# LAUCKS FOUNDATION

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As a public service, the Laucks Foundation calls attention to published material that might contribute toward clarification of issues affecting world peace, equity among peoples and environmental responsibility.

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**A note to our friends and readers:** We are proud to announce a generational change in the administration of the Laucks Foundation. At our annual meeting in October 1997, Mary Laucks was elected Laucks Foundation president and Brian Swanson, vice president. They will continue as joint editors of the Reprint Mailing and take over the foundation's administrative duties. Eulah Laucks will continue as chair of the board and direct long term planning. The new format for the reprint mailing, inaugurated in July, continues with the second of the five-part series on human population growth. In this issue we reprint four articles which discuss the ideas of "carrying capacity" and optimum human population:

**"Ecologists Look at the Big Picture"** by Anne Moffat, *Science,* 13 September 1996

**"Natural Resources and an Optimal Human Population"** by David Pimentel, Rebecca Harman, Mathew Pacenza, Jason Pecarsky, and Marcia Pimentel, *Population and Environment*, May 1994

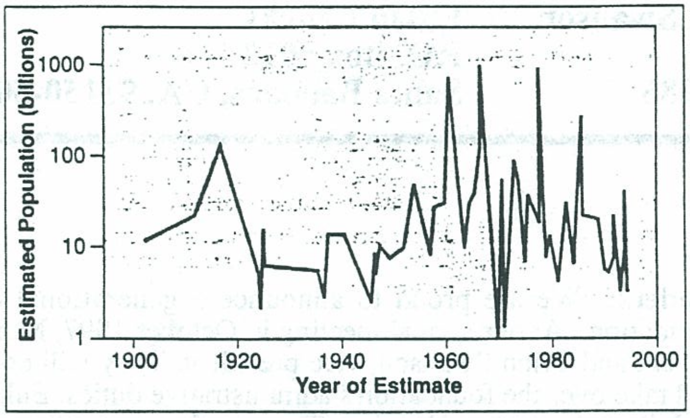
**"Revisiting Carrying Capacity: Area-Based Indicators of Sustainability"** by William Rees, *Population and Environment*, January 1996

**"How Many People can the Earth Support"** by Joel Cohen, *The Sciences*, November 1995

Estimates of how many people the earth can support have been made since the seventeenth century and the idea of an optimum human population remains a topic of active discussion. For most of human history, both economic and human population growth have been considered inherently good. However, today as world population approaches six billion, many are beginning to question at least the latter assumption. Still, many mainstream economists (so-called "neoclassical economists") take as axiomatic that economic growth can continue indefinitely, fueled in part by population growth. Some economists believe technological innovation and human creativity will overcome any physical limits to the earth's ability to sustain human life (see, for instance, J. Simon and H. Kahn (eds.) *The Resourceful Earth: A Response to Global 2000* , Blackwell,1984). Even those who promote "sustainable development" (e.g. The Brundtland Report: The World Commission on Environment and Development, *Our Common Future*, Oxford University Press, 1987) recommend economic growth as the solution to the explosive population growth in developing nations. The articles we have reprinted in this issue are all critical of neoclassical economics, but approach the question, "How many people can the earth support?" from different perspectives.

# Ecologists Look at the Big Picture

How many people can the Earth support? The answer depends in part on how much land, water, and energy are available, so ecologists have often sought a solution using the same tools they apply to natural systems: looking at current patterns of food production and resource use, then extrapolating. But estimates have ranged from 1.5 billion to as many as 1 trillion people, depending on standard of living, new technologies, and so on.



SOURCE: AMERICAN DEMOGRAPHICS

**Crowd capacity.** Estimates of how many humans can live on Earth have fluctuated from 1 billion to 1 trillion and show little sign of stabilizing.

At a crowded session on human population at the recent ecology meetings,* several speakers noted that resolution may come from a broader approach that includes social and economic dimensions. The bottom line, they say, is that human beings can choose to consume less and so boost Earth's carrying capacity. Such analyses are expected to yield a more realistic outlook and a bleak view of the choices ahead, suggesting, for example, that long-term prospects for maintaining the American lifestyle—or extending it to the nearly 6 billion people now on Earth—are grim.

This may seem all too obvious to some, but it is a novel idea when applied to this question, for most models of carrying capacity have assumed level or increased consumption, notes Cornell University agricultural scientist David Pimentel. The new analyses, he says, "are the first to consider reduced consumption as a realistic option for the future." And while previous models chiefly dealt with a defined set of ecological resources, the new studies wrestle with a dizzying array of variables, from modes of transport to amount of waste generated. "The natural sciences are valuable," says population biologist Joel Cohen of Rockefeller University in New York City. "But they can't stand alone." Yet for all the touted virtues of interdisciplinary work, this new style of analysis has yet to yield hard estimates of just how many people can live on Earth.

Scientists anxiously watching population shoot up have been trying to calculate Earth's carrying capacity for centuries. But as Cohen noted in his talk, the resulting numbers haven't converged over time. For example, Stanford University biologists Paul Ehrlich, Anne Ehrlich, and Gretchen Daily recently estimated optimal population at about 1.5 billion, while in 1994 Paul Waggoner of the Connecticut Agricultural Experiment Station estimated that Earth could support 1 trillion people, assuming improved agriculture.

Cohen argues that many analyses have come up with wildly different figures because they rely on simple biological parameters, such as the amount of arable land per capita, then extrapolate. That ignores the human choices that influence these parameters at least as much as natural constraints, he says. A billion beef-eaters require much more land than a billion vegetarians, for example, and people may change their preferences as resources become scarce. "Ecological limits appear not as ceilings but as trade-offs," says Cohen, who is now assessing the consequences of such trade-offs. For example, cotton clothes use fewer resources than wool, which requires land for raising sheep.

Similarly, population biologist William Rees of the University of British Columbia presented another type of model that takes into account how a society's choices may affect its "ecological footprint"—the area of productive land needed to support it. His analysis suggests that each American leaves at least a 5.0-hectare footprint, each Canadian 4.3 hectares, and most Europeans 3.5 hectares. To bring the developing world up to the living standard of Canada, assuming available technology, would require two more planet Earths, says Rees.

This approach, marrying natural constraints with human economic choices, gets high marks from some. "Mr. Cohen's reasoned resolution of the issues points the way to a reconciliation" of diverse estimates, says Harvard University sociologist Nathan Keyfitz.

But Cohen is so convinced that estimates of carrying capacity are elastic, depending on standard of living, that he won't give a numerical estimate—a position that draws scorn from other scientists. It's "not helpful in the policy arena," says Ehrlich, who claims that his own work also incorporates social variables, although not in the same detail. "Science draws conclusions, and he draws none," Ehrlich says. But there is at least one point on which Cohen and his critics can agree: There are some serious limits to sustaining the lifestyles common in the developed world.

–Anne Simon Moffat

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* Meeting of the Ecological Society of America, 11–14 August, Providence, RI.

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# Natural Resources and an Optimum Human Population

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## INTRODUCTION

The world's human population is currently more than 5.6 billion, and projected to reach nearly 8.4 billion by the year 2025 and possibly a disastrous 15 billion by 2100 (PCC, 1989). Presently a quarter million humans are added each day. Many leading scientists and public organizations are concerned about the rapid growth in population numbers and the deterioration of natural resources and the environment caused by human numbers and activities (CEQ, 1980; Keyfitz, 1984; Hardin, 1986; Demeny, 1986; Ehrlich & Ehrlich, 1990; Holdren, 1992). As populations and their consumerism increase, basic resources are depleted; this leads to environmental degradation while freedom of individual choice and quality of life decline (Durning, 1989; Durham, 1992). Worldwide at present from 1.2 billion (Durning, 1989) to 2 billion people (Abernethy, Vanderbilt University, personal communication, 1992) are living in poverty, malnourished, diseased, and experiencing short life-spans. In the United States 32 million now are living in poverty (USBC, 1991).

The natural resources required to sustain human life include ample supplies of fertile land, forests, water, energy, and diversity of natural biota. The interdependencies of these resources and their current and pro-

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jected future status are analyzed in this paper. We propose an optimum population for the United States and the world based on a high standard of living while maintaining the sustainability of renewable resources and the environment. The goal is to determine the population size that will insure the possibility of individual prosperity for everyone while maintaining a quality environment. This information will assist the public and governments to make thoughtful decisions that lead to reducing population numbers and consumption levels while effectively managing natural resources and the environment to sustain future generations.

## POPULATIONS AND CONSUMPTION OF RESOURCES

Human behavior demonstrates a strong will to survive, to reproduce, and to achieve some level of prosperity and quality of life. However, individuals as well as societies differ in their view of what they consider a satisfactory life. Contrasting some aspects of life in the United States, China, and world reveals disparities in lifestyles which most often are functions of the natural resources available per person (Tables 1 and 2). Furthermore most of these basic resources are finite and are not unlimited in their supplies; as human populations continue to grow, prosperity and quality of life can be expected to decline (Fornos, 1987; UNFPA, 1991).

### TABLE 1

**Foods and Feed Grains Supplied per Capita (kg) per Year in the United States, China, and the World**

| Food/Feed | USA[a] | China[b] | World[c] |
|---|---|---|---|
| Food grain | 77 | 265 | 201 |
| Vegetables | 129 | 180 | 130 |
| Fruit | 46 | 15 | 53 |
| Meat & Fish | 88 | 32 | 47 |
| Dairy products | 258 | 4 | 77 |
| Eggs | 14 | 6 | 6 |
| Fats & oils | 29 | 6 | 13 |
| Sugar & sweeteners | 70 | 7 | 25 |
| Total food | 711 | 515 | 552 |
| Feed grains | 663 | 70 | 166 |
| Grand Total | 1374 | 585 | 718 |
| Kcal/person/day | 3600 | 2500 | 2667 |

[a] Putnam and Allshouse (1991).
[b] All food item data, except vegetables, are from AMPRC (1989); the vegetable data are from D. Wen, Institute of Ecology, Shenyang, China, PC, 1991. Feed grains are from Ding Junsheng (1988).
[c] FAO (1991), except for feed grain data which is from FAO (1989).

### TABLE 2

**Resources Used per Capita per Year in the United States, China, and the World to Supply Basic Needs**

| Resources | USA | China | World |
|---|---|---|---|
| Land | | | |
| Cropland (ha) | 0.52[a] | 0.13[b] | 0.28[g] |
| Pasture (ha) | 1.3[a] | 0.35[b] | 0.58[g] |
| Forest (ha) | 1.3[a] | 0.15[b] | 0.76[g] |
| Total (ha) | 3.12 | 0.63 | 1.62 |
| Water (liters × $10^6$) | 1.9[a] | 0.43[c] | 0.66[h] |
| Fossil Fuel | | | |
| Oil equivalents (liters) | 10,000[e] | 700[f] | 1,500[i] |
| Forest Products (kg) | 1,400[e] | 40[d] | 70[e] |

[a] USDA (1990); [b] Shi Yulin (1991); [c] Sun Julin (1990), Water Use in China from Wen Dazhong, Inst. of Appl. Ecology, Shenyang, China, PC, 1992; [d] SSBPRC (1991); [e] USBC (1991); [f] SSBPRC (1990); [g] Buringh (1989); [h] WRI (1991); [i] UNEP (1985).

The present population of the United States is 258 million, and it is growing at a rate of 1.1% per year (USCB, 1992). If the number of immigrants are increased as proposed by the President and Congress, then the rate of U.S. population growth will increase at a greater rate. China already has a population of 1.2 billion, and despite the governmental policy of permitting only one child per couple, it is growing at a rate of 1.4% (PRB, 1991). The world population is now 5.6 billion and growing at a rate of 1.7%. Based on these data, the world population is expected to double in 41 years and the U.S. population to double in 63 years.

Each American consumes about 23 times more goods and services than the average third world citizen, and also each person in the United States consumes about 53 times more goods and services than a Chinese citizen (PRB, 1991). Achieving the U.S. standard of living is impossible for the rest of the world, based both on projections of future resource availability and population growth. The excessive consumption levels characteristic of Americans depend on the importation of natural resources from other countries of the world (USBC, 1991) and are reflected in the highest debt of any nation in the world.

Since the 1850s, Americans have relied increasingly on energy sources other than human power for their food and forest products. The relatively cheap and abundant supplies of fossil fuel have been substituted for human and draft animal energy. Commercial fertilizers and pesticides as well as machinery have let U.S. farmers diminish the level of human energy they must expend to farm the land. Chinese farmers use as much fertilizer and pesticides per hectare as American farmers. But they also depend on about 1,200 hrs/ha per year of human labor for grain production, compared with only 10 hrs/ha per year in the United States (Wen & Pimentel, 1984).

Industry, transportation, home heating, and food production account for most of the fossil energy consumed in the United States (DOE, 1991a). In China most fossil energy is used by industry and a lesser amount for food production (Kinzelbach, 1983; Smil, 1984). Per capita use of fossil energy in the United States is 10,000 liters of oil equivalents per year or almost 14 times the level in China (Table 2). U.S. per capita energy consumption is nearly 7 times that of the world average.

The relative affluence presently enjoyed by Americans has been made possible by our abundant supplies of fertile cropland, water, and fossil energy per capita. As our population continues to grow (Figure 1), we will inevitably experience resource shortages similar to those now being experienced by China and other nations (Tables 1 and 2).

