WILL LIMITS OF THE EARTH'S RESOURCES CONTROL HUMAN NUMBERS?

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INTRODUCTION

The current world population is about 6 billion. Based on the present growth rate of 1.5% per year, the population is projected to double in approximately 46 years (PRB, 1996). Because population growth can not continue indefinitely, society can either voluntarily control its numbers or let natural forces such as disease, malnutrition, and other disasters limit human numbers (Pimentel et al., 1994a; Bartlett, 1997-98). Increasing human numbers, especially in urban areas, and increasing food, water, air, and soil pollution by pathogenic organisms and chemicals, are causing a rapid increase in the prevalence of disease and number of human deaths (WHO, 1992, 1995; Murray and Lopez, 1996; Pimentel et al., 1998a). Currently, food shortages are critical, with more than 3 billion humans malnourished worldwide -- the largest number and proportion ever (FAO, 1992a, b; Neisheim, 1993; McMichael, 1993; Maberly, 1994; Bouis, 1995; WHO, 1995; WHO 1996). An estimated 40,000 children die each day due to malnutrition and other diseases (WHO, 1992).

The planet's numerous environmental problems emphasize the urgent need to evaluate the available environmental resources and how they relate to the requirements of a rapidly growing human population (Hardin, 1993; Cohen, 1995). 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 for them. (Pimentel et al., 1994a; Bartlett, 1997-98). In addition, we suggest appropriate policies and technologies that would improve the standard 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 (Lubchenco, 1998). As human populations continue to expand and finite resources are divided among increasing numbers of people, it will become more and more difficult to maintain prosperity and a quality of life, and personal freedoms will decline (UNFPA, 1991; RS and NAS, 1992; Rees, 1996).

During recent decades there has been a dramatic worldwide population increase. The U.S. population doubled during the past 60 years from 135 million to more than 270 million (NGS, 1995) and, based on the current U.S. growth rate of approximately 1% per year (USBC, 1996), is projected to double again to 540 million in the next 70 years . China's population is 1.3 billion and, despite the governmental policy of permitting only one child per couple, it is still growing at an annual rate of 1.2% (SSBPRC, 1990).

India has nearly 1 billion people living on approximately one-third of the land of either the United States or China. India's current population growth rate is 1.9%, which translates to a doubling time of 37 years (PRB, 1996). Together, China and India constitute more than one-third of the total world population. Given the steady decline in per capita resources, it is unlikely that India, China, and the world population in total will double.

In addition to limitations due to population increases, high per capita consumption levels in the United States and other developed nations also put pressure on natural resources. For example, each American consumes about 50-times more goods and services than the average Chinese citizen (PRB, 1996). Americans consume more goods and services because of relatively abundant per capita land, water, energy, and biological resources, as compared to the Chinese (Table 1). Achieving an average European standard of living ($12,310 per capita/yr) or an average U.S. standard of living ($26,000 per capita/yr) appears unrealistic for most countries because of serious shortages of the basic natural resources (PRB, 1996). This does not imply that both developed and developing countries can not use their resources more efficiently than they are at present through the implementation of appropriate policies and technologies.

Thus far, the relative affluence enjoyed by most Americans has been possible because of an abundant supply of fertile cropland, water, and fossil energy. As the U.S. population continues to expand, however, resource shortages similar to those now being experienced by China and other developing nations will become more common (Tables 1 and 2). Accelerated declines in the U.S. standard of living are likely if the U.S. population increases as projected during the next 70 years, from 270 million in 1998 to 540 million (Grant, 1996; Pimentel and Pimentel, 1996).

STATUS OF WORLD ENVIRONMENTAL RESOURCES

The quantity and quality of arable land, water, energy, and biological resources determine the current and future status of the support services for human life. Measurable shortages of fertile land, water, and fossil energy now exist in many regions of the world (Worldwatch Institute, 1992; WRI, 1994; WRI, 1998).

Land Resources

More than 99% of human food comes from the terrestrial environment -- less than 1% comes from the oceans and other aquatic ecosystems (FAO, 1991; Pimentel and Pimentel, 1996). Worldwide, food and fiber crops are grown on 11% of the Earth's total land area of 13 billion hectares (Figure 1). Globally, the annual loss of land to urbanization and highways ranges from 10 to 35 million hectares per year, with half of this lost land coming from cropland (Doeoes, 1994). Most of the remaining land area (23%) (Figure 1), is unsuitable for crops, pasture, and forests because the soil is too infertile or shallow to support plant growth, or the climate and land are too cold, dry, steep, stony, or wet (Buringh, 1989).

