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Will Limited Land, Water, and Energy Control Human Population Numbers in the Future?

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Abstract Nearly 60% of the world's human population is malnourished and the numbers are growing. Shortages of basic foods related to decreases in per capita cropland, water, and fossil energy resources contribute to spreading malnutrition and other diseases. The suggestion is that in the future only a smaller number of people will have access to adequate nourishment. In about 100 years, when it is reported that the planet will run out of fossil energy, we suggest that a world population of about two billion might be sustainable if it relies on renewable energy technologies and also reduces per capita use of the earth's natural resources.

Keywords Sustainable world population · Fossil fuels · Population growth · Agricultural land degradation

Introduction

Developed and developing nations need to provide a good quality life for their people while coping with rapid population growth, but "Population is the issue no one wants to touch" (Meadows 2000). The current world population is about 6.8 billion. Based on the present growth rate of 1.2% per year, the population is projected to double in approximately 58 years (Chiras 2006; PRB 2008). Because population growth cannot continue indefinitely, society can either voluntarily control its numbers or let natural forces such as disease, malnutrition, and other disasters limit human numbers (Bartlett 1997–98; Pimentel *et al*. 1999). Increasing human numbers especially in urban areas, and increasing pollution of food, water, air, and soil by pathogenic disease organisms and chemicals, are causing a rapid increase in the prevalence of disease and human mortality (Murray and Lopez 1996; Pimentel *et al*. 2007). Currently, more than 3.7 billion humans are malnourished worldwide—the largest number ever (WHO 2005a, b).

The planet's numerous environmental problems highlight the urgent need to evaluate available land, water, and energy resources and how they relate to the requirements of a rapidly growing human population (Pimentel and Pimentel 2008). In this article we assess the carrying capacity of the Earth's natural resources, and suggest that humans should voluntarily limit their population growth, rather than letting natural forces control their numbers (Bartlett 1997–98; Ferguson 1998; Pimentel *et al*. 1999). In addition, we suggest appropriate policies and technologies that would improve standards of living and quality of life worldwide.

Population Growth and Consumption of Resources

All of our basic resources, such as land, water, energy, and biota, are inherently limited because of human abundance. At the current growth rate of 1.2% the world's population will double to 13 billion in 58 years (PRB 2008).

The U.S. population doubled during the past 70 years from 151 million to more than 305 million, and based on current growth of approximately 1.1% per year (USCB 2002, 2009) is projected to double again to 600 million in the next 64 years. China's population is 1.3 billion, and despite government policy permitting only one child per

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couple, is still growing at an annual rate of 0.6% (PRB 2008). Note that the rate of population growth in the U.S. is nearly double that of the Chinese population.

In addition to limitations due to population size, high per capita consumption levels in the United States and other developed nations put further pressure on natural resources. Americans consume several times more goods and services because of relatively abundant per capita land, water, energy, and biological resources, as compared to the Chinese (PRB 2008). However, industrialized China emits more carbon dioxide than the U.S., largely due to its heavy use of coal (NEAA 2008). Achieving an average European standard of living ($35,000 per capita/yr.) or an average U.S. standard of living ($45,000 per capita/yr.) appears unrealistic for most countries because of serious shortages of basic natural resources (PRB 2008). This does not imply that both developed and developing countries cannot use their resources more efficiently than they are at present through the implementation of appropriate policies and technologies.

Thus far, Americans enjoy relative affluence because of fertile cropland, abundant water, and cheap fossil energy. If the U.S. population continues to expand as projected, however, resource shortages similar to those now being experienced by China and other developing nations will become more common (Table 1), and accelerated declines in living standards are likely.

Status of World Environmental Resources

The quantity and quality of cropland, water, energy, and biological resources determine the current and future status of the support services for human life. There are measurable shortages of fertile land, water, and fossil energy in many regions of the world, making it appropriate to ask, “Are we consuming too much?” (Arrow *et al*. 2004).

Table 1 Resources used and/or available per capita per year in the United States, China, and the world to supply the basic needs of humans (FAO 1998, 2006; Goklany 2001)

Resources	U.S.	China	World
Land			
Cropland (ha)	0.59	0.10	0.22
Pasture (ha)	0.79	0.30	0.52
Forest (ha)	1.01	0.15	0.61
Total	3.06	0.71	2.00
Water (liters × 10^6)	1.7	0.45	0.60
Fossil fuel			
Oil equivalents (liters)	9,500	700	2,100

FAO (1998, 2006); Goklany (2001)

Land Resources

More than 99% of human food (calories) in the world is derived from the terrestrial environment. Although only 0.3% comes from the oceans and other aquatic ecosystems (FAO 2003), even these resources are being stressed near to breaking point.