## STATUS OF WORLD ENVIRONMENTAL RESOURCES

What standard of living will be experienced by each person in the United States and the world in the future? We have already suggested that this depends on population numbers and the quality and quantity of land, water, and energy as well as of biological resources and the technologies employed to manage these resources. The U.S. population currently has 258 million consumers of these vital resources, many of which are being depleted, with no hope of renewal after the next hundred years. Reports indicate that the average standard of living in the United States began to decline during the last decade (Fuchs & Reklis, 1992) and is projected to continue to decline if the U.S. population doubles its numbers during the next 63 years (USCB, 1992). The world population, as mentioned, is projected to double in just 41 years (PRB, 1991) and already shortages of fertile land, water, and fossil energy exist in many regions (WRI, 1991; Worldwatch, 1992).

### *Land Resources*

More than 98% of world food comes from the terrestrial environment and the remaining small percentage comes from ocean, lake, and other

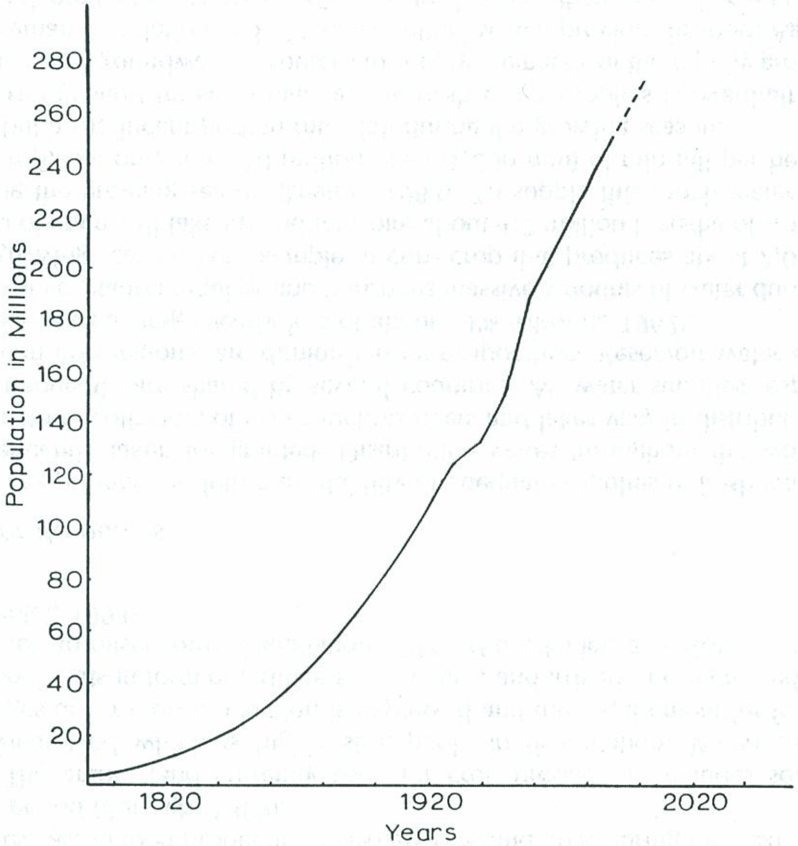

**FIGURE 1.** Rapid growth in the U.S. population from 1800 to date. At the current growth rate, the U.S. population is projected to double in 63 years (USCB, 1992).

aquatic ecosystems (Pimentel & Hall, 1989). Worldwide, food and fiber crops are grown on 12% of the earth's total land area (Buringh, 1989). Another 24% of the land is used as pasture to graze livestock that provide meat and milk products. Forests cover an additional 31% (Buringh, 1989). The small percentage of forestland and grassland set aside as protected national parks to conserve biological diversity amounts to only 3.2% of the total terrestrial ecosystem (Reid & Miller, 1989). The remaining portion of land area (34%) is mostly unsuitable for crops, pasture, and forests because it is too cold, too dry, steep, stony, or wet, or the soil is too shallow to support plant growth (Buringh, 1989) (Table 3).

To provide a diverse nutritious diet of plant and animal products,

**TABLE 3**

**Land Area (Million ha) Uses in Major Regions of the World (WRI, 1991)**

| Region | Total Area | Cropland | Pasture | Forest | Other[a] |
|---|---|---|---|---|---|
| Africa | 2,965 | 184 | 792 | 688 | 1,301 |
| N. America | 2,139 | 274 | 368 | 684 | 813 |
| S. America | 1,753 | 140 | 468 | 905 | 240 |
| Asia | 2,679 | 450 | 678 | 541 | 1,010 |
| Europe | 473 | 140 | 84 | 157 | 92 |
| Total | 10,009 | 1,188 | 2,390 | 2,975 | 3,456 |
| | 100% | 12% | 24% | 30% | 34% |

[a] Land that is either too dry, too steep, or too cold to use for agriculture and forestry.

about 0.5 ha of cropland per capita is needed (Lal, 1989). The United States is at this level now, but the world average is only 0.28 ha of cropland available per capita, or nearly one-half this optimum value (Table 2). This shortage of productive cropland is in part the cause of the food shortages and poverty that many humans are experiencing today.

Currently, a total of 1,374 kg of agricultural products are produced annually to feed each American while the Chinese's supply averages only 585 kg/capita/yr (Table 1). Note that the world value is 718 kg/capita/yr. Based on available data (Tables 1 and 2) each person in China eats essentially a vegetarian diet. Further they have reached the carrying capacity of their agricultural system, even with huge inputs of fossil energy now used on Chinese farms (Wen & Pimentel, 1990).

Escalating land degradation threatens most crop and pasture land throughout the world (Lal & Pierce, 1991). The major types of degradation include water and wind erosion, salinization, and water-logging of soils (Mabbutt, 1989). Indeed, more than 10 million hectares of productive arable land are severely degraded and abandoned each year (Pimentel et al., 1992). Moreover, each year an additional 5 million hectares of new land must be put into production to feed the 96 million humans added yearly to the world population. Most of this total of 15 million ha needed for replacement and expansion is coming from the world's forests. The urgent need for agricultural land accounts for 80% of the deforestation now occurring worldwide (Myers, 1990).

Soil erosion, the single most serious cause of soil loss and land degradation, is more intense than ever before in history (Pimentel & Hall, 1989; WRI, 1991; Pimentel, 1993). In Africa during the past 30 years, the rate of soil loss has increased 20 times (Tolba, 1989). Wind erosion is so serious in China that Chinese soil is detected in the Hawaiian atmosphere when planting starts in China (Parrington et al., 1983). Similarly in 1992, soil eroded from Africa was detected in Florida and Brazil (Simons, 1992). Soil erosion on cropland ranges from about 16 t/ha/yr in the USA to 40 t/ha/yr in China (USDA, 1991; Wen, 1993; McLaughlin, 1993). Soil erosion worldwide is about 30 t/ha/yr (Pimentel, 1993). This magnitude of erosion is of particular concern because of the slow pace of soil formation; it takes approximately 500 years for 2.5 cm of topsoil to form under agricultural conditions (OTA, 1982; Elwell, 1985; Troeh et al., 1980). Thus, topsoil is being lost 20 to 40 times faster than it is being replaced.

Erosion adversely affects crop productivity by reducing water availability, water-holding capacity, soil nutrients, soil organic matter, and soil depth. Estimates are that agricultural land degradation can be expected to depress world food production between 15% and 30% during the next 25-year period (Buringh, 1989).

The arable land currently used for crop production includes some marginal land which is highly susceptible to degradation. When such changes occur crop production is depressed and the requirement for fossil energy inputs in form of fertilizers, pesticides, and irrigation is increased in an effort to offset some degradation (OTA, 1982; Follett & Stewart, 1985; Pimentel, 1993).

### *Water Resources*

The present and future availability of adequate supplies of fresh water is frequently taken for granted. Distribution varies throughout the world and natural collectors of water such as rivers and lakes vary in distribution and frequently are shared by several countries. All water supplies, especially in arid regions, are diminished by evaporation. Reservoir water experiences an average yearly loss of about 24% (Meyers, 1962).

All vegetation requires and transpires massive amounts of water during the growing season. For example, a corn crop that produces about 7,000 kg/ha of grain will take up and transpire about 4.2 million liters/ha of water during the growing season (Leyton, 1983). To supply this much water to the crop, not only must 10 million liters (1,000 mm) of rain fall per hectare, but a significant portion must fall during the growing season.

The greatest threat to maintaining fresh water supplies is overdraft of surface and groundwater resources to supply the needs of the rapidly growing human population and of the agriculture which provides its food. Agricultural production "consumes" more fresh water than any other human activity (Falkenmark, 1989). Worldwide about 87% of the fresh water is consumed (made nonrecoverable) by agriculture (Postel, 1989), while in the United States this figure is about 85% (NAS, 1989). An individual requires nearly 3 liters/day of fresh water for drinking, but needs a minimum of 90 liters/day for cooking, washing, and other domestic needs (Brewster, 1987). Each American uses about 400 liters/day for domestic needs (USBC, 1991).

As the world's population grows, so do its water needs. To provide the ever increasing amount of water required to meet human needs is resulting in increased demand for surface water and groundwater resources. For example, by the time the Colorado River enters Mexico it has literally disappeared because of the excessive removal of its water by the states of California, Arizona, and Colorado (Sheridan, 1983). Veltrop (1991) calculates that if the world's population increases about 20%, the demand for water will double.

Surface water and groundwater each supply half of the freshwater supply in the world (Wolman, 1986; Falkenmark, 1989). Groundwater resources are renewed at various rates, but usually at the extremely slow rate of about 1% per year (CEQ, 1980). Because of this slow recharge rate, groundwater resources must be carefully managed to prevent overdraft. Yet humans are not effectively conserving groundwater resources and overdraft is a serious problem worldwide. For example, in Tamil Nadu, India, groundwater levels declined 25 to 30 m during the 1970s because of pumping for irrigation (Postel, 1984; UNFPA, 1991). Beijing, China records a decline in its groundwater table of about 1 m/yr; and in Tianjin, China it drops 4.4 m/yr (Postel, 1984). In the United States overdraft averages 25% higher than replacement (USWRC, 1979). But in some locations, like the U.S. Ogallala aquifer, annual overdraft is 130% to 160% above replacement (Beaumont, 1985). If this continues, this vast aquifer is expected to become non-productive in about 40 years (Soule & Piper, 1992). Loss of available water limits the option of irrigation in arid regions. The irrigation area worldwide is now declining per capita because of salinization, water-logging and population growth (Postel, 1989).

Another major threat to maintaining ample fresh water resources is pollution caused by people and industries. Considerable water pollution is documented in the United States (USBC, 1991) but is more serious in developing countries. For example, in Latin American countries, untreated urban sewage is often dumped into rivers and lakes (WRI, 1991), resulting in fecal-coliform bacterial counts higher than 100,000 per ml of water (0.1/ml is the maximum acceptable level for U.S. drinking water). Pesticides, fertilizers, and sediments pollute water resources as they accompany eroded soil; industries dump toxic chemicals untreated into

rivers and lakes (WRI, 1991). Pollution by sewage, as well as various chemical wastes, makes water unsuitable for human drinking and for application to crops.

### *Biological Resources*

In addition to land, water resources, and crop and livestock species, humans depend on the millions of other species that exist in agroecosystems and nature (Pimentel et al., 1992). Humans have no technologies that can substitute for the service provided by wild biota. In the United States there are approximately 500,000 species of plants, animals, and microbes that provide many essential functions for humans including: pollination of crop and wild plants; recycling manure and other organic wastes; degrading chemical pollutants; and purifying water and soil (Pimentel et al., 1992). These diverse species also serve as a vital reservoir of genetic material for future development of agriculture and forestry. Yet the world is losing about 150 species per day because of human activities of deforestation, pollution, applying pesticide application, urbanization, etc. (Reid & Miller, 1989).

Ecologists have reported that if sufficient natural biological diversity is to be maintained to ensure a quality environment, then about one-third of the terrestrial ecosystem should be preserved as natural vegetation (Odum, 1971). This biomass is essential to provide food, shelter, and protection for these valuable species and ensures their preservation (Pimentel et al., 1992).

Clearly humans need these organisms as well as their livestock and crop species. For example, honey bees and wild bees play an essential role in pollinating about $30 billion worth of U.S. crops annually in addition to pollinating natural plant species. It has been calculated that honey bees and wild bees in New York State on a bright, sunny day in July pollinate $10^{12}$ blossoms (Pimentel, 1994). Humans have no technology to substitute for this natural service supplied by wild biota.

### *Energy Resources*

Some form of energy is expended to provide humans with all their needs. About 369 quads from all energy sources per year are used worldwide, the amount directly related to the rapid growth in the world population and the environmental degradation imposed by human activity (Pimentel & Pimentel, 1979) (Table 4). Although worldwide about 50% of all solar energy captured by photosynthesis is used by humans, it is inade-

## TABLE 4

Fossil and Solar Energy Use in the USA and World

| | USA[a] | | World[b,c] | |
|---|---|---|---|---|
| | Quads | % | Quads | % |
| Total energy | 85.1 | 100 | 368.9 | 100 |
| Fossil energy | 78.5 | 92.3 | 319.2 | 86.5 |
| Solar energy | 6.6 | 7.7 | 49.7 | 13.5 |
| Hydropower | 3.0 | 3.5 | 21.2 | 5.7 |
| Biomass | 3.6 | 4.2 | 28.5 | 7.8 |

[a]DOE, 1991a; [b]DOE, 1991b; [c]UNEP, 1985.

quate to meet their needs of food and forest products (Pimentel, 1989; Pimentel & Pimentel, 1991). To make up the addition, about 319 quads ($10^{15}$ BTU or $337 \times 10^{18}$ Joules) of fossil energy are utilized worldwide each year (UNEP, 1985; IEA, 1991), of which 79 quads are consumed in the United States (DOE, 1991a). These 79 quads represent nearly 3 times the 28 quads of solar energy harvested as crop and forest products, and about 40% more energy than is captured by U.S. vegetation. Fossil energy has also been used to fuel a wide array of human activities including industrial production, fuel for automobiles and trucks, highway construction, heating and cooling of buildings, and packaging of all goods.