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 of cropland per capita 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 (Lal, 1989; Giampietro and Pimentel, 1994). The average per capita world cropland now is only 0.27 ha, or about half the amount needed according to industrial nation standards (Table 1). This shortage of productive cropland is one underlying cause of the current worldwide food shortages and poverty (Leach, 1995; Pimentel and Pimentel, 1996). For example, in China, the amount of available cropland is only 0.08 ha per capita, and rapidly declining due to continued population growth and extreme land degradation (Leach, 1995). This minute amount of arable land forces the Chinese people to consume primarily a vegetarian diet (Table 2).

Currently, a total of 1,481 kg/yr per capita of agricultural products is produced to feed Americans, while the Chinese food supply averages 785 kg/yr per capita (Table 2). By all measurements, the Chinese have reached or exceeded the limits of their agricultural system (Brown, 1997). 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, indicates severe problems for the future (Wen and Pimentel, 1992). The Chinese already import large amounts of grain from the United States and other nations, and are planning to increase these imports in the future (Alexandratos, 1995).

Escalating land degradation threatens most crop and pasture land throughout the world (Lal and Pierce, 1991; Pimentel et al, 1995). The major types of degradation include water and wind erosion, and the salinization and water-logging of irrigated soils (Kendall and Pimentel, 1994). Worldwide, more than 10 million hectares of productive arable land are severely degraded and abandoned each year (Houghton, 1994; Pimentel et al., 1995). Moreover, an additional 5 million hectares of new land must be put into production each year to feed the nearly 84 million humans annually added to the world population. Most of the 15 million hectares needed yearly to replace lost land is coming from the world's forests (Houghton, 1994; WRI, 1996). The urgent need for more agricultural land accounts for more than 60% of the deforestation now occurring worldwide (Myers, 1990).

Agricultural erosion by wind and water is the most serious cause of soil loss and degradation. Current erosion rates are greater than ever previously recorded (Pimentel and Hall, 1989; Pimentel et al., 1995). 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 (USDA, 1994; Wen, 1993; McLaughlin, 1993). Worldwide, soil erosion averages approximately 30 t/ha/yr, or about 30-times faster than the replacement rate (Pimentel, 1993). During the past 30 years, the rate of soil loss in Africa has increased 20-fold (Tolba, 1989). Wind erosion is so serious in China that Chinese soil can be detected in the Hawaiian atmosphere during the spring planting period (Parrington et al., 1983). Similarly, soil eroded by wind in Africa can be detected in Florida and Brazil (Simons, 1992).

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 (Pimentel et al., 1995). Estimates are that agricultural land degradation alone can be expected to depress world food production between 15% and 30% by the year 2020 (Buringh, 1989). These estimates emphasize the need to implement known soil conservation techniques, including biomass mulches, no-till, ridge-till, terracing, grass strips, crop rotations, and combinations of all of these. All these techniques essentially require keeping the land protected from wind and rainfall effects with some form of vegetative cover (Pimentel et al., 1995; Pimentel and Kounang, 1998).

The current high erosion rate throughout the world is of great concern because of the slow rate of topsoil renewal; it takes approximately 500 years for 2.5 cm (1 inch) of topsoil to form under agricultural conditions (OTA, 1982; Elwell, 1985; Troeh et al., 1991; Pimentel et al., 1995). Approximately 3,000 years are needed for the natural reformation of topsoil to the 150 mm depth needed for satisfactory crop production.

The fertility of nutrient-poor soil can be improved by large inputs of fossil-based fertilizers. This practice, however, increases dependency on the limited fossil fuels stores necessary to produce these fertilizers. And even with fertilizer use, soil erosion remains a critical problem in current agricultural production (Pimentel et al., 1995). Crops can be grown under artificial conditions using hydroponic techniques, but the costs in terms of energy and dollars is approximately 10-times that of conventional agriculture (Schwarz, 1995).

The arable land currently used for crop production already includes a considerable amount of marginal land, land that is highly susceptible to erosion. When soil degradation occurs, the requirement for fossil energy inputs in the form of fertilizers, pesticides, and irrigation is increased to offset the losses, thus creating non-sustainable agricultural systems (OTA, 1982; Follett and Stewart, 1985; Pimentel, 1993; Pimentel et al., 1995).