As Botsford *et al*. (1997) note “the global marine catch is approaching its upper limit” and “management has failed to achieve a principal goal, sustainability.” Worldwide, food and fiber crops are grown on 11% of the Earth’s total land area of 13 billion hectares. Globally, the annual loss of land to urbanization and highways ranges from 10 to 35 million hectares (approximately 0.5%) (Döös 1994). Much of this land is prime cropland, including prime coastal and river valley land (Döös 2002; Ho and Lin 2004).

In 1960, when the world population numbered about 3 billion, approximately 0.5 ha of cropland was available per capita worldwide. This half a hectare is needed to provide a diverse, healthy, nutritious diet of plant and animal products—similar to the typical diet in the United States and Europe (Giampietro and Pimentel 1994). The average per capita world cropland is now only 0.22 ha, or about 40% the amount needed according to industrial nation standards (Table 1).

Grain production, the most efficient use of cropland because it provides more than 80% of world food, has not kept pace with population growth (Cassman *et al*. 2003). Grain consumption per capita has declined 12% from its peak in 1984 to 2006 (Kondratyev *et al*. 2003; Earth Policy Organization 2008). If the amount of grain land remains the same in 2050 as it was in 2000, grain land per capita will shrink from 0.10 to only 0.07 ha due to population growth (Larsen 2003). Already, in China the amount of available cropland is only 0.10 ha per capita, and rapidly declining due to continued population growth and extreme land degradation (Pimentel and Wen 2004). This shortage of productive cropland is one underlying cause of current worldwide food shortages and poverty (Leach 1995; Pimentel and Pimentel 2008).

Currently, Americans consume a total of nearly 916 kg/yr per capita of food products, (USDA 2007). While the Chinese consume less per capita, by all measurements, they have reached or exceeded the limits of their agricultural system (Pimentel and Wen 2004). Their reliance on large inputs of fossil-fuel based fertilizers—as well as other limited inputs—to compensate for shortages of arable land and severely eroded soils will present severe problems in the future (Wen and Pimentel 1992).

Since cropland has become relatively scarce worldwide, farmers will need to produce increasing amounts from what is currently available. This intensification exacerbates land degradation, including water and wind erosion, and the salinization and water-logging of irrigated soils (Kendall and Pimentel 1994; Crosson 1997), threatening most crop and pasture land worldwide (Fischer *et al*. 2005). Worldwide, more than 10 million hectares of productive arable land are heavily degraded and abandoned each year (Pimentel 2006).

The urgent need for more agricultural land accounts for 60% to 70% of deforestation now occurring worldwide (Myers 1990; Butler 2009), which, in turn, is the prime cause of soil degradation and loss of freshwater in South America and Asia and a major contributor to soil degradation on other continents (Oldeman *et al*. 1990). The vast majority of any future cropland expansion is expected to occur in Latin America and sub-Saharan Africa, leading to massive losses of the world's remaining tropical and temperate forests, savannahs, and grasslands (Kloverpris *et al*. 2008)

Current erosion rates of agricultural land by wind and water, the most serious causes of soil loss and degradation (Oldeman *et al*. 1990), are greater than ever (Pimentel 2006). On average, humans have increased soil erosion at least tenfold from what is geologically normal, with some areas eroding at a thousand times the normal rate (Montgomery 2007). Soil erosion on cropland ranges from about 13 tons per hectare per year (t/ha/yr) in the United States to 40 t/ha/yr in China (Pimentel and Wen 2004). Worldwide, soil erosion averages approximately 30 to 40 t/ha/yr, or about 30- to 40-times faster than the replacement rate (Pimentel 2006). Soil eroded by wind in Africa is detected in Florida and Brazil each year (Pimentel 2000).

Erosion adversely affects crop productivity by reducing the water-holding capacity of the soil, water availability, nutrient levels and organic matter in the soil, and soil depth (Sanchez 2002). Croplands on steeper slopes are especially at risk for accelerated erosion. Over the next century, 33% of the steepest of U.S. cropland is projected to fall out of production due to erosion (Montgomery 2007). Estimates project that agricultural land degradation alone can be expected to depress world food production between 15% and 30% by the year 2020 (Crosson 1997; Pimentel 2000). The global economic cost of soil erosion is estimated to be about $400 billion per year (Lal 1997), emphasizing the need to implement known soil conservation techniques, including biomass mulches, no-till, ridge-till, terracing, cover crops, grass strips, crop rotations, or combinations of all of these. All these techniques essentially require keeping the land protected from wind and rainfall energy with some form of vegetative cover.

