 129) stated "The population explosion, the shortage of resources, the pollution of the environment, exploitation of one human group by another, famine and war – all have their roots in that great adaptive change from foraging to production." Given the current environmental crisis, after only 10 000 years of agricultural expansion, it is curious that he called this change adaptive.

Other more recent data are available. For example, for the period of 1989–91, the world crop production index rose 25% over the 1979–81 level. The increase over the period of 1994–96 was 41.3% greater than the 1979–81 level (World Development Indicators, 1998). Similarly, the food production index for the same time periods rose 25.6% and 45.6%. The livestock production index rose 24.1% and 46.6%, again for the same time periods. World cereal yield in kilograms per hectare rose from 2,230 to 2,561 over the periods 1979–81 to 1994–96. Thus food production has increased sufficiently, i.e., produced sufficient food surpluses, to keep the world population growing catastrophically (Quinn, 1998b) even though food production increases have slowed since 1983. For instance, per capita grain production started declining after 1983 (Pimentel et al., 1999). Note, grains make up 80% to 90% of world food.

It is clear that world human food availability continues to grow, but at reduced rates (Allaby, 1984; Pimentel et al., 1999). Livestock currently consume 130 million tons of grain in the US, enough to feed about 400 million people (Pimentel, 1996; Pimentel et al., 1995). Certainly there would be even more human food available if dependence on livestock was decreased. However, because human population is a function of food availability, the resulting increase in available human food would induce a commensurate rise in population. This population increase would ultimately exacerbate the starvation and malnutrition predicament. Since it is known that human population expansion is correlated with a decrease in available land, water, energy, and biological resources, there is a suggested cause and effect relationship between these decreases and human population growth.

Given that the increases in food availability cause increases in population growth, this accounts for the reduction in global biodiversity. Humans are now utilizing about 50% of the world's biomass for their own use (Pimentel and Pimentel, 1996). Clearly, as the amount of human food and, contingently, the number of humans escalates, the biomass available for other species goes down and biodiversity declines.

5. Population increases and human diseases

Many of the variables that affect population size are density-dependent factors (Emmel, 1973; Gotelli, 1998). As the density of the human population increases, the amount of resources available to individuals decreases. Beyond a certain population density, health declines and mortality rates increase.

At first glance, human health seems unrelated to natural resources; but upon closer consideration, it becomes apparent that both the quality and quantity of natural resources (e.g., food and water) play a central role in human health. Increases in diseases associated with diminishing quality of water, air, and soil resources provide evidence of a declining standard of living. Profound differences exist in the causes of death between develop*ed* and develop*ing* regions of the world. Communicable, maternal, and/or prenatal diseases account for 40% of the deaths in developing regions but only 5% in developed regions (WHO, 1996b). While there is a complex set of factors responsible, large population increases followed by inadequate food, and contaminated water and soil are the major contributors to diseases and other health problems, especially in developing countries (Pimentel et al., 1998).

As populations increase in size, risks to health grow as well, and this occurs especially rapidly in areas where sanitation is inadequate. Human deaths due to infectious diseases increased more than 60% from 1982 to 1992 (WHO, 1992, 1995).

Overcrowded urban environments, especially those without proper sanitation, are of great public health concern because they have the potential to be the source of disease epidemics (Iseki, 1994; Holden, 1995) and increased pollution (Brown and Nielsen, 2000; Plant et al., 2000; Jayne, 1999; Lelieveld et al., 1999; Carpenter and Watson, 1994; Bartiaux and van Ypersele, 1993; Alper, 1991; Brinckman, 1985). For example, dengue – spread by the mosquito *Aedes aegypti* which breeds in water holding containers including tin cans, old tires, and other containers – is spreading rapidly in crowded tropical cities (Lederberg et al., 1992; Gubler and Clark, 1996). Currently there are 30 to 60 million infections of dengue per year, with a dramatic increase since 1980 (Monath, 1994). Approximately 65% of the world's infectious diseases are spread from person to person (WHO, 1996a). In addition to the increase in infectious diseases that now cause 35% of human deaths (Ramalingaswami, 1996), it is estimated that another 40% of human deaths each year can be attributed to various environmental factors, especially organic and chemical pollutants (Pimentel et al., 1998).