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 the availability of water. Between 1960 and 1997, the per capita availability of freshwater worldwide declined by about 60% (Hinrichsen, 1998). Another 50% decrease in per capita water supply is projected by the year 2025 (Hinrichsen, 1998).

All vegetation requires and transpires massive amounts of water during the growing season. Agriculture commands more water than any other activity on the planet. Currently, 65% of the water removed from all sources worldwide is used solely for irrigation (Postel, 1997). Of this amount, about two-thirds is consumed by plant-life (non-recoverable) (Postel, 1997). For example, a corn crop that produces about 8,000 kg/ha of grain uses more than 5 million liters/ha of water during the growing season (Leyton, 1983). To supply this much water to the crop, approximately 1,000 mm of rainfall per hectare -- or 10 million liters of irrigation -- is required during the growing season (Pimentel et al., 1997a).

The minimum amount of water required per capita for food is about 400,000 liters per year (Postel, 1996). In the United States, the average amount of water consumed annually in food production is 1.7 million liters per capita per year (USDA, 1996), more than 4-times the minimum requirement. The minimum basic water requirement for human health, including drinking water, is 50 liters per capita per day Gleick (1996). The U.S. average for domestic usage, however, is 8-times higher than that figure, at 400 liters per capita per day (Postel, 1996).

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 (WRI, 1994; Brown, 1995). 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, such as the Middle East, have even strained international relations between severely water-starved nations (Gleick, 1993).

The greatest threat to maintaining fresh water supplies is depletion of the surface and groundwater resources that are used to supply the needs of the rapidly growing human population. Surface water is not always managed effectively, resulting in water shortages and pollution that threaten humans and the aquatic biota that depend on it. The Colorado River, for example, is used so heavily by Colorado, California, Arizona, and other states, that by the time the river reaches Mexico, it is usually no more than a trickle running into the Sea of Cortes (Sheridan, 1983).

Groundwater resources are also mismanaged and over-tapped. Because of their slow recharge rate, usually between 0.1% to 0.3% per year (UNEP, 1991; Covich, 1993), groundwater resources must be carefully managed to prevent depletion. Yet, humans are not effectively conserving groundwater resources. In Tamil Nadu, India, groundwater levels declined 25 to 30 m during the 1970s as a result of excessive pumping for irrigation (Postel, 1989; UNFPA, 1991). 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 (USWRC, 1979). In an extreme case like the Ogallala aquifer under Kansas, Nebraska, and Texas, the annual depletion rate is 130% to 160% above replacement (Beaumont, 1985). If these rates continue, this aquifer, so vital to irrigation and countless communities, is expected to become non-productive by 2030 (Soule and Piper, 1992).

High consumption of surface and groundwater resources, in addition to high implementation costs, is beginning to limit the option of irrigation in arid regions. Furthermore, salinized and waterlogged soils -- both soil problems that result from continued irrigation (Postel, 1997) -- that have become unproductive are reducing the amount of possible irrigation area per capita.

Although no technology can double the flow of the Colorado River, or enhance other surface and ground water resources, improved environmental management and conservation can increase the efficient use of available freshwater. For example, drip irrigation in agriculture can reduce water use by nearly 50% (Tuijl, 1993). In developing countries, though, equipment and installation costs, as well as limitations in science and technology, often limit the introduction and use of these more efficient technologies.

Desalinization of ocean water is not a viable source of the freshwater needed by agriculture, because the process is energy intensive and, hence, economically impractical. The amount of desalinized water required by 1 hectare of corn would cost $14,000, while all other inputs, like fertilizers, cost only $500 (Pimentel et al., 1997a). This figure does not even include the additional cost of moving large amounts of water from the ocean to agricultural fields.

Another major threat to maintaining ample fresh water resources is pollution. Considerable water pollution has been documented in the United States (USBC, 1996), but this problem is of greatest concern in countries where water regulations are less rigorously enforced or do not exist. Developing countries discharge approximately 95% of their untreated urban sewage directly into surface waters (WHO, 1993). Of India's 3,119 towns and cities, only 209 have partial sewage treatment facilities and a mere 8 have full waste-water treatment facilities (WHO, 1992). A total of 114 cities dump untreated sewage and partially cremated bodies directly into the sacred Ganges River (NGS 1995). Downstream, the polluted water is used for drinking, bathing, and washing. This situation is typical of many rivers and lakes in developing countries (WHO, 1992).