The current high erosion rates throughout the world are of great concern because of the slow rate of topsoil renewal; it takes approximately 500 years for 2.5 cm (1 in.) of topsoil to form under agricultural conditions (Troeh *et al*. 2004a). The U.S. is losing soil at ten times the rate of sustainable replacement, and the rate is higher in the rest of the world (NAS 2003).The effects of climate change are expected to lead to increased intensity of storm events worldwide (SWCS 2003), with predictions of 20% to almost 300% increases in erosion rates in some areas as a result of high-intensity rainfall (Nearing *et al.* 2004; Montgomery 2007).

The fertility of nutrient-poor soil can be improved by large inputs of fossil-based fertilizers. The global doubling of grain yields from 1961 to 2000 can be partially attributed to the 700% increase in fertilizer use during the same period (Matson *et al.* 1997; Tilman *et al*. 2001). This practice, however, increases dependency on limited fossil fuels necessary to produce these fertilizers.

If the U.S. population were reduced from the current 305 million to 200 million, per capita cropland would increase to about 0.7 ha (USDA 2007). Using more crop rotations, cover crops, grass strips, mulches and other types of soil conservation technologies will require additional cropland. Still the U.S. should have ample cropland available for domestic food production, plus some for export.

Water Resources

The present and future availability of adequate supplies of freshwater for human and agricultural needs is already critical in many regions, like the Middle East (Postel 1997). Rapid population growth and increased total water consumption are rapidly depleting available water. Between 1950 and 1995, per capita availability of freshwater worldwide declined by about 70% (Gleick 2008–2009).

All vegetation requires and transpires massive amounts of water during the growing season. Agriculture uses more water than any other activity on the planet. Currently, 70% of water removed from all sources worldwide is used solely for irrigation (Pimentel and Wilson 2004). Of this, about two-thirds are consumed by plant life (non-recoverable) (Postel 1997). For example, a corn crop that produces about 9,000 kg/ha of grain uses about 7 million liters/ha of water during the growing season (Pimentel and Pimentel 2008). To supply this much water, approximately 1,000 mm of rainfall per hectare—or 10 million liters of water—is required. The estimated "minimum amount of water required per capita for food is about 400,000 l per year worldwide and in the United States, the average amount of water consumed annually in food production is 1.7 million liters per capita per year" (Sustainable World Water 2002). Most of the 1.7 million liters is for irrigated food production.

Water resources and population densities are unevenly distributed worldwide. Even though the *total* amount of water made available by the hydrologic cycle is enough to provide the world's current population with adequate fresh water—according to the *minimum* requirements cited above—most of this total water is concentrated in specific regions, leaving other areas water-deficient. Water demands already far exceed supplies in nearly 80 nations of the world (Gleick 1993). In China, more than 300 cities suffer from inadequate water supplies, and the problem is intensifying as the population increases (Berk and Rothenberg 2003). In arid regions, such as the Middle East and parts of North Africa, where yearly rainfall is low and irrigation is expensive, the future of agricultural production is grim and becoming more so as populations continue to grow. Political conflicts over water in some areas have even strained international relations between critically water-starved nations (Gleick 1993).

Because of their slow recharge rates, usually between 0.1% and 0.3% per year (Wheal 1991; Covich 1993), groundwater resources must be carefully managed to prevent depletion. Yet, groundwater resources are also mismanaged and over-tapped. In the state of Tamil Nadu, India, groundwater levels declined 25–30 m during the 1970s as a result of excessive pumping for irrigation (UNFPA 1991; Pimentel 2002). In Beijing, the groundwater level is falling at a rate of about 1 m/yr; while in Tianjin, China, it drops 4.4 m/yr (Postel 1997). In the United States, aquifer overdraft averages 25% higher than replacement rates. In an extreme case such as the Ogallala aquifer under Kansas, Nebraska, and Texas, the annual depletion rate is 100% to 140% above replacement (Ehrlich and Ehrlich 1997). In parts of Arizona, water in some aquifers is being withdrawn 10-times faster than the re-charge rate (Gleick *et al.* 2002).

Desalinization of ocean water is not a viable source for freshwater needed by agriculture, because the process is energy intensive and, hence, economically impractical. A desalinization system in East Africa, for example, reports 70% less energy than other systems, yet still requires 2.3 kwH (nearly 2,000 kcal) per cubic meter (1,000 l) of water (Gilau *et al.* 2007). The amount of desalinized water required by 1 ha of corn would cost $14,000, while all other inputs, like fertilizers, cost only $500 (Pimentel *et al.* 2004). This figure does not even include the additional cost of moving large amounts of water from the ocean to inland agricultural fields.