Worldwide waterborne infections account for 80% of all infectious diseases and 90% of infectious diseases in developing countries (Epstein et al., 1994). Lack of sanitary conditions contributes to about two billion human infections of diarrhoea with about four million deaths per year, mostly among infants and young children (WHO, 1992).

Developing countries discharge approximately 95% of their untreated urban sewage directly into surface waters (WHO/UNEP, 1993). Of India's 3,119 towns and cities, just 209 have partial treatment facilities and only eight have full wastewater treatment facilities (WHO, 1992). Downstream, the untreated water is used for drinking, bathing, and washing.

In the United States, nearly 50% of the lake water is polluted by erosion runoff containing nitrates, phosphates, and other chemicals (Gleick, 1993). Non-point sources of US pollution, especially agricultural runoff (e.g., animal wastes and pesticides) also contribute to disease problems.

Schistosomiasis, long associated with water and unsanitary conditions, is expanding worldwide and currently causes an estimated one million deaths annually (Pimentel et al., 1998). This expansion follows an increase in habitats for the snail intermediate-host population made by various human activities, such as the construction of dams and irrigation channels (Shiklomanov, 1993). For example, construction of the Aswan High Dam in Egypt led to an explosion in the incidence of *Schistosoma mansoni* from 5% in 1968 to 77% in 1993 (Shiklomanov, 1993). Infections of *S. heamatobium* ranged between 2% and 11% before dam construction in 1968, but increased to between 44% and 77% in 1990 (Akhtar and Verhasselt, 1990).

Malaria, a mosquito-borne disease, infects more than 500 million humans each year, killing approximately 2.7 million people (Marshall, 1997; Travis, 1997). Environmental changes, including more polluted water and deforestation, have fostered the high incidence and increase in malaria.

In addition, air pollutants adversely affect the health of about four to five billion people worldwide each year (World Bank, 1992; Leslie and Haraprasad, 1993; WHO/UNEP, 1993). Increasingly, air pollution is associated with the expanding world population; the burning of fossil fuels; increased release of industrial chemical emissions; and more automobiles.

Globally, especially in developing nations where people cook with fuelwood and coal over open fires, about four billion humans suffer from exposure to smoke each year (WHO, 1992; World Bank, 1992; Leslie and Haraprasad, 1993; WHO/UNEP, 1993). This smoke contains large quantities of particulate matter (Leslie and Haraprasad, 1993) and more than 200 chemicals, including several carcinogens (Godish, 1991) and represents pollution levels considerably above those acceptable by the World Health Organization (WHO, 1992; World Bank, 1992; Leslie and Haraprasad, 1993; WHO/UNEP, 1993). Of the estimated 2.7 million deaths per year related to air pollution, 2.2 million are caused by pollutants from wood and other fuels burned indoors for cooking and heating (UNDP, 1999).

One of the most severe human diseases related to shortages of natural resources is malnutrition. This malnutrition relates to shortages of calories, protein, vitamins (e.g., vitamin A), iron, iodine, and others. Today, more than three billion people (one-half of the world population) suffer from malnutrition (WHO, 1996a), the largest number and proportion ever in history. In other words, as the global population has grown, the number and proportion of malnourished individuals has grown. Thus it can be asserted that the increase in the number and proportion of people suffering from malnutrition is a function of population size.

Poverty and lack of sanitation can be as severe in certain urban sectors as they are in rural areas; several studies point to inequalities even within different parts of individual cities (Pimentel et al., 1998). Urban environments, especially those without proper sanitation, are becoming a cause for concern due to their high potential for the spread of disease due to overcrowding (Holden, 1995). The high density of people in urban environments provides no protection from pollution caused by accumulation of city wastes in water, air, and soil, and creates favorable conditions for the rapid spread of infectious diseases that can easily reach epidemic proportions (WHO, 1992).