Overall, approximately 95% of the water in developing countries is polluted (WHO, 1992). There are, however, serious problems in the United States as well. EPA (1994) reports indicate that 37% of U.S. lakes are unfit for swimming due to runoff pollutants and septic discharge.

Pesticides, fertilizers, and soil sediments 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, 1991). Pollution by sewage and disease organisms, as well as some 100,000 different chemicals used globally, makes water unsuitable not only for human drinking but also for application to crops (Nash, 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).

Energy Resources

Over time, people have relied on various sources of power. These sources have ranged 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 improving the general quality of life in many ways, including protection from numerous diseases (Pimentel and Pimentel, 1996).

About 365 quads (1 quad = 10^{15} BTU or 383 x 10^{18} Joules) from all energy sources are used worldwide per year (International Energy Annual, 1995). Current energy expenditure is directly related to many factors, including rapid population growth, urbanization, and high consumption rates (Fodor, 1999) (Table 3). Increased energy use also contributes to environmental degradation (Pimentel and Pimentel, 1996). Energy use has been growing even faster than world population growth. From 1970 to 1995, energy use was increasing at a rate of 2.5% (doubling every 30 years) whereas the worldwide population only grew at 1.7% (doubling about 40 years) (PRB, 1996; International Energy Annual, 1995). From 1995 to 2015, energy use is projected to increase at a rate of 2.2% (doubling every 32 years) compared with a population growth rate of 1.5% (doubling every 47 years) (PRB, 1996; International Energy Annual, 1995).

Although about 50% of all the solar energy captured by photosynthesis worldwide is used by humans, it is still inadequate to meet all of the planet's needs for food worldwide (Pimentel and Pimentel, 1996). To make up for this shortfall, about 345 quads of fossil energy (oil, gas, and coal) are utilized worldwide each year (International Energy Annual, 1995). Of this, 81 quads are utilized in the United States (DOE, 1995a,b). The U.S. population consumes 40% more fossil energy than all the solar energy captured by harvested U.S. crops, forest products, and other vegetation each year (Pimentel and Pimentel, 1996).

Industry, transportation, home heating, and food production account for most of the fossil energy consumed in the United States (DOE, 1991; DOE, 1995a). Per capita use of fossil energy in the United States is 8,740 liters of oil equivalents per year, more than 12-times the per capita use in China (Table 1). In China, most fossil energy is used by industry, but a substantial amount, approximately 25%, is used for agriculture and the food system (Smil, 1984; Wen and Pimentel, 1992).

Develop*ed* nations annually consume about 70% of the fossil energy worldwide, while the develop*ing* nations, which have about 75% of the world population, use only 30% (International Energy Annual, 1995). The United States, with only 4% of the world's population, consumes about 22% of the world's fossil energy output (Pimentel and Pimentel, 1996). Fossil energy use in the different U.S. economic sectors has increased 20- to 1,000-fold in the past 3 to 4 decades, attesting to America's heavy reliance on this finite energy resource to support their affluent lifestyle (Pimentel and Hall, 1989; Pimentel and Pimentel, 1996).

Several developing nations that have high rates of population growth are increasing fossil fuel use to augment their agricultural production of food and fiber. In China, there has been a 100-fold increase in fossil energy use in agriculture for fertilizers, pesticides, and irrigation since 1955 (Wen and Pimentel, 1992).

Fertilizer production on the whole, though, has declined by more than 21% since 1989, especially in the developing countries, due to fossil fuel shortages and high prices (Brown, 1996). In addition, the overall projections of the availability of fossil energy resources for fertilizers and all other purposes are discouraging because of the limited stores of these fossil fuels.

The world supply of oil is projected to last approximately 50 years at current production rates (BP, 1994; Ivanhoe, 1995; Campbell, 1997; Duncan, 1997; Youngquist, 1997). Worldwide, the natural gas supply is adequate for about 50 years and coal for about 100 years (BP, 1994; Bartlett and Ristinen, 1995; Youngquist, 1997). These estimates, however, are based on current consumption rates and current population numbers. If all people in the world enjoyed a standard of living and energy consumption rate similar to that of the average American, and the world population continued to grow at a rate of 1.5%, the world's fossil fuel reserves would last about 15 years (Campbell, 1997; Youngquist, 1997).