Another major threat to maintaining ample fresh water resources is pollution. Considerable water pollution has been documented in the United States (USCB 2008), but this problem is of greatest concern in countries where water regulations are less rigorously enforced or do not exist. Developing countries discharge approximately 90% to 95% of their untreated urban sewage directly into surface waters (WHO 1993; Pollution Problem 2009). Downstream, the polluted water is used for drinking, bathing, cooking, and washing (WHO 1992).

Overall, approximately 95% of the water in developing countries is polluted (WHO 1992). There are, however, also serious problems in the United States. The Environmental Protection Agency (EPA 1994) reports that 40% of U.S. lakes are unfit for swimming due to runoff pollutants and septic discharge.

Pesticides, fertilizers, and soil sediments as well as some 100,000 different chemicals applied to crops (Nash 1993) pollute water resources when they accompany eroded soil into a body of water. In addition, industries all over the world often dump untreated toxic chemicals into rivers and lakes (WRI 1993; WHO 1993). Although some new technologies and environmental management practices are improving pollution control and the use of resources, there are economic and biophysical limits to their use and implementation (Gleick 1993).

Food Production

Reducing the calorie intake from about 3,747 kcal per day to about 2,300 kcal would improve the health of the U.S. population. Moreover, a primarily plant-based Mediterranean diet of minimally processed foods and seasonal and locally produced foods is highly recommended (Willett *et al*. 1995).

What has been thought of as waste (manure) from livestock will be a valuable source of nutrients for crop production and an energy source in the form of biogas (Ro *et al.* 2007; Cantrell *et al*. 2008). All livestock should be moved back on farms to make use of the manure and produce biogas.

The primary plant foods in the future will probably be rice, wheat, corn, potatoes, soybeans, cabbage, and a few other plant foods. All of these crops can be produced without any liquid fuel except for the 60 l of ethanol per hectare to run small tractors (Pimentel *et al*. 2008a). For a population of 200 million, estimated as sustainable for the U.S. in the absence of fossil fuels, the area of cropland needed would be 100 million ha, based on 0.5 ha/capita. This reflects the present use of cropland in the U.S., and is estimated to be applicable to a fossil fuel-free future because lower crop yields could be offset by a decrease in the consumption of meat.

The ethanol required to operate the tractors would therefore amount to 60 billion liters. Although with current conventional corn technology the energy balance in producing ethanol is negative, if an organic corn production technology were employed similar to that in Table 2, then the energy balance would become positive (output exceeds input). Growing corn this way is likely to yield a useful 2,000 l of ethanol per ha, so the area of corn needed to produce the ethanol would be 30 million ha. The total of 130 million ha is less than the total area of cropland in the USA, but only ethanol needed for producing crops has been accounted for, and liquid fuels will be needed for other reasons.

Table 2 Energy inputs and costs of corn production per hectare (8,000 kg corn) in the United States and potential for reduced energy inputs compared with 8,228 kcal X 1000 total energy inputs for conventional United States corn tillage. Pimentel *et al*. (2008a,b); Pimentel and Patzek (2008)

Inputs	Quantity	kcal × 1000
Labor	15 h	608
Machinery	10 kg	185
Ethanol	60 L	684
Nitrogen	Legumes	1,000
Phosphorus	45 kg	187
Potassium	40 kg	130
Lime	600 kg	169
Seeds	21 kg	520
Irrigation	0	0
Herbicides	0	0
Insecticides	0	0
Electricity	13.2 kWh	34
Transport	75 kg	25
Total		3,542

It may be noted that although processing the 8,000 kg/ha of corn shown in Table 3 into 2,000 l of ethanol would require an estimated 9 million kcal of non-liquid energy, this is mostly heat energy that could come from wood or an electrical energy source.

The 30 million ha needed for ethanol production adds 30% to the 100 million ha of cropland needed to grow crops for consumption. Using draft animals would require much the same actual area. Two teams (four horses) would be needed to manage 20 ha in a practical manner, and this would require 7 ha of land to provide the corn, hay and pasture needed for the horses (Morrison 1946; Ferguson 2008). Thus 100 million hectares would require 35 million hectares of land for horses. This is a larger area but only 3% would be cropland (Morrison 1946), i.e., about 1 million ha of cropland; so horse power could be a better choice.

Table 3 Potential renewable energy for the United States

Energy technology	Current quads	Projected (2100) quads[c]
Biomass	3.3[a]	7
Hydroelectric	2.9[a]	5
Geothermal	0.3[a]	3
Solar thermal	0.06[b]	10
Photovoltaics	0.06[b]	10
Wind power	0.3[a]	8
Biogas	0.001[b]	0.5
TOTAL	6.8	43.5

[a] EIA (2008)

[b] USCB (2008)

[c] Calculated from Pimentel (2008)

Of the 400 million draft animals used in world agriculture, 19 million are located in sub-Saharan Africa, primarily oxen (Muvirimi and Ellis-Jones 1999). Although there is a tradition of using oxen and horses, donkeys and cows will increasingly be used for draft power (Muvirimi and Ellis-Jones 1999).