Fossil energy is used to feed an increasing number of humans as well as improve the quality of life in many basic ways, such as protecting humans from numerous diseases. For example, delivering clean water has helped to eliminate a wide array of disease organisms that are transmitted in polluted water.

Developed nations annually consume about 80% of the fossil energy worldwide while the developing nations, which have about 75% of the world population, consume only 20% (UNEP, 1985; DOE, 1991a). The United States consumes about 25% of the world's fossil energy annually.

Several developing nations that have high rates of population growth are increasing the use of fossil fuels in their agricultural production. For example, since 1955 there has been a 100-fold increase in the use of fossil energy in Chinese agriculture (Wen & Pimentel, 1984). Similarly, fossil energy use in different U.S. economic sectors has increased 20- to 1,000-fold in the past 3 to 4 decades, attesting to our heavy reliance on this finite energy resource (Pimentel & Hall, 1989).

Projections of the availability of fossil energy resources are discouraging. A recent report published by the U.S. Department of Energy (DOE, 1991a) based on current oil-drilling data indicates that the estimated amount of national oil reserves has plummeted. This means that instead of the 35-year supply of U.S. oil reserves that was projected about 4 years ago, the current known and discoverable potential oil reserves are now limited to a 10- to 13-year supply at present rates of pumping (DOE, 1990; Lawson, 1991). Since the United States is now importing more than half its oil, a serious problem already exists (Gibbons & Blair, 1991).

The world supply of oil is greater than that of the United States and is projected to last about 35 years at current pumping rates (Matare, 1989). Both in the United States and the world, the natural gas supply is adequate for about 35 years and coal for about 100 years (Matare, 1989). Other estimates range as high as 150 years for total fossil energy, primarily coal (BP, 1991). However, these estimates are based on current consumption rates and current population numbers. If all people in the world enjoyed a standard of living and energy consumption similar to the U.S. average, and the world population continued to grow at a rate of 1.7% per year, the world's fossil fuel reserves would last a mere 20 years.

At present about 34% of total U.S. energy consumption is electricity, and nuclear energy provides 18% of the electric needs (USBC, 1991). Nuclear energy production of electricity has some advantages over fossil fuels because it requires less land than coal-fired plants, causes fewer human injuries and deaths, and its use does not contribute to acid rain and global warming (Holdren, 1991; Meeks & Drummond, 1991). However, there are several limitations to the expansion of the use of nuclear fission and fusion energy in the future.

First, uranium resources are limited worldwide and are expected to last about 100 years, without nuclear breeder reactors (Hafele, 1991). Second, the risks of disposing radioactive wastes and lack of public acceptance for storage of wastes may influence the widespread use of both fission and fusion energy (Hafele, 1991). Fusion technology will require a great many years of research for development before it will be ready for use (Matare, 1989).

Both nuclear fission and fusion technologies produce enormous amounts of waste heat, which is a serious environmental pollutant (Bartlett, 1989). For example, it has been estimated that if the number of nuclear power plants in the United States were increased from the current 108 to 1,500, the temperature of aquatic ecosystems in the United States would increase about 10°C (H. Kendall, Department of Physics, MIT, personal communication, 1992). This degree of heat pollution would cause a major loss of biological diversity in aquatic systems and would also alter existing climate patterns which influence agricultural and forestry production.

## TRANSITION FROM FOSSIL TO RENEWABLE ENERGY

With the imminent decline in fossil fuels, a transition should be made to move from reliance on fossil energy to renewable energy sources. Research on ways to convert solar energy into usable energy, and developing new sources such as nuclear fusion energy should be given priority. Many solar energy technologies have been developed but at present are in limited use. These include: solar thermal receivers, photovoltaics, solar ponds, windpower, hydropower, and biomass. Using available technologies, biomass also can be converted into liquid fuel such as methanol; however, this process is inefficient and costly (ERAB, 1981;1982; Brower, 1990).

As recently as 1850, when the U.S. population was only 23 million, the United States was dependent on wood biomass, a form of solar energy, for 91% of its energy (Pimentel & Pimentel, 1979). Gradually the use of biomass fuel declined, and today we depend on fossil energy for 93% of our energy needs, while biomass energy makes up only 3.5%; hydropower provides the remaining 3.5% (Pimentel et al., 1994).

In contrast, 33% of the total energy (about 90 quads) now consumed annually by people in developing countries is solar-based. In particular, poorer people in developing countries depend primarily upon biomass energy. Of the total solar energy source, biomass comprises about 81%; the remainder is provided by hydropower (UNEP, 1985). Of the biomass, about 51% is fuelwood, 38% crop residues, and 11% dung (Pimentel et al., 1986).

If the U.S. population declines in numbers, then reliance on biomass energy will probably increase. However, use of biomass has several limitations, including competition for land areas and degradation of the environment caused by the removal of biomass from the land (ERAB, 1981; Pimentel et al., 1989a,b; Pimentel, 1992).

Consider that the total amount of solar energy captured by vegetation each year in the United States is 54 quads, which includes all the solar energy captured by agricultural crops, forests, lawns, gardens, and wild vegetation (Pimentel et al., 1978). Because of limiting factors, such as lack of water and soil nutrients, this biomass yield cannot be increased to any great extent (ERAB, 1981). The total solar energy captured by U.S. agricultural crops and forest products is about 28 quads or slightly more than half of the solar energy captured by all vegetation (ERAB, 1981). Because this portion of biomass energy provides vital food, fiber, pulp, and lumber, it can only be harvested and used to a very limited extent as biomass energy. This leaves only 26 quads of energy from other forests and wild vegetation to be used for biomass energy. However, each American uses large amounts of forest products for paper and building; and we now import 19% of the forest products (USBC, 1991). These needs further diminish the amount of biomass that can be used as an energy source.

During this era of fossil fuels, use of these finite sources of energy has escalated to a level where it is out of balance with supply. The more than 258 million Americans use 40% more fossil energy than the total amount of solar energy captured each year by all U.S. plant biomass (ERAB, 1981). In China and Europe the situation is more critical. Worldwide, humans burn over 50% more fossil energy than the solar energy captured by their total available plant biomass. American, European, Chinese, and other societies' consumption of resources, especially nonrenewable fossil fuels, is out of balance with the ecosystem.

The availability of land that can be devoted just to biomass energy production is a major constraint to reliance on it to replace fossil fuels. The United States is fortunate in having more arable land per person than any other nation on earth. At present three-quarters of this land is devoted to agriculture and commercial forestry (USDA, 1990); urbanization and roadways occupy another 10%. Thus a relatively small percentage of U.S. land is available for increasing biomass energy resources and developing other solar energy technologies. In most other nations (e.g., Europe and China) the availability of land per person is much less than it is in the United States and the need for more land to provide food is more critical because of increasing numbers of people (Buringh, 1989).

Estimates are that only approximately 0.1% of the total solar energy reaching the earth can be harvested as biomass in temperate and tropical regions (ERAB, 1981). With this constraint, large land areas are needed to produce adequate supplies of biomass (Tables 3 and 5). Solar energy is captured by plants only during the growing season, and production is limited in the temperate region by temperature and in the tropics often by lack of rainfall. Nutrient shortages also play a role in limiting biomass production.

Furthermore the limited area available for developing and expanding solar energy technologies leads to a conflict between land uses for food and forest products and that required for solar energy (Pimentel et al., 1984). This limits the potential of solar energy technologies. The amount of land required to provide solar-based electricity for a city of 100,000 people in the United States illustrates the land constraints. However, it must be emphasized that electricity provides 34% of total U.S. energy used; therefore if total energy were supplied by these solar energy systems, 3 times more land would be required for a city of 100,000 people. To provide the needed 1 billion kWh/yr from a sustainable biomass wood system would require the maintenance of 200,000 hectares of permanent forest (Table 5). Hydropower also is, in part, land based. On average about 13,000 hectares of land are needed for an adequate sized reservoir to provide hydropower for 100,000 people. The environmental and cultural impacts of creating reservoirs are significant because the land covered with water is often productive agricultural land, or is land used in various ways for human sustenance (Thurston, 1991).

Photovoltaic units require a significant amount of land, 2700 ha, to supply 1 billion kWh per year (Table 5). Some of these units can be placed on the roofs of buildings to reduce land area requirements. It is calculated that approximately 10% of the needed area can be supplied by mounting the photovoltaic units on the roofs of buildings (based on the average sized housing unit, with an average number of stories, and average roof area [USBC, 1991]). Thus, all solar energy systems have significant land requirements, and/or environmental limitations because of the toxic materials used in construction (Pimentel et al., 1984). Equally important, large amounts of energy and mineral resources are needed to manufacture solar collectors.

The water resources used in agriculture and forestry are also needed to operate several of the solar energy systems including hydropower, biomass, and solar ponds. Severe competition already exists for fresh water resources throughout the world and will escalate as solar energy systems encroach on water supplies (WRI, 1991).

### TABLE 5

### Land Resource Requirements for Construction and Function of Energy Facilities that Produce 1 Billion kWh/yr of Electricity for a City of of 100,000 People

| Electrical Energy Technology | Land in Hectares |
|---|---|
| Solar Thermal Central Receiver | 1,800[a] |
| Photovoltaics | 2,700[a] |
| Wind Power | 11,700[a] |
| Hydropower | 13,000[a] |
| Forest Biomass | 200,000[a] |
| Solar Ponds | 5,200[a] |
| Nuclear | 68[a] |
| Coal | 90[a] |
| Geothermal | 40[b] |

[a] Modified after Pimentel et al. (1984).
[b] Flavin and Lenssen (1991).

Although the conversion of biomass like corn grain into fuel energy appears promising at first glance, 72% more energy is used in the production of ethanol than the energy it provides (Pimentel, 1991). Furthermore, the land area needed to provide the raw material is enormous; about 6 ha of corn grain is needed to provide the ethanol fuel for one U.S. car for one year, assuming zero energy inputs for the distillation. Then too, the land planted to corn for ethanol would not be available for food production.

If we make the optimistic assumption that the current level of 7 quads of solar energy collected and used annually in the United States could be increased 5-fold without adversely affecting agriculture, forestry, or the environment, then about 35 quads of solar energy could be produced per year (Pimentel et al., 1984; Ogden & Williams, 1989). This is only about 40% of the current energy consumption in the United States, which totals about 86 quads (Table 4). Producing the total 35 quads would require about 90 million ha or nearly 10% of U.S. land area devoted to solar energy systems. We project that hydropower, wind power, solar thermal, passive heating and cooling, and photovoltaics will provide most of the 35 quads needed per year. The remaining energy will come from the other solar energy systems.

Compared with the United States, the world terrestrial ecosystem is not as favorable. Estimates are that, if 500 to 600 million ha were devoted to solar energy production systems worldwide, about 200 quads of energy might be available each year. This is about two-thirds of the total current world annual use of solar and fossil fuels combined (369 quads). This is an optimistic estimate. It does not take into consideration current and future competition for land and water needed for food and forest production and the requirements of solar energy technologies. Most importantly, this projection does not take into consideration that the world population is projected to double or triple within the next 100 years and that vital land resources are being degraded or lost under the pressures exerted by the growing human population.

## IMPROVED USE OF RESOURCES

The prime resources—land, water, energy, and biological resources—function interdependently and each can be manipulated to a degree to make up for a partial shortage in one or more of the others. For example, to bring desert land into agricultural production, it can be irrigated. This can occur only if groundwater or river water is available, if sufficient fossil energy is available to pump and move the water, and if the soil is suitable for irrigation and fertile to support crop growth. Because the availability of these essential resources is fast diminishing, the options for substitution are also diminishing. This emphasizes the need to examine alternative strategies.

Large quantities of fossil based fertilizers are major sources of nutrient enhancement of agricultural soils throughout the world. Yet in the United States about $18 billion per year of fertilizer nutrients are lost as they are eroded along with soils (Troeh et al., 1980). Further, U.S. livestock manures, which have an amount of nitrogen equal to that in commercial nitrogen fertilizer applied to agriculture each year, are underutilized and wasted. Significant quantities of fossil energy could be saved if effective soil conservation methods were implemented, and if manures were used more extensively as a substitute for commercial fertilizer (Pimentel et al., 1989a,b).

Pesticides are also fossil based in their production and are wasted (Pimentel, 1990). Since 1945 the use of synthetic pesticides in the United States has grown 33-fold, yet crop losses to pests continue to increase (Pimentel et al., 1991). For example, despite a 1,000-fold increase in the use of insecticides on corn, corn losses to insects have risen nearly 4-fold (Pimentel et al., 1991). Pesticide use has increased because agricultural technologies have been changed. For some major crops like corn, crop rotations have been abandoned. Now about 40% of U.S. corn land is used to grow corn continuously as a monoculture. This has caused an increase in the number of corn pests and in pesticides required to protect the crop (Pimentel et al., 1991). Adopting sustainable and environmentally sound agricultural technologies, including a return to crop rotations, would stem soil erosion, conserve fertile land, reduce water requirements for irrigation, decrease pesticide and fertilizer use, and thus save fossil fuel, soil, and water resources (Pimentel et al., 1989a,b).