Malnutrition and other diseases are interrelated and, as might be expected, parasitic infections and malnutrition coexist where there is poverty, poor sanitation (Shetty and Shetty, 1993) and high population density (Gotelli, 1998). Malnourished individuals, especially children, are seriously affected by parasitic infections because these infections can reduce the nutrient availability from the children's diet. Intestinal parasites, like hookworms, reduce the uptake of nutrients in infected humans. They increase the loss of nutrients through diarrhoea and dysentery, impair nutrient absorption, frequently diminish appetite and food intake, and directly ingest blood (Shetty and Shetty, 1993). Hookworms, for instance, can remove up to 30 cc of blood from an infected person each day, leaving the individual weak and susceptible to other diseases (Hotez and Pritchard, 1995). An estimated 5% to 20% of an individual's daily food intake is used to offset a parasitic illnesses and stress of the disease (Pimentel and Pimentel, 1996).

It has been said that the suffering of those who are currently malnourished could be ameliorated through improved food distribution (Hay, 1981). Kofi Annan (1997), Secretary-General of the United Nations stated: "The world has enough food. What it lacks is the political will to ensure that all people have access to this bounty, that all people enjoy food security." Also, alternatives to increasing food production have been suggested. For example, the nutrition of the world population might be improved temporarily with better distribution of total world food without increasing production. For instance, it might be possible to feed the current six billion people a minimal but nutritionally adequate diet, if all food produced in the world was shared and distributed equally (Cohen, 1995). Yet, there are problems with this proposal. For example, how many people in developed and developing countries who have more than their basic needs of food resources would be willing to share their food and pay for its production and distribution? Whether or not improved distribution occurs, if food production continues to increase, the world population is projected to increase to 12 billion in the next 50 years (based on current growth rates). Severe shortages of land, water, energy, and biological resources will increase malnutrition and food shortages (Abernethy, 1993). This also points to the reality that food production will be capped at some point, as the planet's ability to produce food is finite.

6. The effects of *halting increases* in food production

The population growth curve characteristic of most species is sigmoid or s-shaped. This is as true for paramecia as it is for larger organisms with long life cycles such as birds, trees, and mammals. Growth starts slowly, accelerates rapidly in exponential form, and then decelerates as it approaches the asymptote of environmental limits. For all species limited by density-dependent factors, including humans, this limit can be determined by food availability. The food may also be called one of the carrying capacity limits of the environment. Once a population has reached a food limitation, a relative equilibrium may be reached. This equilibrium involves fluctuations in population size, and these fluctuations follow the periodic fluctuations of food levels and/or predation and disease outbreaks. Generally, as feeder populations increase, the food resources decrease. This is followed by a decrease in the feeder populations which allows food resources to again increase. These long-term oscillations in population density may occur with many years between peaks and depressions (Emmel, 1973 p. 86–98; Chitty, 1995).

By increasing agricultural production, humans have continually 'raised the ceiling', i.e., the asymptote of food limitation. That is, through agricultural production, the amount of human food produced is increased. This sets the occasion for a decline in human food resources which may occur through events such as drought or other problems. Thus, when the food resources decline, it may occur in a precipitous fashion. This future crisis may be the direct result of increasing the human population beyond the carrying capacity of the environment. In other words, the higher the ceiling, the more serious the crash. Robson (1981) suggested that famines do not occur divorced from intensive agricultural production.

Quinn (1996) has called our program of increasing food production in order to maintain population growth 'totalitarian agriculture'. In response to the claim that food production must be increased to feed a growing population, Quinn (1998c) has responded that

> If six billion people can be fed by totalitarian agriculture, then the same six billion can be fed by sustainable agriculture. The difference between totalitarian agriculture and sustainable agriculture is not technique or output (since a turnip is a turnip however it's produced) but rather **program**. The program of totalitarian agriculture is to increase food production in order to outpace population growth that is fueled by the very increases it produces, and this is what makes it unsustainable.