If we continue to hope that new discoveries of oil will postpone the arrival of the peak of oil production (projected for the year 2004), we should remember that the projected date of the peak moves back only at the rate of 5.5 days per billion barrels of oil that are added to the geological estimate of the world's total oil resource (Bartlett, 1998).

Youngquist (1997) reports that current oil and gas exploration drilling data has not borne out some of the earlier optimistic estimates of the amount of these resources yet to be found in the United States. Both the production rate and proved reserves have continued to decline. Domestic 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 yearly amounts (DOE, 1991;BP, 1994; Youngquist, 1997). Analyses suggest that at present (1998) the United States has consumed about three-quarters of the recoverable oil that was ever in the ground, and that we are currently consuming the last 25% of our oil (Bartlett, 1998). The United States is now importing about 60% of its oil, which puts the U.S. economy at risk due to fluctuating oil prices and difficult political situations, such as the 1973 oil crisis and the 1991 Gulf War (U.S. Congressional Record, 1997).

At present, electricity represents about 34% of total U.S. energy consumption (nuclear power contributes about 20% of the electric needs) (USBC, 1996). Nuclear production of electricity has some advantages over fossil fuels because its production requires less land than coal-fired plants and its use does not contribute to acid rain and global warming (Holdren, 1991; Pimentel et al, 1994b). Nuclear power, however, once seen as the future of electrical production, is currently suffering major economic difficulties. No new construction permits for nuclear power facilities have been issued in the United States during the past 25 years (Youngquist, 1997).

Nuclear fission currently supplies approximately 20% of the electric energy consumed in the United States without producing carbon dioxide, a major greenhouse gas that significantly contributes to global warming. Rasmussen (1978) posed an interesting question on this subject: "How does one compare the risk of [nuclear] proliferation, the possible but unlikely meltdown of a plutonium-containing core, and the long-term risks of [nuclear] waste disposal to the risks of climate modification by CO_2 emission, health effects of SO_2 and NOx and the impact of mining and transport of large amounts of coal? How does one estimate the increased risks of global conflict if failure to exploit the nuclear option leads to increased pressures on world oil supplies?"

Nuclear *fusion* has long been the subject of major efforts, yet the goal of achieving commercial fusion power remains elusive even after 50 years of intense research. It seems unwise to depend on nuclear fusion for commercial energy, at least in the near future (Bartlett, 1994).

All of the chemical and nuclear energy that society consumes 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 the 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). Releasing this heat into the environment can have adverse effects on aquatic and terrestrial ecosystems (Bartlett, 1989, 1994).

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 (von Weizacker et al., 1997). Some of the necessary changes to reduce consumption would entail more efficiently designed buildings, appliances, and industrial systems (von Weizacker et al., 1997).

Using available renewable energy technologies, such as biomass and wind power, an estimated 200 quads of renewable energy could be produced worldwide from 20% to 26% of the land area (Pimentel et al., 1994b; Yao Xlang-Jun, personal communication, Cornell University, 1998). A self-sustaining renewable energy system producing 200 quads of energy per year for about 2 billion people [see following section "Transition to an optimum population with appropriate technologies" for an explanation for the 2 billion figure] would provide each person with 5,000 liters of oil equivalents per year (half of America's current consumption per year but an increase for most people of the world) (Pimentel et al., 1998a). 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 (Daily, 1996).

Biological Resources

In addition to land, water resources, crops and livestock species, humans depend on the presence and functioning of approximately 10 million other species existing in agroecosystems and nature (Pimentel et al., 1992; Sagoff, 1995). Although approximately 60% of the world's food supply comes from rice, wheat, and corn species (Wilson, 1988), as many as 20,000 other plant species are used by humans for food (Vietmeyer, 1995). Humans have no technologies which can substitute for the food -- and some medicines -- that 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, chemical pollutant degradation, and water and soil purification (Pimentel et al., 1997b). Humans, again, have no synthetic substitutes for such ecosystem services (Daily, 1996).

These living organisms are an important resource for crop protection (Waage, 1991). Approximately 99% of potential pests are controlled by diverse natural enemy species, as well as the development of pest resistance in host-plants that came from wild plants in natural ecosystems (DeBach and Rosen, 1991). Great effort needs to be focused on the use of diverse natural enemies and the genetics of host-plant resistance for use in pest control (Klassen, 1988).