Nitrogen nutrients should be produced using nitrogen-fixing legume crops, such as vetch. The U.S. uses 13 million tons of commercial nitrogen per year (USDA 2007). Currently biological nitrogen fixation in the U.S. yields approximately 14 million tons of nitrogen per year (Pimentel 1998). Even with a major reduction in livestock population, possibly 300 million tons of nitrogen could be produced on farms. Note that since 1950 most livestock manure is not produced on farms (NAS 1989). One ton of cow manure has 6 kg of nitrogen, and can only be transported slightly more than 8 km before the nitrogen energy benefits in the manure equal those of inorganic fertilizer (Wiens *et al*. 2008), which is why livestock that are grass-fed must be managed on the farm.

Nitrogen fertilizer can be produced employing electrolysis but requires 8,800 kcal/kg of electrical energy (IFFCO 2008). This electrical energy translates into 26,400 kcal. The energy required for nitrogen production using electrical energy is reportedly much higher than producing nitrogen fertilizer using natural gas, which requires 16,000 kcal per kilogram of nitrogen (Patzek, T., Personal Communication, 2009).

Energy Resources

Over time, people have relied on various sources of power ranging from human, animal, wind, tidal, and water energy, to wood, coal, gas, oil, and nuclear sources for fuel and power. Fossil fuel energy permits a nation's economy to feed an increasing number of humans, as well as to improve the general quality of life in many ways, including the protection from numerous diseases.

About 473 quads (1 quad=10^{15} BTU or $1{,}055\times10^{18}$ Joules) from all energy sources are used worldwide per year (International Energy Annual 2007). Increasing energy expenditure is caused by rapid population growth, urbanization, and high resource consumption rates (Table 1). Increased energy use also contributes to environmental degradation (Pimentel and Pimentel 2008). Energy use has been growing even faster than world population. From 1970 to 1995, energy use was increasing at a rate of 2.5% (doubling every 28 years) whereas worldwide population grew at only 1.7% (doubling every 42 years) (PRB 1996; International Energy Annual 1995–2007). Current energy use is projected to increase at a rate of 2.2% (doubling every 32 years) compared with a population growth rate of 1.2% (doubling every 58 years) (PRB 2008; International Energy Annual 2007).

Although about 50% of all the solar energy captured by photosynthesis worldwide is used by humans, it is still inadequate to meet all of humanity's need for food (Pimentel and Pimentel 2008). To make up for this shortfall, about 473 quads of fossil energy (oil, gas, and coal) are utilized worldwide each year (International Energy Annual 2007). Of this, 109 quads are utilized in the United States (USCB 2008). The U.S. population consumes 70% more fossil energy than all the solar energy captured by harvested U.S. crops, forest products, and other vegetation each year (Pimentel *et al*. 2008b). Industry, transportation, home heating, and food production account for most of the fossil energy consumed in the United States (USCB 2008). Per capita use of fossil energy in the United States is 9,500 l of oil equivalents per year, more than 13 times the per capita use in China (Table 1). In China, most fossil energy is used by industry, but approximately 25% is used for agriculture and the food system (Pimentel and Wen 2004).

Developed nations annually consume about 70% of the fossil energy worldwide, while the developing nations, which have about 75% of the world population, use only 30% (International Energy Annual 2007). The United States, with only 4.5% of the world's population, accounts for almost 25% of the world's carbon emissions from fossil fuels (West 2008; PRB 2009).

Several developing nations that have high rates of population growth are increasing fossil fuel use to augment their agricultural production. In China, there has been a 100-fold increase in fossil energy use in agriculture for fertilizers, pesticides, and irrigation since 1955 (Pimentel and Wen 2004).

Fertilizer production on the whole, though, has declined per capita by more than 22% since 1991, especially in the developing countries, due to fossil fuel shortages and high prices (IFIA 2008).

World oil production has peaked and the world's supply of oil is projected to last approximately 40 years, if use continues at current rates (Energy Information Agency 2008). The earth's natural gas supply is projected to peak at 2020 and coal is projected to peak at 2025 (Energy Information Agency 2008). In the U.S., natural gas supplies are already in short supply and it is projected that the U.S. will deplete its natural gas resources in about 40 years (W. Youngquist, Personal Communication, petroleum geologist, Eugene, Oregon, 2008).