The notion that as the population approaches the asymptote of food limits, mass starvation will ensue has been implied, if not stated explicitly. Throughout the literature on the subject, the position has been "we must increase food production to feed a growing population" (Postel, 2001; Bongaarts, 1994; Waggoner, 1994; Brundtland, 1993; Baron, 1992; Anifowoshe, 1990; Brown, 1989; Robson, 1981). Malthus, in his famous Essay, put forth his 'principle of population' which was his assertion that the population has the capacity to grow faster than the means of subsistence (Petersen, 1979, p. 47). However, due to biological realities, the population cannot be sustained beyond the level of food availability. Because of the Malthusian perspective which is pervasive in our culture, that 'food production must be increased to feed a growing population', that, in fact, is what occurs. The result is annual food production increases that cause annual population increases, with seriously increasing malnutrition and added diseases. However, the evidence indicates that the human population will increase until further food limitations are reached. Then population growth will be restricted (Pimentel and Pimentel, 1996, pp. 23, 296).

If food availability for the population is held constant and population increases continue at 1.4% per year (PRB, 2000), the reduction in per capita food per year is relatively small on average (Quinn, 1998a). For example, if a population consists of 1,000 humans and food availability for this population is held constant forever, and allows for 3,000 calories per person per day (holding other vital nutrients constant relative to calorie count), this is a total calorie count of three million calories per day. Ifthe number of people increases to 1,014, the number of calories per person per day is reduced to 2,959. If the same amount of population growth occurs the next year, the population will grow to 1,028. The calories per person per day will then be 2,918. Repeated twice more, the calories available per person per day will drop to 2,879 and then to 2,838. After four years of 1.4% population growth, calories per person per day is reduced by only 162. After a total of nine years, the reduction in calories is only 353, to a level of 2,648 calories per person per day. The impingement of the food and nutrient limitation, although subtle, will eventually serve to curb human reproduction. This may occur through social mechanisms, choice behavior or reproductive–biological mechanisms. In other words, halting increases in food production will halt the increases in population by means of a reduced birth rate.

Thus, there appears to be two available systemic methods of population control. One is to continue to fuel population growth through increased food production and allow biological mechanisms such as malnutrition and disease to limit the population by means of an increased death rate. The other is to cap the increases in food production and thereby halt the increases in population by means of a reduced birth rate. Instead of depending on malnutrition and disease to limit human numbers, a social mechanism in response to a stable food supply, might be for humans to limit their numbers democratically or consensually or to employ incentives.

7. Cultural bias in science

Cultural bias in science is not new. When Charles Darwin (1859) put forward the notion that humans came into being by an evolutionary process his theory faced strong opposition, especially from the clergy. Evolutionary theory has gained acceptance but is not acknowledged by many segments of society. Perhaps the same cultural bias that interfered with the acceptance of Galileo's observations and assertions supporting Copernican theory (Finocchiaro, 1989), continues to interfere with the acceptance of Darwin's proposals (note the Kansas board of Education's decision to abolish the requirement for teaching evolution – New York Times, August 12, 1999). The view that humans are above the natural physical and biological laws continues today.

A similar bias is also present regarding understanding the cause-and-effect relationship between food production and human population growth. Some, like Julian Simon (1991) hold that humans are exempt from the natural laws of physics and biology and that human behavior occurs as a result of metaphysical forces. P. Waggoner (personal communication, April 1, 1998) stated that "we . . . question whether something (population growth) so dependent on human wishes can be predicted physically." Because of this belief, the use of the scientific method to study human behavior, especially as it relates to population dynamics, is in its infancy, and still looked upon with skepticism (Skinner, 1990).

8. Coda

Clearly, human numbers cannot continue to increase indefinitely and defy all the physical and biological laws. Natural resources are already severely limited, and there is emerging evidence that natural forces are already starting to control human population numbers through malnutrition and other diseases, i.e., through an increased death rate. More than three billion people worldwide are already malnourished. Pollution of water, air, and land has increased, resulting in a rapid increase in the number of humans suffering from serious, pollution-related diseases (Pimentel et al., 1998). Again, it is clear that natural forces are at work to increase human death rates.