The use of more land to produce food reduces the total energy inputs necessary for crop production and would lead to greater solar energy dependence and sustainability in agriculture. This, of course, assumes the availability of sufficient land, halving crop yields per hectare, but maintaining the same total amount of food produced.

## PROSPERITY AND AN OPTIMUM POPULATION

If the United States were to move to a renewable energy economy, with sustainable use of energy, land, water, and biodiversity, and a relatively high standard of living, how large a human population could be supplied? Based on available land and solar energy technologies we project a future U.S. energy supply of approximately 35 quads per year and the use of about 90 million ha of land for solar energy without diminishing agricultural and forest production. It is assumed that individuals would reduce by one-half their current energy use through energy efficiency and conservation; utilize only 5,000 liters of oil equivalents per year; make a major effort to conserve soil and water resources, control air pollution, and efficiently recycle all resources. However, under the above conditions the optimum population would be targeted at about 200 million; significantly less than the current U.S. population of 258 million. Then it would be possible for Americans to continue to enjoy their relatively high standard of living. Fortunately, the United States has sufficient fossil energy reserves, particularly coal, to make this necessary transition and balance in energy resources and population numbers over the next 100 years.

Worldwide, resolving the population-resource equation will be more difficult than in the United States. Already overpopulation, maldistribution of resources, and environmental degradation are causing serious malnourishment and poverty throughout the world, but especially in developing countries (Birdsall, 1980; Lappe & Collins, 1986; Ehrlich & Ehrlich, 1990; Young, 1992).

Worldwide, renewable solar energy could be developed to provide 200 quads of sustainable energy per year, while maintaining needed agricultural and forestry production. That combined with active conservation efforts, a satisfactory standard of living would be possible for everyone. However, the human population would have to be much smaller than the present 5.5 billion.

Based on the estimate that 0.5 ha per capita is necessary for an adequate food supply and assuming a program of soil conservation was implemented, it would be possible to sustain a global population of approximately 3 billion humans. With a self-sustaining renewable energy system producing 200 quads of energy per year and providing each person with 5,000 liters of oil equivalents per year (one-half of America's current consumption/yr but an increase for most people in the world), a population of 1 to 2 billion could be supported living in relative prosperity. This adjustment could be made over a century or more if everyone agreed that protecting human welfare was vital and that all were willing to work to provide a quality life for future generations. Granted a drastic demographic adjustment to 1 to 2 billion humans will cause serious social, economic, and political problems, but to continue rapid population growth to 12 billion or more will result in more severe social, economic, and political conflicts plus catastrophic public health and environmental problems.

Efforts to reduce population numbers to the suggested numbers must occur with individual human rights firmly in mind. The freedom of individuals to decide their own reproductive and familial futures cannot be ignored in the name of population control. At the same time, to do nothing to control population numbers is to condemn future humans to a lifetime of absolute poverty, suffering, starvation, disease, and associated violent conflicts as individual pressures mount. The ultimate control of the human population will be imposed by nature.

## CONCLUSION

Does human society want 10 to 15 billion humans living in poverty and malnourishment or 1 to 2 billion living with abundant resources and a quality environment? Citizens of the United States and the world must support their leaders in making these critical decisions for the future. This fundamental commitment to move toward a sustainable-sized population and an energy-secure future must include the active political participation of all people.

Given the present level of fertility and immigration, the U.S. population will double in 63 years to more than half a billion, or roughly half the size of present day China. Comparisons to the problems now being experienced in China emphasize why the United States will be unable to maintain its present level of prosperity and relatively high standard of living, unless population growth is controlled.

For Americans to continue to enjoy a high standard of living and for society to be self-sustaining in renewable energy and food and forestry products, given U.S. land, water and biological resources, the optimum U.S. population is about 200 million—significantly less than the current level of 258 million. However, with one billion people as now live in China, the U.S. population could be sustained *but* in relative poverty. Sometime soon the United States needs to determine its population policy and vision for the future.

At present the pressure imposed by the large and expanding world population is more serious than that being experienced in the United States. The world population is 5.6 billion with about 1.6 billion humans now malnourished and from 1.2 to 2 billion living in poverty. Fertile cropland, fresh water, and fossil energy resources are now in serious short supply in many regions of the world. Their scarcity accounts for inadequate food and forest production, a deteriorating environment, and a diminished standard of living for most people. At current use levels most oil, natural gas, and coal reserves will be used up within the next century, with actual rates of consumption driven by population growth and rising consumer expectations. In addition, soil degradation is intensifying, water shortages and pollution increasing, forests are being removed, and more biological species are being destroyed than ever before.

Thus far, the Americans as well as world citizens appear unwilling to deal with the growing imbalances of human population and the energy and environmental resources that support all life. Humans have a disappointing record of effectively managing and protecting their essential resources and the environment from over-exploitation in the face of rapidly growing population. World leaders seem not to understand or acknowledge the interdependencies existing among individual standard of living, population density, availability of life-supporting resources, and the quality of the environment. Local, national, and global problems exist because governments have not tried to develop cohesive and cooperative policies that recognize how supplies of the natural resources are affected by human numbers and consumption levels.

Decision making tends to be based on crises; decisions are not made until catastrophe strikes. Thus, decisions are *ad hoc*, designed to protect and/or promote a particular resource or aspect of human well-being instead of examining the problem in a holistic manner. Based on past experience, we expect that leaders will continue to postpone decisions concerning human carrying capacity of the world (Fornos, 1987), maintenance of a standard of living, conservation of resources, and the preservation of the environment until the situation becomes intolerable, or worse still, irreversible.

Starting to deal with the imbalance of the population-resource equation before it reaches a crisis level is the only way to avert a real tragedy for our children's children. With equitable population control that respects basic individual rights, sound resource management policies, support of science and technology to enhance energy supplies and the environment, and with all people working together, an optimum population can be achieved. With such cooperative efforts we would fulfill fundamental obligations to generations that follow—to ensure that individuals will be free from poverty and starvation in an environment that will sustain human life with dignity.

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# Revisiting Carrying Capacity: Area-Based Indicators of Sustainability

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Conventional wisdom suggests that because of technology and trade, human carrying capacity is infinitely expandable and therefore virtually irrelevant to demography and development planning. By contrast, this article argues that ecological carrying capacity remains the fundamental basis for demographic accounting. A fundamental question for ecological economics is whether remaining stocks of natural capital are adequate to sustain the anticipated load of the human economy into the next century. Since mainstream (neoclassical) models are blind to ecological structure and function, they cannot even properly address this question. The present article therefore assesses the capital stocks, physical flows, and corresponding ecosystems areas required to support the economy using "ecological footprint" analysis. This approach shows that most so-called "advanced" countries are running massive unaccounted ecological deficits with the rest of the planet. Since not all countries can be net importers of carrying capacity, the material standards of the wealthy cannot be extended sustainably to even the present world population using prevailing technology. In this light, sustainability may well depend on such measures as greater emphasis on equity in international relationships, significant adjustments to prevailing terms of trade, increasing regional self-reliance, and policies to stimulate a massive increase in the material and energy efficiency of economic activity.

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## WHY CARRYING CAPACITY?

According to Garrett Hardin (1991), "carrying capacity is the fundamental basis for demographic accounting." On the other hand, conventional economists and planners generally ignore or dismiss the concept when applied to human beings. Their vision of the human economy is one in which "the factors of production are infinitely substitutable for one another" and in which "using any resource more intensely guarantees an increase in output" (Kirchner *et al.*, 1985). As Daly (1986) observes, this vision assumes a world "in which carrying capacity is infinitely expandable" (and therefore irrelevant). Clearly there is great division over the value of carrying capacity concepts in the sustainability debate.

This article sides solidly with Hardin. I start from the premise that despite our increasing technological sophistication, humankind remains in a state of "obligate dependence" on the productivity and life support services of the ecosphere (Rees, 1990). Thus, from an ecological perspective, adequate land and associated productive natural capital are fundamental to the prospects for continued civilized existence on Earth. However, at present, both the human population and average consumption are increasing while the total area of productive land and stocks of natural capital are fixed or in decline. These opposing trends demand a revival of carrying capacity analysis in sustainable development planning. The complete rationale is as follows:

### *Definitions: Carrying Capacity and Human Load*

> An environment's carrying capacity is its maximum persistently supportable load (Catton 1986).

For purposes of game and range management, carrying capacity is usually defined as the maximum population of a given species that can be supported indefinitely in a defined habitat without permanently impairing the productivity of that habitat. However, because of our seeming ability to increase our own carrying capacity by eliminating competing species, by importing locally scarce resources, and through technology, this definition seems irrelevant to humans. Indeed, trade and technology are often cited as reasons for rejecting the concept of human carrying capacity out of hand.[1]

This is an ironic error—shrinking carrying capacity may soon become the single most important issue confronting humanity. The reason for this becomes clearer if we define carrying capacity not as a maximum population but rather as the maximum "load" that can safely be imposed on the environment by people. Human load is a function not only of population but also of *per capita* consumption and the latter is increasing even more rapidly than the former due (ironically) to expanding trade and technology. As Catton (1986) observes: "The world is being required to accommodate not just more people, but effectively 'larger' people . . ." For example, in 1790 the estimated average daily energy consumption by Americans was 11,000 kcal. By 1980, this had increased almost twenty-fold to 210,000 kcal/day (Catton 1986). As a result of such trends, *load* pressure relative to carrying capacity is rising much faster than is implied by mere population increases.

### *The Ecological Argument*

Despite our technological, economic, and cultural achievements, achieving sustainability requires that we understand human beings as ecological entities. Indeed, from a functional perspective, the relationship of humankind to the rest of the ecosphere is similar to those of millions of other species with which we share the planet. We depend for both basic needs and the production of artifacts on energy and material resources extracted from nature and *all* this energy/matter is eventually returned in degraded form to the ecosphere as waste. The major material difference between humans and other species is that in addition to our biological metabolism, the human enterprise is characterized by an industrial metabolism. In ecological terms, all our toys and tools (the 'capital' of economists) are "the exosomatic equivalent of organs" (Sterrer, 1993) and, like bodily organs, require continuous flows of energy and material to and from "the environment" for their production and operation. It follows that in a finite world:

- Economic assessments of the human condition should be based on, or at least informed by, ecological and biophysical analyses.
- The appropriate ecological analyses focus on the flows of available energy/matter (essergy) particularly from primary producers—green plants and other photosynthesizers—to sequential levels of consumer organisms in ecosystems (specifically, humans and their economies) and on the return flows of degraded energy and material (wastes) back to the ecosystem.

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[1] According to orthodox theory, free trade is invariably good, resulting in improved living standards and increased aggregate productivity and efficiency—increased carrying capacity—through comparative advantage.

This approach shows that humankind, through the industrial economy, has become the dominant consumer in most of the Earth's major ecosystems. We currently "appropriate" 40% of the net product of terrestrial photosynthesis (Vitousek *et al.*, 1986) and 25-35% of coastal shelf primary production (Pauly & Christensen, 1995), and these may be unsustainable proportions.[2] At the same time some global waste sinks seem full to overflowing.

A fundamental question for *ecological* economics, therefore, is whether the physical output of remaining species populations, ecosystems, and related biophysical processes (i.e., critical self-producing natural capital stocks—see Box 1), and the waste assimilation capacity of the ecosphere, are adequate to sustain the anticipated load of the human economy into the next century while simultaneously maintaining the general life support functions of the ecosphere. This "fundamental question" is at the heart of ecological carrying capacity but is virtually ignored by mainstream analyses.

## *Second Law Arguments*

A related rationale for revisiting carrying capacity flows from consideration of the Second Law of Thermodynamics. In particular, modern formulations of the second law suggest that all highly-ordered systems develop and grow (increase their internal order) "at the expense of increasing disorder at higher levels in the systems hierarchy" (Schneider & Kay, 1992). In other words, complex dynamic systems remain in a nonequilibrium state through the continuous dissipation of available energy and material (essergy) extracted from their host environments. They require a constant input of energy/matter to maintain their internal order in the face of spontaneous entropic decay. Such self-organising nonequilibrium systems are therefore called "dissipative structures."

### Box 1: On Natural Capital

**Natural capital refers to "a stock [of natural assets] that yields a flow of valuable goods and services into the future." For example, a forest or a fish stock can provide a flow or harvest that is potentially sustainable year after year. The stock that produces this flow is "natural capital" and the sustainable flow is "natural income." Natural capital also provides such services as waste assimilation, erosion and flood control, and protection from ultra-violet radiation (the ozone layer is a form of natural capital). These life support services are also counted as natural income. Since the flow of services from ecosystems often requires that they function as intact systems, the structure and diversity of the system may be an important component of natural capital.**

**There are three broad classes of natural capital: *Renewable* natural capital, such as living species and ecosystems, is self-producing and self-maintaining using solar energy and photosynthesis. These forms can yield marketable goods such as wood fibre, but may also provide unaccounted essential services when left in place (e.g., climate regulation). *Replenishable* natural capital, such as groundwater and the ozone layer, is non-living but is also often dependent on the solar "engine" for renewal. Finally, *non-renewable* natural capital such as fossil fuel and minerals, are are analogous to inventories – any use implies liquidating part of the stock.**

**This article takes the position that since adequate stocks of self-producing and replenishable natural capital are essential for life support (and are generally non-substitutable), these forms are more important to sustainability than are non-renewable forms.**

Source: Rees (1995), liberally adapted from Costanza and Daly (1992).