Pest insects, pathogens, and weeds destroy crops and thereby reduce food and fiber supply. Despite the yearly use of 2.5 million tons of pesticides and other controls worldwide, about 40% of all potential crop production is lost to pests (Pimentel, 1997). 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 (O'Toole, 1993). Honey bees and other wild bees play an essential role in pollinating about $40 billion worth of U.S. crops annually (Pimentel et al., 1997b). They also pollinate natural plant species . The economic benefits of biodiversity in the United States are an estimated $300 billion per year and nearly $3 trillion worldwide (Pimentel et al., 1997b).

Ecosystem and species diversity serves as a vital reservoir of genetic material for the future development of agriculture, forestry, pharmaceutical products, and biosphere services. Yet, with each passing day an estimated 150 species are being eliminated because of increasing human numbers and certain human activities, including deforestation, soil and water pollution, pesticide use, urbanization, and industrialization (Reid and Miller, 1989). The rate of extinction of some groups of organisms is 1,000- to 10,000-times faster than that in natural systems (Kellert and Wilson, 1993). One factor in this high extinction rate is humans' utilization of more than 50% of the Sun's energy captured by the entire plant biomass on Earth each year to obtain all their food and fiber. This significantly reduces the photosynthetic biomass available to maintain vital natural biota (Pimentel et al., 1997b).

Environmental pressure from the human population is the prime destructive force on Earth and is the primary cause of reduced biodiversity. Humans currently occupy 95% of the terrestrial environment with either managed agricultural and forest ecosystems or human settlements (Western, 1989). The prime 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 of 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

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. As populations increase in size, risks to health and productivity grow as well, especially in areas where sanitation is inadequate. Human deaths due to infectious diseases increased more than 60% from 1982 to 1992 (WHO, 1992, 1995; Murray and Lopez, 1996).

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, 1994). While there is a complex set of factors responsible, inadequate food and contaminated water and soil are the major contributors to diseases and other health problems, especially in developing countries (Pimentel et al., 1998b).

Disease and malnutrition are interrelated and, as might be expected, parasitic infections and malnutrition coexist where there is poverty and poor sanitation (Shetty and Shetty, 1993). 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., 1998b). 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).

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 are caused by all diseases from water, food, air, and soil each year (WHO, 1995). Shistosomiasis and malaria, common diseases throughout the tropics, are examples of parasitic diseases associated with aquatic systems; hookworms, in addition, thrive in contaminated moist soils in the tropics.

Intestinal parasites introduced into humans through contaminated food, water, and soil, impact health by reducing intake of nutrients in various ways, including the rapid loss of nutrients through diarrhea or dysentery, impairment of nutrient absorption, alteration of appetite and food intake, and blood loss (Shetty and Shetty, 1993). Hookworms, for instance, can remove up to 30 cc of blood from a person in a single day, leaving the person weak and susceptible to other diseases (Hotez and Pritchard, 1995). The estimate is that 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, 1996).

The nutrition of the world population might be improved with better distribution of total world food. For instance, it might be possible to feed the current 6 billion people a minimal but nutritionally adequate diet, if all food produced in the world was shared and distributed equally (Cohen, 1995). However, 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? Also, if the world population doubles to 12 billion, then this option would no longer be possible because of severe shortages of land, water, energy, and biological resources (Abernethy, 1993).

TRANSITION TO AN OPTIMUM POPULATION WITH APPROPRIATE TECHNOLOGIES

The human population has enormous momentum for rapid growth because of the young age distribution both in the U.S population and in the world population (PRB, 1996). If the whole world agreed on and adopted a policy so that only 2.1 children were born per couple, more than 60 years would pass before the world population finally stabilized at approximately 12 billion (Weeks, 1986). On the other hand, a population policy ensuring that each couple produces an average of only 1.5 children would be necessary to achieve the goal of reducing the world population from the current 6 billion to an optimal population of approximately 2 billion (Pimentel et al., 1994a). If this policy were implemented, more than 100 years would be required to make the adjustment to 2 billion people. Again, the prime difficulty in making the adjustment is the young age distribution and growth momentum in the world population (PRB, 1996; Bartlett and Lytwak, 1995; Bartlett, 1997-1998).