Fifty-eight academies of science, including the US National Academy of Sciences, point out that humanity is approaching a crisis with respect to the issues of natural resources, population, and sustainability (NAS, 1994). If the program of 'increasing food production in order to feed a growing population' continues to be pursued, human numbers will continue to increase beyond the ability of the natural community to support those numbers. Then disease, including malnutrition, and other natural controls will limit human numbers. However, population control does not have to occur this way if it is understood that our program of increasing food production continues fueling the population explosion.

Some people believe that for humans to limit their numbers would infringe on their freedom to reproduce. This may be true, but a continued increase in human numbers will infringe on our freedoms from malnutrition, hunger, disease, poverty, and pollution, and on our freedom to enjoy nature and a quality environment. By understanding the relevant scientific laws regarding population dynamics that human population size is a function of food availability, we have an opportunity to ensure the well being of future generations. Individuals will then live in an environment capable of sustaining human, and other life.

Acknowledgements

We wish to thank Edie Hopfenberg, Steven Salmony, and Jeffrey Wysocki for their helpful discussion, useful suggestions and thoughtful review of earlier drafts.

References

Abernethy, V.: 1993, *Population Politics: The Choice that Shapes our Future*, New York, Insight Books.

Abernethy, V.: 1995, 'The demographic-transition model – a ghost story', *Population and Environment* **17**(1), 3–6.

Akhtar, R. and Verhasselt, Y.: 1990, *Disease, Ecology, and Health: Readings in Medical Geography*, Jaipur, India, Rawat Publications.

Allaby, M.: 1984, 'The changing face of agriculture', in E. Hillary (ed.), *Ecology 2000,* New York, Beaufort Books, Inc., pp. 36–56.

Alper, J.: 1991, 'Environmentalists: ban the (population) bomb', *Science* **252**, 1247.

Angerbjorn, A., Arvidson, B., Noren, E. and Stromgren, L.: 1991, 'The effect of winter food on reproduction in the arctic fox, Alopex lagopus: a field experiment', *Journal of Animal Ecology* **60**(2), 705–714.

Anifowoshe, T.O.: 1990, 'Food production – problems and prospects', *GeoJournal* **20**(3), 243–247.

Annan, K.: 1997, 'Secretary-General Urges Action to Reduce Global Hunger by Half by 2015, in World Food Day Message', *Press Release SG/SM/6362 OBV/15*, October 16, 1997, Retrieved July 14, 1999 from the World Wide Web: http://www.un.org/Docs/SG/quotable/6362.htm.

Ausubel, J.: 1996, 'The liberation of the environment', *Daedalus* **125**(3), 1–18.

Baron, L.: 1992, 'Beyond the green revolution: singin' the population blues', *ZPG Reporter* **24**(4), 1–4.

Bartiaux, F. and van Ypersele, J.P.: 1993, 'The role of population growth in global warming', in *International Population Conference/Congres International de la Population*, Montreal 1993, 24 August–1st September,compiled by: International Union for the Scientific Study of Population (IUSSP), Liege, Belgium **4**, 33–54.