This extension of the second law is critical to human carrying capacity. Consider that:

- The human economy is one such highly-ordered, dynamic, far-from-equilibrium dissipative structure. At the same time . . .
- The economy is an open, growing, subsystem of a materially closed, nongrowing ecosphere (Daly, 1992), and is therefore dependent on the formation of essergy in the ecosphere for its growth and development.[3]

This relationship implies that beyond a certain point, the continuous growth of the economy can be purchased only at the expense of increasing disorder or entropy in the ecosphere. This is the point at which consumption by the economy exceeds natural income and would be manifested through the continuous depletion of natural capital—reduced biodiversity, air/water/land pollution, deforestation, atmospheric change, etc. In other words, the empirical evidence suggests that the aggregate human load already exceeds, and is steadily eroding, the very carrying capacity upon which the continued humane existence depends. Ultimately this poses the threat of unpredictable ecosystems restructuring (e.g., erratic climate change) leading to resource shortages, increased local strife, and the heightened threat of ecologically induced geopolitical instability.

In this light, the behavior of complex systems and the role of the economy in the global thermodynamic hierarchy should be seen as fundamental to sustainability, yet both concepts are alien to the dominant development-oriented institutions in the world today.

## *Why Economics Cannot Cope*

Part of the reason for this perceptual gulf is that many of the questions raised by ecological and thermodynamic considerations are invisible to mainstream approaches. Economic analysis is based on the circular flow of exchange value (money flows) through the economy, not on physical flows

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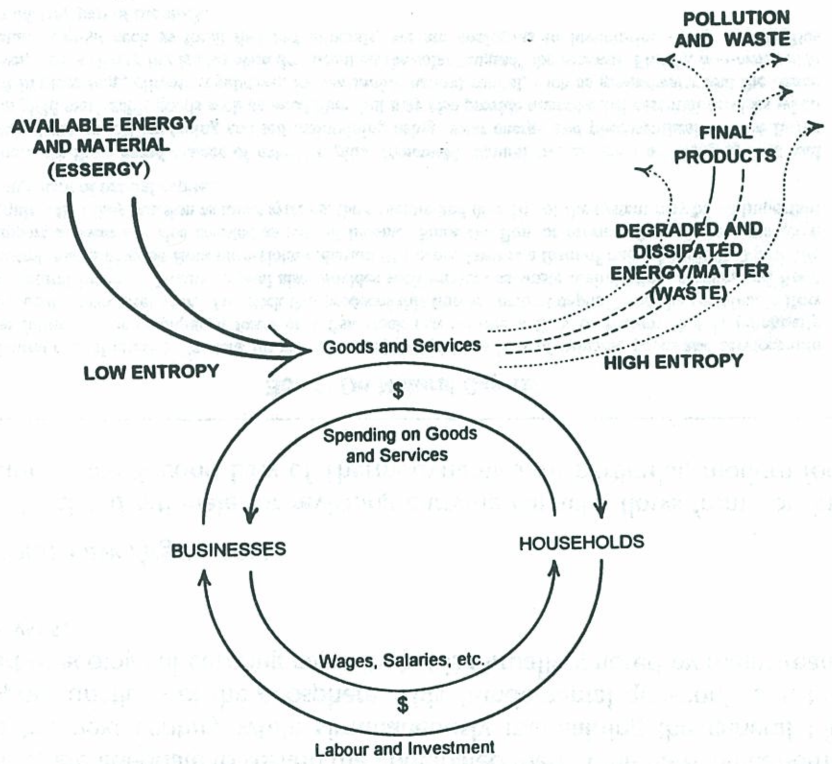
[2] Global fisheries yields have fallen since 1989.

[3] This input to the economy from nature is the "natural income" referred to in Box 1.

**FIGURE 1.** The linear throughput of energy/matter.



The linear throughput of low-entropy energy and matter (upper part of diagram) sustains the economy and drives the circular flows of exchange value (lower part of diagram), yet is invisible to conventional economic analysis.

Source: Rees (1995).

and transformations. Prevailing economic models of growth and sustainability thus "lack any representation of the materials, energy sources, physical structures, and time-dependent processes basic to an ecological approach" (Christensen, 1991). Thus while, the second law is arguably the ultimate governor of economic activity, standard models do not recognize the unidirectional and thermodynamically irreversible flux of available energy and matter upon which the economy depends (Figure 1). Similarly, conventional approaches to conservation and sustainability focus mainly on the money values of marketable resource commodities (e.g., timber) and are insensitive to the intangible (but ultimately more valuable) nonmarket ecological functions of the natural capital that produces them (e.g., the forest ecosystem). Box 2 summarizes this problem.

### Box 2: The Blind Spot in Conventional Analysis

- **Mainstream economics approaches the issue of adequate capital stocks through monetary analysis. However, money and prices are excessively abstracted from the material wealth they are supposed to represent. For example:**
- **Where there are markets for ecologically significant "goods and services," prices do not reflect the size of the corresponding natural capital stocks, whether there are critical minimal levels below which stocks can no longer replenish themselves (the real measure of biophysical scarcity), the functional roles of such stocks in relevant ecosystems, or their ultimate value in sustaining life. Meanwhile...**
- **Many ecological goods and most life-support services remain unpriced and therefore not subject to market signals or related behavioral change of *any* kind. (The ozone layer is a case in point.)**
- **Unfortunately, current efforts to "internalise the externalities," "get the prices right" and otherwise commodify the environment suffer from major data gaps, the functional transparency of natural processes (we don't know they're valuable until they're gone), and other theoretical problems that often render futile attempts to quantify, let alone price, many critical ecological goods and services (Vatn and Bromley 1993). In short...**
- **Standard monetary analyses are blind to ecological structure and function and are therefore incapable of indicating either ecologically meaningful scarcity or incipient systems destabilisation.**

In this light, economists' lack of concern about carrying capacity would seem to derive, in large part, from conceptual weaknesses in their analytic models. The necessary conditions for ecological sustainability can better be defined through the analysis of physical stocks and flows interpreted in light of appropriate ecological and complex systems theory.

## *Technology and Trade: No Boon to Carrying Capacity*

As previously noted, conventional analysts often argue that trade and technology expand ecological carrying capacity. This is a misconception. Even in the best of circumstances, technological innovation does not increase carrying capacity *per se* but only the efficiency of resource use. In theory, shifting to more energy- and material-efficient technologies should enable a defined environment to support a given population at a higher material standard, or a higher population at the same material standard, thereby seeming to increase carrying capacity. However, in either case, the best we could hope for in an increasingly open global economy would be to maintain total human load constant in the vicinity of carrying capacity—the latter would still ultimately be limiting.

In practice, we have not done even this well—the steady gains in efficiency throughout the post-war period have been accompanied by steadily increasing *per capita* and aggregate consumption. It seems that efficiency gains may actually work *against* conservation through the price and income effects of technological savings.

As Saunders (1992) notes, this counterintuitive hypothesis has been the focus of considerable controversy. He tested it using neoclassical growth theory and found that energy efficiency gains might well increase aggregate energy consumption by making energy cheaper and by stimulating economic growth, which further "pulls up" energy use. How might this work? If a firm saves money by switching to more energy- and material-efficient manufacturing processes, it will be able to raise wages, increase dividends, or lower prices, which can lead to increased net consumption by workers, shareholders, or consumers respectively. These behavioral responses to changes in prices and income are referred to as the "rebound effect" by economists (Jaccard, 1991). Similarly, technology-induced money savings by individuals are usually redirected to alternative forms of consumption, canceling some or all of the initial potential benefit to the environment (Hannon, 1975). To the extent that such mechanisms contribute to increased aggregate material consumption and accelerated stock depletion, they indirectly *reduce* carrying capacity.[4]

More generally, however, technology can directly reduce carrying capacity while creating the illusion of increasing it! We often use technology to increase the short-term energy and material flux through exploited ecosystems. This seems to enhance systems productivity while actually permanently eroding the resource base. For example, the effectiveness of electronic fish-finding devices and high-tech catching technology has overwhelmed the reproductive capacity of fish stocks; energy-subsidized intensive agriculture may be more productive than low-input practices in the short term, but it also increases the rate of soil and water depletion. The net effect is to create unsustainable dependencies on enhanced material flows (the technologies involved are often based on nonrenewable resources) while reducing longterm carrying capacity.

The carrying capacity gains from trade are also illusory. While commodity trade may release a local population from carrying capacity constraints in its own home territory, this merely displaces some fraction of that population's environmental load to distant export regions. In effect, local populations import others' "surplus" carrying capacity. The resultant increase in population and resource use in import regions increases the aggregate load of humanity on the ecosphere but there is *no net gain* in carrying capacity since trade reduces the load-bearing capacity of the export regions. Indeed, like technology, trade may even result in reduced global carrying capacity if access to cheap imports (e.g., food) lowers the incentive for people to conserve their own local natural capital stocks (e.g., agricultural land) and leads to the accelerated depletion of natural capital in distant export regions.

These comments are not to be taken as arguments against technology or trade *per se*. Rather the point is to emphasize that conventional assumptions about both should be carefully reexamined in light of carrying capacity considerations and that certain conditions must be satisfied before either can contribute to ecological sustainability.

## APPROPRIATED CARRYING CAPACITY AND ECOLOGICAL FOOTPRINTS

We can now redefine human carrying capacity as the maximum rates of resource harvesting and waste generation (the maximum load) that can be sustained indefinitely without progressively impairing the productivity and functional integrity of relevant ecosystems wherever the latter may be located. The size of the corresponding population would be a function of technological sophistication and mean *per capita* material standards (Rees, 1988). This definition reminds us that regardless of the state of technology, humankind depends on a variety of ecological goods and services provided by nature and that for sustainability, these must be available in increasing quantities from somewhere on the planet as population and mean *per capita* resource consumption increase (see also Overby, 1985).

Now, as noted earlier, a fundamental question for ecological economics is whether supplies of natural capital will be adequate to meet anticipated demand into the next century. Inverting the standard carrying capacity ratio suggests a powerful way to address this critical issue. Rather than asking what population a particular region can support sustainably, the carrying capacity question becomes: How large an area of productive land is needed to sustain a defined population indefinitely, *wherever on Earth that land is located?* (Rees, 1992; Rees & Wackernagel, 1994; Wackernagel & Rees, 1995). Since many forms of natural income (resource and service flows) are produced by terrestrial ecosystems and associated water bodies, it should be possible to estimate the area of land/water required to produce sustainably the quantity of any resource or ecological service used by a defined population at a given level of technology. The sum of such calculations for all significant categories of consumption

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[4] Rebound effects can be avoided if adequate stock depletion taxes or marketable resource quotas are imposed. (Such incentives should be used to stimulate conservation in the first place.) "Ecological taxation" would raise unit resource prices, effectively capturing any efficiency savings and preventing their further circulation in the economy. However, because of reduced material and energy intensity, consumer prices for goods and services would increase less rapidly than resource prices (Rees, 1994a).

would give us a conservative area-based estimate of the natural capital requirements for that population.

A simple mental exercise serves to illustrate the ecological reality behind this approach. Imagine what would happen to any modern human settlement or urban region, as defined by its political boundaries or the area of built-up land, if it were enclosed in a glass or plastic hemisphere completely closed to material flows. Clearly the city would cease to function and its inhabitants would perish within a few days. The population and economy contained by the capsule would have been cut off from both vital resources and essential waste sinks leaving it to starve and suffocate at the same time. In other words, the ecosystems contained within our imaginary human terrarium would have insufficient carrying capacity to service the ecological load imposed by the contained population.

This mental model illustrates the simple fact is that as a result of high population densities, the enormous increase in *per capita* energy and material consumption made possible by (and required by) technology, and universally increasing dependencies on trade, *the ecological locations of human settlements no longer coincide with their geographic locations.* Twentieth century cities and industrial regions are dependent for survival and growth on a vast and increasingly global hinterland of ecologically productive landscapes. It seems that in purely ecological terms, modern settlements have become the human equivalent of cattle feedlots!

Cities necessarily appropriate the ecological output and life support functions of distant regions all over the world through commercial trade and the natural biogeochemical cycles of energy and material. Indeed, the annual flows of natural income required by any defined population can be called its "appropriated carrying capacity." Since for every material flow there must be a corresponding land/ecosystem source or sink, the total area of land/water required to sustain these flows on a continuous basis is the true "ecological footprint" of the referent population on the Earth. (See Box 3 for definitions of these and related indicators.) Calculating its ecological footprint provides a rough measure of the natural capital requirements of any subject population for comparison with available supply.

## *"Footprinting" the Human Economy*

The first step in calculating the ecological footprint of a study population is to estimate the *per capita* land area appropriated (aa) for the production of each major consumption item 'i.' We do this by dividing average annual consumption of that item ['c,' in kg/capita] by its average annual productivity or yield ['p,' in kg/ha] per hectare:

$$aa_i = c_i/p_i$$

**Box 3: A Family of Area-based Sustainability Indicators**

- **Appropriated Carrying Capacity** - The biophysical resource flows and waste assimilation capacity appropriated per unit time from global totals by a defined economy or population.
- **Ecological Footprint** - The corresponding area of productive land and aquatic ecosystems required to produce the resources used, and to assimilate the wastes produced, by a defined population at a specified material standard of living, wherever on Earth that land may be located.
- **Personal planetoid** - The *per capita* ecological footprint ($EF_P/N$).
- **Fair Earthshare** - The amount of ecologically productive land "available" *per capita* on Earth, currently about 1.5 hectares (1995). A fair seashare (ecologically productive ocean – coastal shelves upwellings and estuaries – divided by total population) is just over .5 ha.
- **Ecological Deficit** - The level of resource consumption and waste discharge by a defined economy or population in excess of locally/regionally sustainable natural production and assimilative capacity (also, in spatial terms, the difference between that economy/population's ecological footprint and the geographic area it actually occupies)
- **Sustainability Gap** - A measure of the decrease in consumption (or the increase in material and economic efficiency) required to eliminate the ecological deficit. (Can be applied on a regional or global scale.)