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 with an intense agricultural production system (~8 million kcal/ha) and diverse plant and animal diet for the people. The 0.5 ha of cropland per capita is the level that existed in 1960. Since that time nearly one-third of the world's arable land has been lost due to urbanization, highways, soil erosion, salinization, and water-logging of the soil (WRI, 1994; Pimentel et al., 1998a). In addition, approximately 1.5 ha of land would be required per capita for a renewable energy system (discussed earlier, p. 15). At the same time, the goal would be approximately 1 ha each for forest and pasture production per capita. Of course, it would also be essential to stop all current land degradation associated with soil erosion and other factors (Pimentel et al., 1995). Technologies are currently available for soil conservation in agricultural and forest production; they only need to be implemented (Troeh and Thompson, 1993).

Worldwide, 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, 1995; Brown, 1997; Pimentel and Pimentel, 1996; Postel, 1997). 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 3 billion humans. However, arable land is being degraded and lost at a rate of more than 12 million ha per year (Pimentel et al., 1995; Pimentel et al., 1997c). At this rate of loss, 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% of the world's food (Pimentel et al., 1995; Pimentel et al., 1997c).

A world population of 2 billion, in addition to having adequate food, renewable energy, and forest products, should also have adequate freshwater resources (Postel, 1997). For agricultural and industrial production as well as public needs, we suggest approximately 1.2 million liters per person each year. Water resources, as with soil, would have to be conserved and pollution controlled. Humans would need to cease the overdraft of ground-water resources, instead, using ground-water in a more sustainable manner. Again, technologies are currently available for the effective management and protection of water resources (Postel, 1997).

Some technologists, like Julian Simon (1996), believe that human population growth will not cause any shortage of water and other resources because we have the technologies to provide for the needs of an unlimited population. It would indeed be a wonderful achievement to see these technologists produce crops without water!

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 water pollution, especially in countries where water shortages will only intensify with population growth (Postel, 1997; Pimentel et al., 1997a). If water shortage and pollution problems were reduced, agricultural production would improve and degradation of aquatic ecosystems would decline. If pollution were controlled in most major river and lake systems worldwide, increased fish production would be possible and extinctions of fish species and other valuable aquatic species would be limited.

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). A reduction in extinction rate will protect and preserve most of the essential services provided by natural biodiversity (Pimentel et al., 1997b). How long will it take before technologies to bring about this necessary conservation of resources are implemented?

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 in the future. Research on ways to convert solar energy into usable energy, for example, and research on developing 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, photovoltaics, solar ponds, wind-power, hydropower, and biomass (Pimentel et al., 1994b).

The adjustment of the world population from 6 billion to 2 billion could be made over approximately a century if the majority of the people of the world agree that protecting human health and welfare is vital, and all are willing to work to provide a stable quality of life for ourselves and our children. Although a rapid reduction in population numbers to 2 billion humans could cause social, economic, and political problems, continued rapid growth to 10 or 12 billion people will result in an even dire situation with potentially greater problems. In addition to worldwide catastrophic health and environmental problems, political and economic tensions are likely to increase as fossil fuel production starts to decline after about the year 2010.