Both the production rate and proven reserves of oil and natural gas have continued to decline. In the United States, oil and natural gas production will be substantially less in 20 years than it is today. Neither is now sufficient for domestic needs, and supplies are imported in increasing amounts yearly (USCB 2008). Analyses suggest that at present (2008) the United States has consumed about 90% of its recoverable oil so that we are currently consuming the last 10% of domestic reserves. The United States is now importing about 60% of its oil (USCB 2008).

At present, electricity represents about 34% of total U.S. energy consumption (USCB 2008). Nuclear power production of electricity contributes about 20% and has some advantages over fossil fuels because it requires less land than coal-fired plants and does not contribute to acid rain and global warming.

All chemical and nuclear energy consumed ultimately winds up as heat in the environment. The Second Law of Thermodynamics limits the efficiency of heat engines to about 35%. This means that approximately two-thirds of the potential energy in fuel, whether chemical or nuclear, is converted into heat, while the remaining one-third is delivered as useful work (and, eventually, also converted into heat).

More efficient end-use of electricity can reduce its costs while at the same time reducing environmental impacts. Commercial, residential, industrial, and transportation sectors all have the potential to reduce energy consumption by approximately 33% while saving money (American Physical Society 2008; NASA/C3P 2008). Some of the necessary changes to reduce consumption would entail more efficiently designed buildings, appliances, and industrial systems (American Physical Society 2008; NASA/C3P 2008).

Using available renewable energy technologies, such as biomass and wind power, an estimated 29 quads of energy can be supplied in the U.S. with the full implementation of eight different renewable energy technologies (Table 3) (Pimentel *et al*. 2002). Worldwide we estimate that the need for 200 quads of renewable energy could be produced from 20% to 26% of the land area (Yao Xlang-Jun, personal communication, Cornell University, 1998; Exploring the Future 2001; Zweibel *et al*. 2007). Daily *et al.* (1994), Desvaux (2009), and Mann (2009) all suggest an optimum population for the earth of about 2 billion people. We suggest that a self-sustaining renewable energy system producing 200 quads of energy per year for about this number would provide each person with 5,000 l of oil equivalents per year (half of America's current consumption per year but an increase for most people of the world). However, the appropriation of over 20% of the land area for renewable energy production will further limit the resilience of the vital ecosystem that humanity depends upon for its life support system.

U.S. house size could be reduced from the current average of 2,500 sq. ft. to about 1,000 sq. ft., as it was about 60 years ago and is currently in the British Isles (USCB 2008). Heat would come from wood fuel in the northeast and north-central states. About 2 ha of forest would be needed per home, which would provide about 6 tons of wood fuel per year, adequate for a 1,000 sq. ft. well insulated home. In low rainfall regions where there is little wood fuel available, wind power or photo-voltaics will be used for heat. Here, the problem of intermediacy of energy supply can be offset by storing the heat in large hot-water or sand tanks.

Biological Resources

In addition to land, water resources, crops and livestock species, humans depend on the presence and functioning of approximately 15 million other species existing in agro-ecosystems and nature (McNeely 1999). More than 60% of the world's food supply comes from rice, wheat, and corn species (Brown 2008) and as many as 20,000 other plant species are used by humans for food (Vietmeyer 1995). Humans have no technologies that can substitute for the food—and some medicines—that some plant species in wild biota provide. Plants, animals, and microbes also carry out many essential activities for humans, including pollination of crops and wild plants, recycling manure and other organic wastes, degrading chemical pollutants, and purifying water and soil (Pimentel *et al*. 1997). Humans, again, have no synthetic substitutes for such ecosystem services (Daily and Ehrlich 1996).

Pest insects, pathogens, and weeds destroy crops and thereby reduce food and fiber supply. Despite the yearly use of 3.0 million tons of pesticides and other controls worldwide, about 40% of all potential crop production is lost to pests (Oreke and Dehne 2004). Specifically, in the United States, about 0.5 million tons of pesticides are applied each year, yet pests still destroy about 37% of all potential crop production. Estimates suggest that pesticide use could be reduced by 50% or more, without any reduction in pest control and/or any change in cosmetic standards of crops, through the implementation of sound ecological pest controls, such as crop rotations and biocontrols (Pimentel 1997).

Approximately one third of the United States' and world's food supply relies either directly or indirectly on effective insect pollination (Science Daily 2008). Honeybees and other wild bees play an essential role in pollinating U.S. crops. They also are vital for pollinating natural plants.