In practice, it is often only possible to estimate average *per capita* consumption by dividing aggregate consumption by the referent population size. Of course, many consumption items (e.g., clothing and furniture) embody several inputs and we have found it useful to estimate the a areas appropriated by each significant input separately. Ecological footprint calculations are therefore both more complicated and more interesting than appears from the basic concept. So far we have estimated the land requirements to produce 23 categories of consumer goods and services (Wackernagel & Rees, 1995).

We then compute the total *per capita* ecological footprint ('ef') by summing all the ecosystem areas appropriated by individual items in the annual shopping basket of consumption goods and services:

$$ef = \sum_{i=1}^{i=n} aa_i$$

Thus, the ecological footprint ($EF_P$) of a study population is the *per capita* footprint multiplied by population size (N):

$$EF_P = N(ef)$$

We account for direct fossil energy consumption and the energy content of consumption items by estimating the area of carbon-sink forest that would be required to sequester the carbon dioxide emissions associated with burning fossil fuels ([carbon emissions/capita]/[assimilation rate/hectare]), on the assumption that atmospheric stability is central to sustainability. (An alternative is to estimate the area of land required to produce the biomass energy equivalent [ethanol]of fossil energy consumption. This produces a larger energy footprint than the carbon assimilation method.)

Every effort is made to avoid double-counting in the case of multiple land uses and where there are data problems or significant uncertainty we err on the side of caution. Also, while we define the footprint comprehensively to include the land/water areas required for waste assimilation, our calculations to date do not account for waste emissions other than carbon dioxide. Accounting fully for this ecological function would add considerably to the ecosystem area appropriated by economic activity. Together these factors suggest that our ecological footprint calculations to date are more likely to be under-estimates than over-estimates.

Data from my home city, Vancouver, British Columbia, Canada, serve to illustrate application of the concept. Vancouver proper has a population (1991) of 472,000 and an area of 114 km$^2$ (11,400 hectares). However, the average Canadian requires over a hectare (ha) of crop and grazing land under current land management practices to produce his/her high meat protein diet and about .6 ha for wood and paper associated with various other consumption items. In addition, each "occupies" about .2 ha of ecologically degraded and built-over (e.g., urban) land. Canadians are also among the world's highest fossil energy consumers with an annual carbon emission rate of 4.2 tonnes carbon (15.4 tonnes $CO_2$) *per capita* (data corrected for carbon content of trade goods). Therefore, at a carbon sequestering rate of 1.8 tonnes/ha/yr an additional 2.3 ha of middle-aged North temperate forest would be required as a continuous carbon sink to assimilate the average Canadian's carbon emissions (assuming the need to stabilize atmospheric carbon dioxide levels).

Considering only these data, the terrestrial "personal planetoid" of a typical Vancouverite approaches 4.2 ha, or almost three times his/her "fair Earthshare."[5] On this basis, the 472,000 people living in Vancouver require, conservatively, 2.0 million ha of land for their exclusive use to maintain their current consumption patterns (assuming such land is being managed sustainably). However, the area of the city is only about 11,400 ha. This means that the city population appropriates the productive output of a land area nearly 174 times larger than its political area to support its present consumer lifestyles.[6] While this result might seem extraordinary, other researchers have obtained similar results. Folke *et al.* (1994) report that the aggregate consumption of wood, paper, fiber, and food (including seafood) by the inhabitants of 29 cities in the Baltic Sea drainage basin appropriates an ecosystem area 200 times larger that the area of the cities themselves. (The latter study does not include energy land.)

Many whole developed countries have a similar overwhelming dependence on external ecoproductivity. The Netherlands (area: 33,920 sq km) serves to illustrate: We estimate that the people of Holland require a land area more than 14 to 15 times larger than their country to support current domestic consumption of food, forest products, and energy (Figure 2) (Rees & Wackernagel, 1994). The food footprint alone is more than 100,000 square kilometers, based on world average productivities. Indeed, Dutch government data suggest that the Netherlands appropriates 100,000 to 140,000 km$^2$ of agricultural land, mostly from the third world, for food production (including value-added food products produced in the Netherlands for export) (RIVM, 1991, cited in Meadows *et al.* 1992).[7] This "imported" land is five to seven times the area of Holland's domestic arable land.

It is worth remembering that the Netherlands, like Japan, is often held up as an economic success story and an example for the developing world to follow. Despite small size, few natural resources, and relatively large populations, both Holland and Japan enjoy high material standards and positive current account and trade balances as measured in monetary terms. However, our analysis of physical flows shows that these and most other so-called "advanced" economies are running massive, unaccounted, ecological deficits with the rest of the planet (Table 1). The last two columns in Table 1 represent low estimates of these *per capita* ecological deficits in a selection of developed countries. Even if their land were twice as productive as world averages, many European countries would still run a deficit more than three times larger than domestic natural income.

These data emphasize that all the countries listed, except for Canada, are over-populated in ecological terms—they could not sustain themselves at current material standards if forced by changing circumstances to live on

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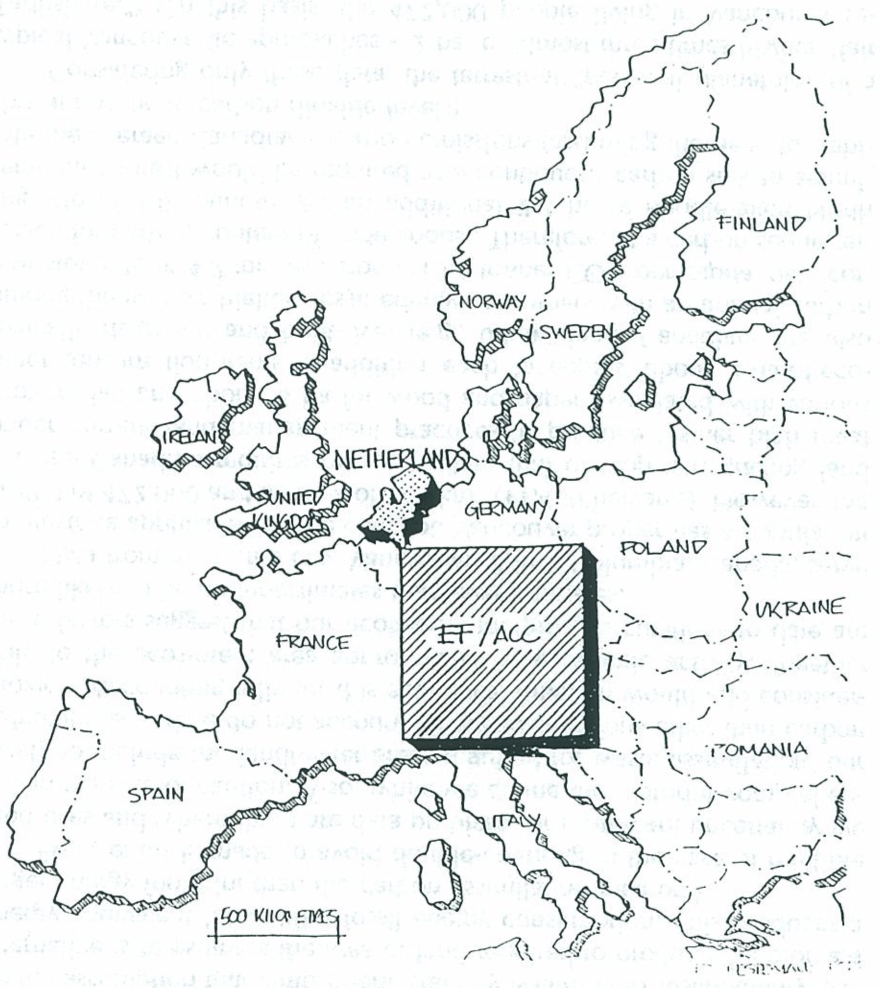
[5] An additional .74 ha of continental shelf "seascape" is appropriated to produce the average Canadian's annual consumption of 24kg of fish.

[6] The Vancouver Regional District (metropolitian area), with 1.6 million inhabitants and a land-base of 2930 km$^2$, has an ecological footprint of 6,720,000 ha, 23 times its geographic area.

[7] Most of the imported "food" is fodder for domestic livestock. This is a sufficient "Second Law" explanation of the fact that animal manure represents one of the most pressing waste disposal problems confronting the Netherlands!

**FIGURE 2.** The ecological footprint of the Netherlands.



With an area of 33,920 square kilometers and a human population density of 440/km², the Netherlands depends on the ecological productivity (carrying capacity) of an area almost 15 times larger than the entire country.

Source: Rees and Wackernagel (1994).

their remaining endowments of domestic natural capital. This is hardly a good model for the rest of the world to follow.

Canada (large area, resource rich, small population) is one of the few developed countries that consumes less than its natural income domestically. However, Canada's natural capital stocks are being depleted by exports of energy, forest, fisheries, agricultural products, etc. In short, Canada's apparent ecological surpluses are being incorporated in part by trade into the ecological footprints—and deficits—of other countries, particularly those of the United States and Japan.

## TABLE 1

### The Ecological Deficits of Industrialized Countries[1]

| Country | Ecologically Productive Land (In Hectares) a | Population (1995) b | Ecol. Productive Land *Per Capita* (In Hectares) c = a/b | National Ecological Deficit *Per Capita* (In Hectares) d = Footpr.-c | National Ecological Deficit *Per Capita* (In % Available) e = d/c |
|---|---|---|---|---|---|
| | | | | *Assuming a 2 Hectare Footprint* | |
| *Countries with 2-3 ha Footprints* | | | | | |
| Japan | 30,340,000 | 125,000,000 | 0.24 | 1.76 | 730% |
| Korea | 8,669,000 | 45,000,000 | 0.19 | 1.81 | 950% |
| | | | | *Assuming a 3 Hectare Footprint* | |
| *Countries with 3-4 ha Footprints* | | | | | |
| Austria | 6,740,000 | 7,900,000 | 0.85 | 2.15 | 250% |
| Belgium | 1,987,000 | 10,000,000 | 0.20 | 2.80 | 1,400% |
| Denmark | 3,270,000 | 5,200,000 | 0.62 | 2.38 | 380% |
| France | 45,385,000 | 57,800,000 | 0.78 | 2.22 | 280% |
| Germany | 27,734,000 | 81,300,000 | 0.34 | 2.66 | 780% |
| Netherlands | 2,300,000 | 15,500,000 | 0.15 | 2.85 | 1,900% |
| Switzerland | 3,073,000 | 7,000,000 | 0.44 | 2.56 | 580% |
| | | | | *Assuming 4.3 (Can) and 5.1 (US) Hectare* | |
| *Countries with 4-5 ha Footprints* | | | | | |
| Canada | 433,000,000 | 28,500,000 | 15.19 | (10.89) | (250%) |
| United States | 725,643,000 | 258,000,000 | 2.81 | 2.28 | 80% |

Source: Revised from Wackernagel and Rees (1995).

[1] Footprints estimated from studies by Ingo Neumann from Trier University, Germany, Dieter Zürcher from Infras Consulting, Switzerland, and our own analysis using World Resources Institute (1992) data.

## *Sustaining Development with Phantom Planets?*

Ecological deficits are a measure of the entropic load and resultant "disordering" being imposed on the ecosphere by so-called advanced countries as the unaccounted cost of maintaining and further expanding their wealthy consumer economies. This massive entropic imbalance invokes what might be called the first axiom of ecological footprint analysis: On a finite planet, not all countries or regions can be net importers of carrying capacity. This, in turn, has serious implications for global development trends.

The current objective of international development is to raise the developing world to present first world material standards. To achieve this objective, the Brundtland Commission argued for "more rapid economic growth in both industrial and developing countries" and suggested that "a five to ten fold increase in world industrial output can be anticipated by the time world population stabilizes some time in the next century" (WCED, 1987).

Let us examine this prospect using ecological footprint analysis. If just the present world population of 5.8 billion people were to live at current North American ecological standards (say 4.5 ha/person), a reasonable first approximation of the total productive land requirement would be 26 billion ha (assuming present technology). However, there are only just over 13 billion ha of land on Earth, of which only 8.8 billion are ecologically productive cropland, pasture, or forest (1.5 ha/person). In short, we would need an additional two planet Earths to accommodate the increased ecological load of people alive today. If the population were to stabilize at between 10 and 11 billion sometime in the next century, five additional Earths would be needed, all else being equal—and this just to maintain the present rate of ecological decline (Rees & Wackernagel, 1994).

While this may seem to be an astonishing result, empirical evidence suggests that five phantom planets is, in fact, a considerable underestimate (keep in mind that our footprint estimates are conservative). Global and regional-scale ecological change in the form of atmospheric change, ozone depletion, soil loss, ground water depletion, deforestation, fisheries collapse, loss of biodiversity, etc., is accelerating. This is direct evidence that aggregate consumption exceeds natural income in certain critical categories and that the carrying capacity of this one Earth is being steadily eroded.[8] In short, the ecological footprint of the present world population/economy already exceeds the total productive area (or ecological space) available on Earth.