Bomford, M.: 1987, 'Food and reproduction of wild house mice: II. A field experiment to examine the effect of food availability and food quantity on breeding in spring', *Australian Wildlife research* **14**(2), 197–206.
Bongaarts, J.: 1994, 'Can the growing human population feed itself?', *Scientific American* **Mar. 270**(3), 36–42.
Bouvier, L. and Grant, L.: 1994, *How Many Americans? Population, Immigration and the Environment*, San Francisco, CA, Sierra Club Books.
Brinckman, J.: 1985, 'Population growth and the toxic contamination of the Great Lakes', *Washington, DC, The Environmental Fund* **TEFdata No. 17**, 1–8.
Brown, L.R.: 1989, 'Feeding six billion', *World Watch* **2**(5), 32–40.
Brown, R.D. and Nielsen, L.A.: 2000, 'Leading wildlife academic programs into the new millennium', *Wildlife Society Bulletin* **28**(3), 495–502.
Brundtland, G.H.: 1993, 'Population, Environment and Development. Rafael M. Salas Memorial Lecture 1993, New York, 28 September 1993', *New York, New York United Nations Population Fund* (*UNFPA*) **ii**, 16p.
Caceres, C.W., Fuentes, L.S. and Ojeda, F.P.: 1994, 'Optimal feeding strategy of the temperate herbivorous fish *Aplodactylus puncatatus*: the effects of food availability on digestive and reproductive patterns', *Oecologia* (*Berlin*) **99**(1–2), 118–123.
Carlotti, F. and Hirche, H.J.: 1997, 'Growth and egg production of female Calanus finmarchicus: an individual-based physiological model and experimental validation', *Marine Ecology Progress Series* **149**(1–3), 91–104.
Carpenter, B. and Watson, T.: 1994, 'More people, more pollution', *US News and World Report* **Sep. 12; 117**(10), 63–65.
Chitty, D.: 1995, *Do Lemmings Commit Suicide?: Beautiful Hypotheses and Ugly Facts*, New York, Oxford University Press.
Christian, J.J., Lloyd, J.A. and Davis, D.E.: 1965, 'The role of endocrines in the self-regulation of mammalian populations', *Recent Progress in Hormone Research* **21**, 501.
Cohen, J.E.: 1995, *How Many People Can the Earth Support?*, New York, Rockefeller University.
Darwin, C.R.: 1859, *On The Origin Of Species By Means Of Natural Selection*, London, J. Murray.
Elton, C.S.:1927, *Animal Ecology*, London, Sidgwick and Jackson, Ltd.
Emmel, T.C.: 1973, *An Introduction to Ecology and Population Biology*, New York, W. W. Norton.
Epstein, P., Ford, T., Puccia, C. and Possas, C.D.A.: 1994, 'Marine ecosystem health. Implications for public health. Diseases in evolution, global changes, and emergence of infectious diseases', *Annals of the New York Academy of Sciences* **740**, 13–23.
Farb, P.: 1978, *Humankind*. Boston, Houghton Mifflin.
Finocchiaro, M.: 1989, *The Gallileo Affair: A Documentary History*, Berkeley, Los Angeles and London, University of California Press.
Gill, C.J. and Rissman, E.F.: 1997, 'Female sexual behavior is inhibited by short- and long-term food restriction', *Physiology and Behavior* **61**(3), 387–394.
Gleick, P.H.: 1993, *Water in Crisis*, New York, Oxford University Press.
Godish, T.: 1991, *Air Quality*, Chelsea, MI, Lewis Publishers.
Gotelli, N.: 1998, *A Primer Of Ecology – Second Edition*, MA, Sinauer Associates.
Gubler, D.J. and Clark, G.G.: 1996, 'Community involvement in the control of Aedes aegypti', *Acta Tropica*, **61**(2), 169–179.
Hay, R.W.: 1981, 'The concept of food supply system with special reference to the management of famine', in R.K. Robson (ed.), *Famine: Its Causes, Effects and Management*, New York, Gordon and Breach, pp. 81–88.
Holden, C.: 1995, 'Cities as disease vectors', *Science* **270**, 1125.
Hotez, P.J. and Pritchard, D.T.: 1995, 'Hookworm infection', *Scientific American* **272**(6), 68–75.
Iseki, M.: 1994, 'Effects of increases in the world's population and the globalization of human life on the incidence of parasitic diseases', *Japanese Journal of Parasitology* **43** 448–452.
Iwamoto, T.: 1978, 'Food availability as a limiting factor on population density of the Japanese monkey and Gelada baboon', in D.J. Chivers and J. Herbert (eds.), *International Primatological Society. Congress* (*6th: 1976 University of Cambridge*) *Recent Advances in Primatology*, London, New York, Academic Press, pp. 287–303.
Jayne, V.: 1999, 'Economies of ecology', *New Zealand Management* **46**(3), 26–30.
Komdeur, J.: 1996, 'Seasonal timing of reproduction in a tropical bird, the Seychelles warbler: A field experiment using translocation', *Journal of Biological Rhythms* **11**(4), 333–350.

Lederberg, J., Shope, R.E. and Oaks, S.C.: 1992, *Emerging Infections: Microbial Threats to Health in the United States*, Washington, DC, National Academy Press.