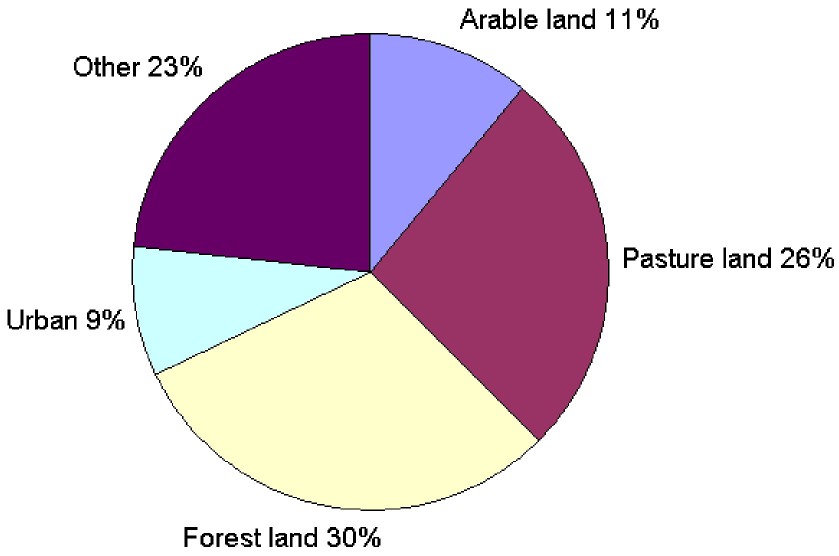
CONCLUSION

Clearly, human numbers can not continue to increase indefinitely. Natural resources are already severely limited, and there is emerging evidence that natural forces already starting to control human population numbers through malnutrition and other severe diseases. More than 3 billion people worldwide are already malnourished, and 3 billion are living in poverty; grain production per capita started declining in 1984 and continues to decline; irrigation per capita declined starting in 1978 and continues; arable land per capita declined starting in 1948 and continues; fish production per capita started declining in 1980 and continues; fertilizer supplies essential for food production started declining in 1989 and continues to do so; loss of food to pests has not decreased below 50% 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 (Pimentel et al., 1998a).

Fifty-eight academies of science, including the U.S. National Academy of Sciences, point out that "Humanity is approaching a crisis point with respect to the interlocking issues" of population, natural resources, and sustainability (NAS, 1994, p. 13). 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, the quality of the environment, environmental resource management, and population density are neither acknowledged nor 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, 1996).

Historically, decisions to protect the environment have been based on isolated crises and are usually made only when catastrophes strike. Instead of examining the problem in a holistic manner, such *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 concerning human carrying capacity of the world may not be addressed until the situation becomes intolerable or, possibly, irreversible.

With a democratically determined population control policy that respects basic individual rights, with sound resource use policies, plus the support of science and technology to enhance energy supplies and protect the integrity of the environment, an optimum population of 2 billion for the Earth can be achieved. With a concerted effort, fundamental obligations to ensure the well-being of future generations can be attained within the 21st century. Individuals will then be free from poverty and starvation and live in an environment capable of sustaining human life with dignity. We must avoid letting humans numbers continue to increase to the limit of the Earth's natural resources and forcing natural forces to control our numbers by disease, malnutrition, and violent conflicts over resources.



Land Area on Earth

(Buringh, 1989; WRI, 1994)

TABLE 1

Resources used and/or available per capita per year in the United States, China, and the world to supply basic needs.

Resources		USA	China	World
Land				
	Cropland (ha)	0.71a	0.08c	0.27e
	Pasture (ha)	0.91a	0.33c	0.57e
	Forest (ha)	1.00a	0.11c	0.75e
	Total (ha)	3.49	0.52	1.59
Water (liters x 10^6)		1.7b	0.46c	0.64c
Fossil Fuel Oil equivalents (liters)		8740b	700d	1570f
Forest Products (kg)		1091b	40c	70g

a) USDA (1993);
b) USBC (1996);
c) PRC (1994); Bennett, (1995),
d) SSBPRC (1990);
e) Buringh (1989);

f) International Energy Annual (1995);
g) UNEP (1985).

TABLE 2

Foods and feed grains supplied per capita (kg) per year in the United States, China, and the world.

Food/Feed	USA[1]	China	World[2]
Food grain	100	387a	171
Vegetables	105	198a	69
Fruit	125	35a	57
Meat & fish	137	62a	45
Dairy products	247	7b	70
Eggs	14	14a	6
Fats & oils	28	5b	11
Sugar & sweeteners	62	7b	19
Total food	818	406b	448
Feed grains	663	70b	166
Grand Total	1481	476b	614
kcal/person/day	3644	2734b	2698

1. USDA (1993).
2. Agrostat Data Base (1992).
a. Wan Baorui (1996).
b. Agrostat Data Base (1992)

TABLE 3

Fossil and solar energy use in the USA and world (Quads)

	USA	World
Petroleum	33.71a	141.2 b
Natural gas	20.81a	77.6b
Coal	19.43a	93.1b
Nuclear power	6.52a	23.3b
Biomass	6.80a	28.50c

Hydroelectric power	3.00d	23.81c
Geothermal and wind power	0.30d	0.80c
Biofuels (ethanol)	3.40d	7.00f
Total consumption	93.97	395.31

a DOE, 1995a
b International Energy Annual 1995, DOE/EIA-219 (95)
c DOE, 1995b
d DOE, 1993 (thermal equivalents for hydropower)
e Pimentel et al., 1994c
f Pimentel and Pimentel, 1996

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