This situation is, of course, largely attributable to consumption by that wealthy quarter of the world's population who use 75% of global resources. The WCED's "five- to ten-fold increase in industrial output" was deemed necessary to address this obvious inequity while accommodating a much larger population. However, since the world is already ecologically full, sustainable growth on this scale using present technology would require at five to ten additional planets.

## ADDRESSING THE DOUBLE-BIND OF SUSTAINABILITY

Humankind now seems to be the victim of a global "catch-22" of its own making. More material growth, at least in the poor countries, seems essential for socioeconomic sustainability, yet any global increase in material throughput is ecologically unsustainable. What does ecological footprint analysis have to say about this double bind and how we might get out of it? One can draw several conclusions from the above analysis that address one or both sides of the dilemma:

- The wealthy already consume on average three times their fair share of sustainable global output. Since additional material growth in rich countries would appropriate additional carrying capacity further reducing the ecological space available to poor countries, it is both ecologically dangerous and morally questionable. To the extent we can create room for growth, it should be allocated to the third world.
- Confidence in the ability of unregulated trade and technology to overcome ecological limits on material growth cannot be justified. Indeed, it is arguable that under prevailing assumptions, expanding trade and dominant technologies are allowing humanity dangerously to overshoot long-term global carrying capacity.
- Trade has been a major contributor to increasing gross world product in recent years. However: a) trade is one of the mechanisms by which the rich appropriate carrying capacity and increase their own ecological footprints, and b) to the extent that trade increases total human load on the ecosphere and accelerates the depletion of natural capital, it reduces the ecological safety net for all and brings us closer to global limits. Global terms of trade must therefore be reexamined to ensure that it is equitable, socially constructive, and confined to true ecological surpluses. At the very least, prices must reflect ecological externalities and the benefits of growth from trade should flow to those who need them most (see Rees, 1994b).
- On a finite planet, ecological trade is a zero-sum game—there can be no net importation of carrying capacity for the world as a whole. Ecological footprint analysis provides a useful tool for the development of regional ecological (i.e., physical) accounts. These would assist coun-

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[8] We should remember Liebigs "Law of the Minimum" in this context. The productivity and ultimately the survival of any complex system dependent on numerous essential inputs or sinks is limited by that single variable in least supply.

tries or (bio-)regions to compute their true ecological loads on the ecosphere and to monitor their ecological/thermodynamic trade balances. Such accounts would also enable the world community to ensure that aggregate global flows do not exceed sustainable natural income (global carrying capacity).

- Urbanization, globalization, and trade all reduce the negative feedback on local populations from unsustainable land and resource management practices. (For example, trade enables us to discount the value of local natural capital and blinds us to the negative consequences of our over-consumption which often accrue in distant export regions.) This provides a further argument to shift the emphasis in development from global economic integration and inter-regional dependency toward intra-regional ecological balance and relative self-reliance. (If all regions were in ecological steady-state the aggregate effect would be global stability.) This position is compatible with Daly's and Goodland's (1993) recommended alternative "default position" on international trade, that we should strive "to reduce rather than increase the entanglement between nations."
- Ecological footprint analysis supports the argument that to be sustainable, economic growth must be much less material and energy intensive than at present (see, for example, Pearce, 1994). It therefore supports the case for ecological tax reform in aid of resource conservation (von Weizsäcker, 1994). For example, depletion taxes and marketable quotas on natural capital inputs to the economy would: a) stimulate the search for more materially and energy efficient technologies; b) preempt any resultant cost savings, thereby preventing the economic benefits of efficiency gains from being redirected to additional or alternative forms of consumption, and; c) generate an investment fund that could be used to rehabilitate important forms of self-producing natural capital (Rees, 1994a).
- Ecological footprint analysis provides a measure of both individual countries' ecological deficits and the global sustainability gap (Box 3). The latter in particular is a measure of the extent to which the human economy must be dematerialized in order to fit within global carrying capacity. The present and related analyses confirm that a "factor-10" reduction in the material and energy intensity per unit of economic service, as suggested by researchers at the Wuppertal Institute in Germany (Schmidt-Bleek, 1993a;b), is a reasonable if daunting goal.[9]

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[9] "Reasonable" because a reduction in throughput of this magnitude seems necessary, "daunting" because a reduction of this magnitude through material efficiency alone seems impossible, at least within in the next few decades. Sustainability may require that competitive individualism and the consumer lifestyle give way to cooperative mutualism and an economy of sufficiency.

## CONCLUSION

Appropriated carrying capacity and ecological footprint analysis provide several informative area-based indicators of sustainability. Unfortunately, these same indicators reveal that we are presently falling distressingly short of achieving that elusive goal. Such findings do not, however, support a counsel of despair. Rather, ecological footprint analysis raises a cautionary signal, suggests a variety of concrete sustainability guidelines, and supports a broadly-based program of reforms that could redirect us in the direction we all seem to want to go. In short, to the extent that the assumptions and prescriptions of this approach are a better reflection of material reality that those of mainstream models, the present analysis is a good news story. The bad news is that most of the world seems committed as never before to the well-worn expansionist path.

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# HOW MANY PEOPLE CAN THE EARTH SUPPORT?

*The answers depend as much on social, cultural, economic and political choices as they do on constraints imposed by nature*

### BY JOEL E. COHEN

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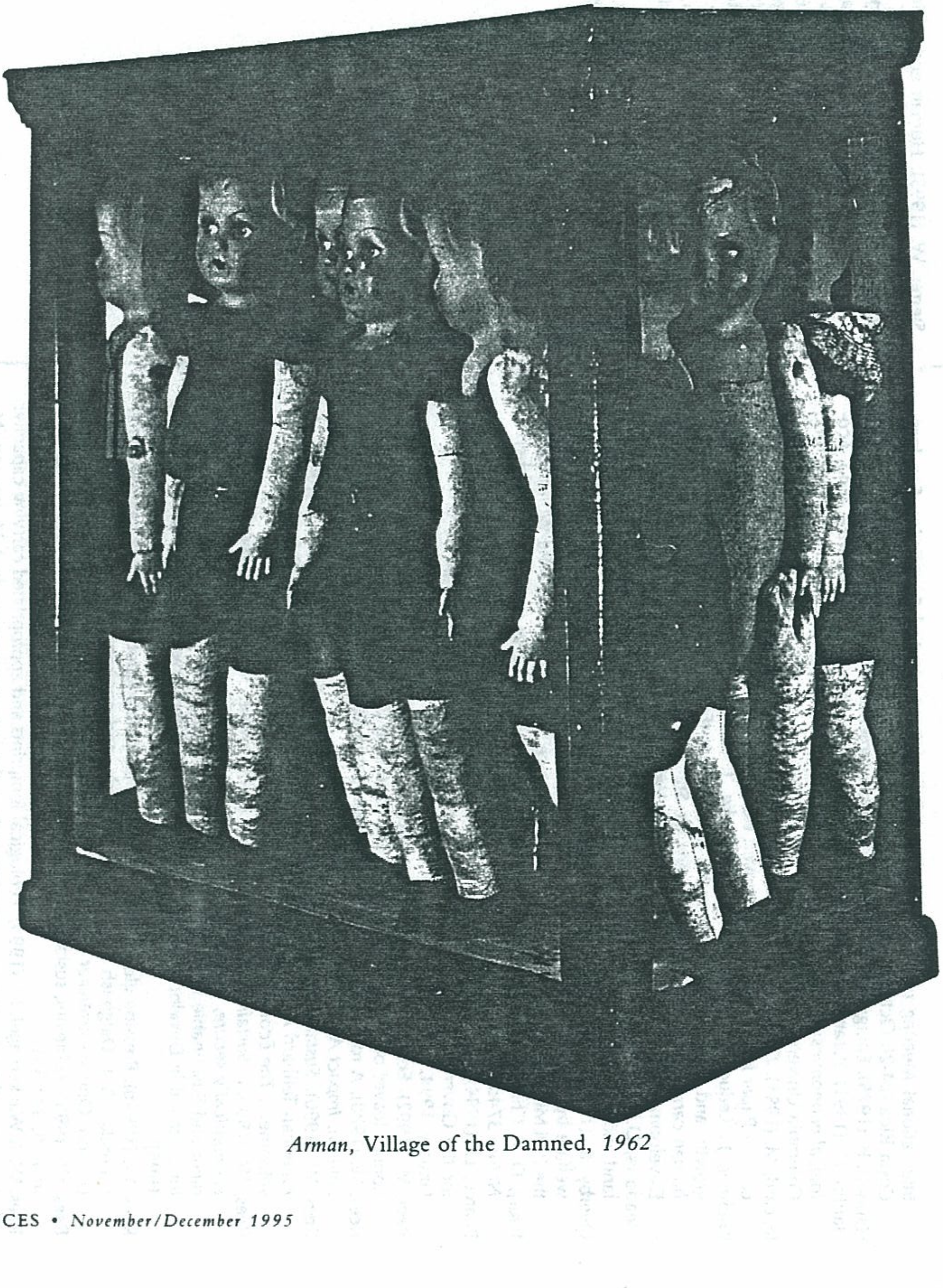

*Arman,* Village of the Damned, *1962*

On April 25, 1679, in Delft, Holland, the inventor of the microscope, Antoni van Leeuwenhoek, wrote down what may be the first estimate of the maximum number of people the earth can support. If all the habitable land in the world had the same population density as Holland (at that time about 120 people for every square kilometer), he calculated, the earth could support at most 13.4 billion people—far fewer than the number of spermatozoans his lenses had revealed in the milt of a cod.

In subsequent centuries, van Leeuwenhoek's estimate has been followed by dozens of similar calculations. Around 1695 a Londoner named Gregory King estimated that the earth's "Land If fully Peopled would sustain" at most 12.5 billion people. In 1765 a German regimental pastor, Johann Peter Süssmilch, compared his own figure (13.9 billion) with the estimates of van Leeuwenhoek, the French military engineer Sébastien Le Prestre de Vauban (5.5 billion) and the English writer and cartographer Thomas Templeman (11.5 billion).

In recent decades estimates of maximum population have appeared thicker and faster than ever before. Under the rubric of "carrying capacity" they crop up routinely in environmental debates, in United Nations reports and in papers by scholars or academic politicians trained in ecology, economics, sociology, geography, soil science or agronomy, among other disciplines. Demographers, however, have been strangely silent. Of the more than 200 symposiums held at the 1992 and 1993 annual meetings of the Population Association of America, not one session dealt with estimating or defining human carrying capacity for any region of the earth. Instead, professional demographers tend to focus on the composition and growth of populations, restricting their predictions to the near term—generally a few decades into the future—and framing them in conditional terms: *If* rates of birth, death and migration (by age, sex, location, marital status and so on) are such-and-such, *then* population size and distribution will be so-and-so.

Such conditional predictions, or forecasts, can be powerful tools. Projections by the U.N. show dramatically that *if* human populations continued to grow at 1990 rates in each major region of the world, *then* the population would increase more than 130-fold in 160 years, from about 5.3 billion in 1990 to about 694 billion in 2150. Those figures are extremely sensitive to the future level of average fertility. If, hypothetically, from 1990 onward the average couple gradually approached a level of fertility just one-tenth of a child more than required to replace themselves, world population would grow from 5.3 billion in 1990 to 12.5 billion in 2050 and 20.8 billion in 2150. In contrast, if (again hypothetically) starting in 1990 and ever after couples bore exactly the number of children needed to replace themselves, world population would grow from 5.3 billion in 1990 to 7.7 billion in 2050 and would level off at around 8.4 billion by 2150.

> If populations *continue to grow at 1990 rates, the world population will increase to 694 billion by the year 2150.*

The clear message is that people cannot forever continue to have, on average, more children than are required to replace themselves. That is not an ideological slogan; it is a hard fact. Conventional agriculture cannot grow enough food for 694 billion people; not enough water falls from the skies. The finiteness of the earth guarantees that ceilings on human numbers do exist.

Where are those ceilings? Some people believe that any limit to human numbers is so remote that its existence is irrelevant to present concerns. Others declare that the human population has already exceeded what the earth can support in the long run (how long is usually left unspecified). Still others concede that short-term limits may exist, but they argue that technologies, institutions and values will adapt in unpredictable ways to push ceilings progressively higher so that they recede forever. The differences of opinion are buttressed by vast disparities in calculation. In the past century, experts of various stripes have made estimates of human carrying capacity ranging from less than a billion to more than 1,000 billion. Who, if anybody, is right?

For several years I have been trying to understand the question, "How many people can the earth support?" and the answers to it. In the process I came to question the question. "How many people can the earth support?" is not a question in the same sense as "How old are you?"; it cannot be answered by a number or even by a range of numbers. The earth's capacity to support people is determined partly by processes that the social and natural sciences have yet to understand, partly by choices that we and our descendants have yet to make.

In most of its scientific senses, *carrying capacity* refers to a population of wild animals within a particular ecosystem. One widely used ecology textbook defines it as follows: "Number of individuals in a population that the resources of a habitat can support; the asymptote, or plateau, of the logistic and other sigmoid equations for population growth." Even within ecology, the concept of carrying capacity has important limitations. It applies best under stable conditions and over relatively short spans of time. In the real world, climates and habitats fluctuate and change; animals adapt to their conditions and eventually evolve into new species. With each change, the carrying capacity changes, too.

When applied to human beings, the concept becomes vastly more volatile. I have collected twenty-six definitions of human carrying capacity, all published since 1975. Most of them agree on a few basic points—for instance, that the concept refers to the number of people who can be supported for some period (usually not stated) in some mode of life considered plausible or desirable. Most of the definitions recognize that ecological concepts of carrying capacity must be extended to allow for the role of technology. Most also agree that culturally and individually variable standards of living, including standards of environmental quality, set limits on population size well before the physical requirements for sheer subsistence start to become an issue.