Lee, R.B.: 1969, '!Kung Bushman subsistence an input–output analysis', in A.P. Vayda (ed.), *Environment and Cultural Behavior: Ecological Studies in Cultural Anthropology*, Garden City, NY, Natural History Press, pp. 47–79.

Lee, R.B. and DeVore, I.: 1976, *Kalahari Hunter-Gatherers*, Cambridge, Harvard University Press.

Leslie, G.B. and Haraprasad, V.: 1993, 'Indoor air pollution from combustion sources in developing countries', *Indoor Environment* **2**, 4–13.

Lelieveld, J., Ramanathan, V. and Crutzen, P.J.: 1999, 'The global effects of Asian haze', *IEEE Spectrum* **36**(12), 50–54.

Marchetti, C., Meyer, P.S. and 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**, 1–30.

Marshall, E.: 1997, 'African malaria studies draw attention', *Science* **276**, 275–299.

McKillup, S.C. and McKillup, R.V.: 1994, 'Reproduction and growth of the smoot pebble crab Philyra laevis (Bell 1855) at two sites in South Australia during 1990–91', *Transactions of the Royal Society of South Australia* **118**(3–4), 245–251.

Monath, T.P.: 1994, 'The risk to developed and developing countries', *Proceedings of the National Academy of Sciences of the United States of America* **91**, 2395–2400.

NAS.: 1994, *Population Summit of The World's Scientific Academies*, Washington, DC, National Academy of Sciences Press.

Petersen, W.: 1979, *Malthus*, Cambridge, Harvard University Press, pp. 46–48.

Pimentel, D.: 1966, 'Complexity of ecological systems and problems in their study and management', in K. Watt (ed.), *Systems Analysis In Ecology*, New York and London, Academic Press, pp. 15–35.

Pimentel, D.: 1988, 'Herbivore population feeding pressure on plant hosts: feedback evolution and host conservation', *Oikos* **53**, 289–302.

Pimentel, D.: 1996, 'Human demography and environmental resources', in: B. Nath, L. Hens and D. Devuyst (eds), *Sustainable Development*, Brussels, Belgium, VUB University Press, pp. 111–136.

Pimentel, D. and Pimentel, M.: 1996, *Food, Energy and Society, Revised Edition*, Boulder, CO, University Press.

Pimentel, D. and Pimentel, M.: 1997, 'Too many people for food resources and the environment', *Politics and the Life Sciences* **16**(2), 217–219.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R. and Blair, R.: 1995, 'Environmental and economic costs of soil erosion and conservation benefits', *Science* **267**, 1117–1123.

Pimentel, D., Tort, M., D'Anna, L.,Krawic, A., Berger, J., Rossman, J., Mugo, F., Doon, N., Shriberg, M., Howard, E.S., Lee, S. and Talbot, J.: 1998, 'Increasing disease incidence: environmental degradation and population growth', *BioScience* **48**(10), 817–826.

Pimentel, D., Bailey, O., Kim, P., Mullaney, E., Calabrese, J., Walman, L., Nelson, F. and Yao, X.: 1999, 'Will limits of the Earth's resources control human numbers?', *Environment, Development, and Sustainability* **1**(1), 19–39.

Plant, J., Smith, D., Smith, B. and Williams, L.: 2000, 'Environmental geochemistry at the global scale', *Journal of the Geological Society* **157**(4), 837–849.

Population Reference Bureau (PRB): 2000, *2000 World Population Data Sheet*, Washington, DC, PRB, Inc.

Postel, S.: 2001, 'Growing more food with less water', *Scientific American* **Feb. 284**(2), 46–50.

Quinn, D.:1992, *Ishmael: A Novel*, New York, Bantam/Turner Books.

Quinn, D.: 1996, *The Story of B*, New York, Bantam Books.

Quinn, D.: 1997, 'The Question (ID Number 83: – February 16, 1997)', Retrieved March 3, 1999 from the World Wide Web: http://www.ishmael.org/Interaction/QandA/Detail.CFM?Record=83.