Worldwide, environmental pressure from the human population is the prime destructive force and the primary cause of reduced biodiversity (Pimentel *et al*. 2006). Humans currently occupy 95% of the terrestrial environment with either managed agricultural and forest ecosystems or human settlements (Western 1989). The major focus of world biological conservation has been on protecting national parks that cover only 3.2% of the world's terrestrial area (Reid and Miller 1989). However, most species diversity occurs in managed terrestrial environments, so increased efforts should be devoted to improving the sustainability of agricultural and forest ecosystems (Pimentel *et al.* 1992).

Resources and Human Diseases

As world population increases and resources are limited, human health suffers. Populations living in polluted regions are prone to infectious diseases, including tuberculosis, diarrhea, and parasitic worms. WHO (2008) reports that the world's annual death rate is 58 million. Diseases, including malnutrition, cause 18 million deaths per year. Poverty in developing countries reduces the availability of foods and increases malnutrition. WHO (2005a, b) reports nearly 60% of the world population is malnourished.

About 90% of the diseases occurring in developing countries result from a lack of clean water (WHO 1992). Worldwide, about 4 billion cases of disease are contracted from water and approximately 50 million deaths result from all diseases from water, food, air, and soil each year (WHO 2004). About 6,000 people die each day from a lack of access to clean water (Rijsberman 2004). Shistosomiasis and malaria, common diseases throughout the tropics, are examples of parasitic diseases associated with aquatic systems (Hotez and Pritchard 1995).

Intestinal parasites introduced through contaminated food, water, and soil, impact health by reducing intake of nutrients in various ways (Shetty and Shetty 1993). Hookworms, for instance, which thrive in contaminated moist soils in the tropics, can remove up to 30 ml of blood from a person in a single day, leaving them weak and susceptible to other diseases, including HIV/AIDS, which affects up to 37% of the population of some countries (Hotez and Pritchard 1995; Stillwaggon 2006). From 5% to 20% of an infected person's daily food intake is used to offset other illnesses and physical stress caused by disease, thereby diminishing his/her nutritional status (Pimentel and Pimentel 2008).

Transition to an Optimum Population with Appropriate Technologies

The human population has enormous potential for rapid growth because of the young age distribution both in the U.S. and throughout the world (PRB 2008). Future population growth is highly dependent on the path that future fertility takes (WPP 2006). If the whole world agrees on and adopts a policy of only two children per couple, it would be more than 100 years before the world population finally stabilizes at approximately 13 billion (Weeks 1986). A more daunting projection is that if fertility remains at present levels, the population will reach nearly 13 billion by 2050 (Cohen 2003).

However, a population policy ensuring that each couple produces an average of only one child would be necessary to achieve the goal of reducing world population from the current 6.8 billion to an optimal population of approximately 2 billion in slightly more than 100 years. Even with the United Nation's projection of declining fertility rates, population will reach 9.1 million by mid-century (UN 2005).

Our suggested 2 billion population carrying capacity for the Earth is based on a European standard of living for everyone and sustainable use of natural resources. For land resources, we suggest 0.5 ha of cropland per capita (the level that existed in 1960) with an intense agricultural production system (~8 million kcal/ha) and a diverse plant and animal diet for the people. In addition, approximately 1.5 ha of land would be required per capita for a renewable energy system. At the same time, the goal would be to have approximately 1 ha each for forest and pasture production per capita. Of course, all current land degradation associated with soil erosion would have to stop (Pimentel *et al*. 1995), but technologies are currently available for soil conservation in agricultural and forest production which only need to be implemented (Troeh *et al.* 2004b). In recent years there has been a growth in the adoption of “conservation tillage” and “zero-tillage” systems. These systems maintain a crop residue cover of the soil, rather than leaving the soil unprotected, as in conventional production, which increases organic matter decomposition that contributes to global warming.

Balancing the population-resource equation will be difficult because current overpopulation, poor distribution of resources, and environmental degradation are already causing serious malnourishment and poverty throughout the world, especially in developing countries (Gleick 1993; WHO 2005a, b). Wheat demand is projected to increase by 40% by 2020 and most demand will be from developing countries (Pingali and Rajaram 1999). The current shift to wheat and rice based diets is most apparent in developing countries, which are projected to have a per capita increase of 6%, from 62 kg per capita in 1993 to 66 kg per capita in 2020 (Rosegrant *et al*. 1999). In the future, more food will have to be produced on less land and with fewer water resources. Based on the estimate that 0.5 ha per capita is necessary for an adequate and diverse food supply, it would be possible to sustain a global population of approximately 2 billion humans. Cropland land is being degraded and lost at a rate of more than 20 million ha per year. At this rate, in just 42 years there will be sufficient arable land for a population of only 2 billion. It is critical to adopt soil and water conservation techniques to protect the soil resources that currently produce more than 99.7% of the world's food.