In other respects, however, the definitions vary widely or even contradict one another. How long must a population be sustainable? Does it make sense to speak of local or regional carrying capacity—or do trade and the need for inputs from outside any specified region imply that only a global scale will do? More fundamental, how constraining are constraints? Some definitions deny the existence of any finite carrying capacity altogether, holding that human ingenuity will win out over any natural barriers; others acknowledge that the limits are real but recognize that human choices, now and in the future, will largely decide where those limits fall.

IN MY OPINION, THAT LAST POINT—THE INTERplay of natural constraints and human choices—is the key to making sense of human carrying capacity. The deceptively simple question "How many people can the earth support?" hides a host of thorny issues:

*Ex-Voto Statuettes, Byblos, Eighteenth Century* B.C.

### How many people at what average level of material well-being?

THE HUMAN CARRYING CAPACITY OF THE EARTH WILL OBviously depend on the typical material level at which people choose to live. Material well-being includes food (people choose variety and palatability, beyond the constraints imposed by physiological requirements); fiber (people choose cotton, wool or synthetic fibers for clothing, wood pulp or rag for paper); water (tap water or Perrier or the nearest river or mud hole for drinking, washing, cooking and watering your lawn, if you have one); housing (Auschwitz barracks, two men to a plank, or Thomas Jefferson's Monticello); manufactured goods; waste removal (for human, agricultural and industrial wastes); natural-hazard protection (against floods, storms, volcanoes and earthquakes); health (prevention, cure and care); and the entire range of amenities such as education, travel, social groups, solitude, the arts, religion and communion with nature. Not all of those features are captured well by standard economic measures.

### How many people with what distribution of material well-being?

AN ECOLOGIST, AN ECONOMIST AND A STATISTICIAN WENT bow hunting in the woods and spied a deer. The ecologist shot first, and his arrow landed five meters to the left of the deer. The economist shot next, and her arrow landed five meters to the right of the deer. The statistician looked at both arrows, looked at the deer, and jumped up and down shouting: "We got it! We got it!"

Estimates of human carrying capacity rarely take into account the scatter or distribution of material well-being throughout a population. Yet paying attention to average well-being while ignoring the distribution of well-being is like using an average arrow to kill a deer. People who live in extreme poverty may not know or care that the global average is satisfactory, and the press of present needs may keep them from taking a long-term view. For example, thanks to genetic engineering, any country with a few Ph.D.'s in molecular plant biology and a modestly equipped laboratory can insert the genes to create stronger, more disease-resistant, higher-yielding plants. If every region has the scientific and technical resources to improve its own crop plants, the earth can support more people than it can if some regions are too poor to help themselves.

### How many people with what technology?

THE COMPLEXITIES OF TECHNOLOGICAL CHOICES OFTEN disappear in heated exchanges between environmental pessimists and technological optimists:

ECOLOGIST: When a natural resource is being consumed faster than it is being replenished or recycled, an asset is being depleted, to the potential harm of future generations.

TECHNOLOGIST: If new knowledge and technology can produce an equivalent or superior alternative, then future generations may turn out to be better off.

TAXPAYER: Which natural resources can be replaced by technology yet to be invented, and which cannot? Will there be enough time to develop new technology and put it to work on the required scale? Could we avoid future problems, pain and suffering by making other choices now about technology or ways of living? [*No answer from ecologist or technologist.*]

The key to the argument is time. As Richard E. Benedick, an officer of the U.S. Department of State who has also served with the World Wildlife Fund, worried:

> While it is true that technology has generally been able to come up with solutions to human dilemmas, there is no guarantee that ingenuity will always rise to the task. Policymakers must contend with a nagging thought: what if it does not, or what if it is too late?

### How many people with what domestic and international political institutions?

POLITICAL ORGANIZATION AND EFFECTIVENESS AFFECT human carrying capacity. For example, the United Nations Development Program estimated that developing countries could mobilize for development as much as $50 billion a year (an amount comparable to all official development assistance) if they reduced military expenditures, privatized public enterprises, eliminated corruption, made development priorities economically more rational and improved national governance. Conversely, population size, distribution and composition affect political organization and effectiveness.

How will political institutions and civic participation evolve with increasing numbers of people? As numbers increase, what will happen to people's ability to participate effectively in the political system?

What standards of personal liberty will people choose?

How will people bring about political change within existing nations? By elections and referendums, or by revolution, insurrection and civil war? How will people choose to settle differences between nations, for instance, over disputed borders, shared water resources or common fisheries? War consumes human and physical resources. Negotiation consumes patience and often requires compromise. The two options impose different constraints on human carrying capacity.

### How many people with what domestic and international economic arrangements?

WHAT LEVELS OF PHYSICAL AND HUMAN CAPITAL ARE ASsumed? Tractors, lathes, computers, better health and better education all make workers in rich countries far more productive than those in poor countries. Wealthier workers make more wealth and can support more people.

What regional and international trade in finished goods and mobility in productive assets are permitted or encouraged? How will work be organized? The invention of the factory organized production to minimize idleness in the use of labor, tools and machines. What new ways of organizing work should be assumed to estimate the future human carrying capacity?

### How many people with what domestic and international demographic arrangements?

ALMOST EVERY ASPECT OF DEMOGRAPHY (BIRTH, DEATH, age structure, migration, marriage, and family structure) is subject to human choices that will influence the earth's human carrying capacity.

A stationary global population will have to choose between a long average length of life and a high birthrate. It must also choose between a single average birthrate for all regions, on the one hand, and a demographic specialization of labor on the other (in which some areas have fertility above their replacement level, whereas other areas have fertility below their replacement level).

Patterns of marriage and household formation will also influence human carrying capacity. For example, the public resources that have to be devoted to the care of the young and the aged depend on the roles played by families.

POLICY MAKERS MUST WONDER:
*Will new technology*
*always save the day?*
*What if it arrives too late?*

In China national law requires families to care for and support their elderly members; in the United States each elderly person and the state are largely responsible for supporting that elderly person.

### How many people in what physical, chemical and biological environments?

WHAT PHYSICAL, CHEMICAL AND BIOLOGICAL ENVIRONMENTS will people choose for themselves and for their children? Much of the heat in the public argument over current environmental problems arises because the consequences of present and projected choices and changes are uncertain. Will global warming cause great problems, or would a global limitation on fossil-fuel consumption cause greater problems? Will toxic or nuclear wastes or ordinary sewage sludge dumped into the deep ocean come back to haunt future generations when deep currents well up in biologically productive offshore zones, or would the long-term effects of disposing of those wastes on land be worse? The choice of particular alternatives could materially affect human carrying capacity.

### How many people with what variability or stability?

HOW MANY PEOPLE THE EARTH CAN SUPPORT DEPENDS ON how steadily you want the earth to support that population. If you are willing to let the human population rise and fall, depending on annual crops, decadal weather patterns and long-term shifts in climate, the average population with ups and downs would include the peaks of population size, whereas the guaranteed level would have to be adjusted to the level of the lowest valley. Similar reasoning applies to variability or stability in the level of well-being; the quality of the physical, chemical and biological environments; and many other dimensions of choice.

### How many people with what risk or robustness?

HOW MANY PEOPLE THE EARTH CAN SUPPORT DEPENDS ON how controllable you want the well-being of the population to be. One possible strategy would be to maximize numbers at some given level of well-being, ignoring the risk of natural or human disaster. Another would be to accept a smaller population size in return for increased control over random events. For example, if you settle in a previously uninhabited hazardous zone (such as the flood plain of the Mississippi River or the hurricane-prone coast of the southeastern U.S.), you demand a higher carrying capacity of the hazardous zone, but you must accept a higher risk of catastrophe. When farmers do not give fields a fallow period, they extract a higher carrying capacity along with a higher risk that the soil will lose its fertility (as agronomists at the International Rice Research Institute in the Philippines discovered to their surprise).

### How many people for how long?

HUMAN CARRYING CAPACITY DEPENDS STRONGLY ON THE time horizon people choose for planning. The population that the earth can support at a given level of well-being for twenty years may differ substantially from the population that can be supported for 100 or 1,000 years.

The time horizon is crucial in energy analysis. How fast oil stocks are being consumed matters little if one cares only about the next five years. In the long term, technology can change the definition of resources, converting what was useless rock to a valuable resource; hence no one can say whether industrial society is sustainable for 500 years.

IN PRACTICE, RELIGION *does not seem to be decisive in setting average levels of fertility for Roman Catholics.*

Some definitions of human carrying capacity refer to the size of a population that can be supported indefinitely. Such definitions are operationally meaningless. There is no way of knowing what human population size can be supported indefinitely (other than zero population, since the sun is expected to burn out in a few billion years, and the human species almost certainly will be extinct long before then). The concept of indefinite sustainability is a phantasm, a diversion from the difficult problems of today and the coming century.

### How many people with what fashions, tastes and values?

HOW MANY PEOPLE THE EARTH CAN SUPPORT DEPENDS ON what people want from life. Many choices that appear to be economic depend heavily on individual and cultural values. Should industrial societies use the available supplies of fossil fuels in households for heating and for personal transportation, or outside of households to produce other goods and services? Do people prefer a high average wage and low employment or a low average wage and high employment (if they must choose)?

Should industrial economies seek now to develop renewable energy sources, or should they keep burning fossil fuels and leave the transition to future generations? Should women work outside their homes? Should economic analyses continue to discount future income and costs, or should they strive to even the balance between the people now living and their unborn descendants?

I am frequently asked whether organized religion, particularly Roman Catholicism, is a serious obstacle to the decline of fertility. Certainly in some countries, church policies have hindered couples' access to contraception and have posed obstacles to family planning programs. In practice, however, factors other than religion seem to be decisive in setting average levels of fertility for Roman Catholics. In 1992 two Catholic countries, Spain and Italy, were tied for the second- and third-lowest fertility rates in the world. In largely Catholic Latin America, fertility has been falling rapidly, with modern contraceptive methods playing a major role. In most of the U.S. the fertility of Catholics has gradually converged with that of Protestants, and polls show that nearly four-fifths of Catholics think that couples should make up their own minds about family planning and abortion.

Even within the church hierarchy, Catholicism shelters a diversity of views. On June 15, 1994, the Italian bishops' conference issued a report stating that falling mortality and improved medical care "have made it unthinkable to sustain indefinitely a birthrate that notably exceeds the level of two children per couple." Moreover, by promoting literacy for adults, education for children and the survival of infants in developing countries, the church has helped bring about some of the social preconditions for fertility decline.

On the whole the evidence seems to me to support the view of the ecologist William W. Murdoch of the University of California, Santa Barbara: "Religious beliefs have only small, although sometimes significant, effects on family size. Even these effects tend to disappear with rising levels of well-being and education."

IN SHORT, THE QUESTION "HOW MANY PEOPLE can the earth support?" has no single numerical answer, now or ever. Human choices about the earth's human carrying capacity are constrained by facts of nature and may have unpredictable consequences. As a result, estimates of human carrying capacity cannot aspire to be more than conditional and probable: if future choices are thus-and-so, then the human carrying capacity is likely to be so-and-so. They cannot predict the constraints or possibilities that lie in the future; their true worth may lie in their role as a goad to conscience and a guide to action in the here and now.

The following beautiful quotation from *Principles of Political Economy,* by the English philosopher John Stuart Mill, sketches the kind of shift in values such action might entail. When it was written, in 1848, the world's population was less than one-fifth its present size.

*Sandy Skoglund,* Maybe Babies, *1983*

There is room in the world, no doubt, and even in old countries, for a great increase of population, supposing the arts of life to go on improving, and capital to increase. But even if innocuous, I confess I see very little reason for desiring it. The density of population necessary to enable mankind to obtain, in the greatest degree, all the advantages both of cooperation and of social intercourse, has, in all the most populous countries, been obtained. A population may be too crowded, though all be amply supplied with food and raiment. It is not good for man to be kept perforce at all times in the presence of his species. A world from which solitude is extirpated, is a very poor ideal. . . . Nor is there much satisfaction in contemplating the world with nothing left to the spontaneous activity of nature; with every rood of land brought into cultivation, which is capable of growing food for human beings; every flowery waste or natural pasture ploughed up, all quadrupeds or birds which are not domesticated for man's use exterminated as his rivals for food, every hedgerow or superfluous tree rooted out, and scarcely a place left where a wild shrub or flower could grow without being eradicated as a weed in the name of improved agriculture. If the earth must lose that great portion of its pleasantness which it owes to things that the unlimited increase of wealth and population would extirpate from it, for the mere purpose of enabling it to support a larger but not a better or a happier population, I sincerely hope, for the sake of posterity, that they will content to be stationary, long before necessity compels them to it.

It is scarcely necessary to remark that a stationary condition of capital and population implies no stationary state of human improvement. There would be as much scope as ever for all kinds of mental culture, and moral and social progress; as much room for improving the Art of Living, and much more likelihood of its being improved, when minds ceased to be engrossed by the art of getting on. Even the industrial arts might be as earnestly and as successfully cultivated, with this sole difference, that instead of serving no purpose but the increase of wealth, industrial improvements would produce their legitimate effect, that of abridging labour. . . . Only when, in addition to just institutions, the increase of mankind shall be under the deliberate guidance of judicious foresight, can the conquests made from the powers of nature by the intellect and energy of scientific discoverers, become the common property of the species, and the means of improving it and elevating the universal lot. ●

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