Quinn, D.: 1998a, 'Reaching for the Future with All Three Hands', Earth Day Address by Daniel Quinn, Kent State University, Retrieved March 3, 1999 from the World Wide Web: http://www.ishmael.org/Education/Writings/kentstate.shtml.

Quinn, D.: 1998b, 'The Question (ID Number 169: – February 15, 1998)', Retrieved March 3, 1999 from the World Wide Web: http://www.ishmael.org/Interaction/qanda/Detail.CFM?Record=169.

Quinn, D.: 1998c, 'The Question (ID Number 208: – March 28, 1998)', Retrieved March 3, 1999 from the World Wide Web: http://www.ishmael.org/Interaction/qanda/Detail.CFM?Record=208.

Ramalingaswami, V.: 1996, 'Infectious diseases in a changing world', *Current Science* **70**(12), 1050–1056.

Robson, J., (ed.): 1981, *Famine: Its Causes, Effects and Management*, New York, Gordon and Breach.

Scott, D.E. and Fore, M.R.: 1995, 'The effect of food limitation on lipid levels, growth and reproduction in the marbled salamander, Ambystoma opacum', *Herpetologica* **51**(4), 462–471.

Schinkel, P.G.: 1963, 'Nutrition and sheep production – a review', *Proceedings of the World Conference on Animal Production* **1**, 199.

Shetty, P.S. and Shetty, N.: 1993, 'Parasitic infection and chronic energy deficiency in adults', *Supplement to Parasitology* **107**, S159–S167.

Shiklomanov, I.A.: 1993, 'World fresh water resources', in P. Gleick (ed.), *Water in Crisis: A Guide to the World's Fresh Water Resources*, Oxford (UK), Oxford University Press, pp. 13–24.

Simon, J.L.: 1991, 'Energy not finite resource because alternative forms perpetuate it', Anchorage Times, January 25, 1991. Also in Roanoke Times & World-News, February 10, 1991, under title 'The worriers are wrong: we aren't depleting energy, other resources'.

Skinner, B.F.: 1990, 'Can psychology be a science of mind?', *American Psychologist* **45**(11), 1206–1210.

Travis, J.: 1997, 'Hitting malaria parasites early and hard', *Science News* **151**(2), 23.

UNDP.: 1999, 'Choices', *The Human Development Magazine* **8**(1), 28.

USBC.: 1998, *Statistical Abstract of the United States 1996*, Vol. 200th edn., Washington, DC: US Bureau of the Census, US Government Printing Office.

USDA.: 1998, *Agricultural Statistics*, Washington, DC, USDA.

Waggoner, P.E.: 1994, *How Much Land Can Ten Billion People Spare for Nature?* Report 121, Council for Agricultural Science and Technology (CAST), Ames Iowa.

Wayne, N.L., Wade, G.N. and Rissman, E.F.: 1991, 'Effects of food restriction and social cues on sexual maturation and growth in male musk shrews (Suncus murinus)', *Journal of Reproduction and Fertility* **91**(1), 385–392.

WHO.: 1992, *Our Planet, our Health: Report of the WHO Commission on Health and Environment*, Geneva, World Health Organization.

WHO.: 1995, *Bridging the Gaps*, Geneva, World Health Organization.

WHO.: 1996a, *Micronutrient Malnutrition: Half the World's Population Affected*, World Health Organization, 13 Nov. 1996 no. 78, pp. 1–4.

WHO.: 1996b, *Investing in Health Research and Development*, Geneva, World Health Organization.

WHO/UNEP.: 1993, *Urban Air Pollution in Megacities of the World*, Geneva, World Health Organization and the United Nations Environment Programme.

World Bank: 1992, *China: Long-term Issues and Options in the Health Transition*, Washington, DC, The World Bank.

World Development Indicators: 1998, *Agricultural Output and Productivity*, Washington, DC, The World Bank.

Young, A.: 1999, 'Is there really spare land? A critique of estimates of available cultivable land in developing countries', *Environment, Development and Sustainability* **1**(1), 3–18.

Zinn, H.: 1995, *A People's History of the United States: 1492-present*, New York, Harper Perennial, pp. 1–22.