A reduction in the world population to approximately 2 billion, in addition to a reduced per capita consumption rate, would help reduce the current severe pressure on surface and groundwater resources and decrease water pollution. If water shortage and pollution problems were reduced, agricultural production would improve and degradation of aquatic ecosystems would decline. Appropriate technologies that conserve soil and water resources, and reduce pollution in soil, water, and atmospheric resources would help avert the alarming extinction rates of almost all species (Kellert and Wilson 1993), which in turn would protect and preserve most of the essential functions provided by natural biodiversity (Pimentel *et al*. 1997).

With the exhaustion of fossil fuels and associated increases in costs and pressure from global climate change, significant changes will also have to take place in energy use and practices. Fossil fuel shortages and global warming problems will force a transition to renewable energy sources within the next 100 years. Research on ways to convert solar energy into usable energy, for example, and research to develop other new power sources will have to be given a much higher priority. Although many solar technologies have been investigated, most are only in limited use. The most promising of renewable sources of energy include: solar thermal receivers, photo-voltaics, solar ponds, wind-power, hydropower, and biomass (Pimentel 2008).

Global warming caused by CO_2 and other greenhouse gases is a major challenge facing humans (Vorosmarty *et al*. 2000). The IPCC (2007) states that “warming of the climate system is unequivocal, as is now evident from observation of increase in global temperature, widespread melting of snow and ice and rising global average sea level.” Greenhouse gases are essential to maintaining a reasonable temperature on earth; without the gases, the planet would be so cold as to be uninhabitable. However, an excess of greenhouse gases can raise the temperature of the planet to high levels. Efforts underway to reduce the CO_2 emissions have been to date unsuccessful. A 1% increase in the population results in a 1% increase in carbon dioxide emissions. Consumption of energy and other human activities contribute to the greenhouse gas problems (Shi 2003).

The adjustment of the world population from 6.8 billion to 2 billion could be achieved over approximately a century, but only if the majority of people agree that protecting human health and welfare is vital, and are willing to work towards a stable quality of life for themselves and their children. Although a rapid reduction in population numbers to 2 billion humans could cause social, economic, and political problems, continued rapid growth to 13 billion people will result in a dire situation with major starvation and disease outbreaks. Worldwide catastrophic health and environmental problems will reduce human numbers but with major disturbances in human lives and welfare.

Conclusion

Clearly, the world's human population cannot continue to increase indefinitely. Natural resources are critically limited, and there is emerging evidence that natural forces are already starting to control human population numbers through malnutrition and other severe diseases. More than 3.7 billion people worldwide are malnourished, and 3 billion are living in poverty; grain production per capita has been declining since 1984; irrigation per capita has been declining since 1978; arable land per capita has been declining since 1948; fish production per capita has been declining since 1980; fertilizer supplies essential for food production have been declining since 1989; loss of food to pests has not decreased below 52% since 1990; and pollution of water, air, and land has increased, resulting in a rapid increase in the number of humans suffering from serious, pollution-related diseases.

Fifty-eight academies of science, including the U.S. National Academy of Sciences, recognize that "Humanity is approaching a crisis point with respect to the interlocking issues" of population, natural resources, and sustainability (NAS 1994). The report points out that science and technology have a limited ability to meet the basic needs of a rapidly growing human population with rapidly increasing per capita demands. Unfortunately, most individuals and government leaders appear unaware, unwilling, or unable to deal with the growing imbalances between human population numbers and the energy and environmental resources that support all life. The interdependence among the availability of life-supporting resources, individual standard of living, quality of the environment, environmental resource management, and population density are neither acknowledged nor easily understood. Although we humans have demonstrated effective environmental conservation in certain cases (e.g., water), overall we have a disappointing record in protecting essential resources from over-exploitation in the face of rapidly growing populations (Pimentel and Pimentel 2008).

Historically, decisions to protect the environment have been based on isolated crises and catastrophes. Instead of examining the problem in a holistic, proactive manner, these ad hoc decisions have been designed to protect and/or promote a particular resource or aspect of human well-being in the short-term. Our concern, based on past experience, is that these urgent issues relating to human carrying capacity of the world may not be addressed holistically until the situation becomes intolerable or, possibly, irreversible.

Through the use of a population policy that respects individual rights, and effective resource use policies, as well as science and technology to enhance energy supplies and protect the integrity of the environment, an optimum population of 2 billion people can be achieved. With a concerted effort, fundamental obligations to ensure the well-being of future generations can be attained within the twenty-first century. Individuals will then be able to live free from poverty and starvation, in an environment that is capable of sustaining human life with dignity. We must avoid allowing the human population to continue to increase beyond the limit of the Earth's natural resources, which will inevitably lead to increased disease, malnutrition, and violent conflicts over limited resources.

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