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Determining the long-term carrying capacity of Earth -- that is, the number of people that the planet can support without irreversibly reducing its ability to support people in the future -- is an exceedingly complex problem. About all we can be sure of now is that, with present and foreseeable technologies, the human population has already exceeded that capacity. Even today's 5.2 billion people can only be supported by a continuing depletion of humanity's one-time inheritance from the planet: non-renewable resources including deep, rich agricultural soils, "fossil" groundwater, and the diversity of non-human species.

Carrying capacity is a function of characteristics of both the human species and the planet. Through cultural evolution, human beings may quickly shift their demand for and ability to extract different resources. At the same time, natural and anthropogenic processes change the distribution and abundance of resources in the short and medium term. This paper addresses the latter aspect of carrying capacity: the influence of global change on the planet's capability of supporting people over the next 20 to 100 years.

Carrying capacity can be broken down into a number of interacting elements, including food, energy, ecosystem services (such as provision of fresh water, flood control, and recycling of nutrients; Ehrlich and Ehrlich, 1981), the epidemiological environment, social structure, politics, and culture. Applying the reasoning of Liebig's "law of the minimum," overall carrying capacity is determined by whichever component yields the lowest carrying capacity. Much of our discussion here focuses on food because, although it may not ultimately be the limiting resource of human population size, food production is a crucial factor that is very sensitive to global change. In addition, basic human nutritional requirements are relatively inflexible and easy to quantify in contrast to other elements: there is no substitute for food.

It is especially critical to evaluate carrying capacity now because the human population has clearly exceeded local and regional carrying capacities in many parts of the world (FAO, UNFPA, & IIASA, 1982), as shown by an increasing failure of food production to keep pace with population growth. For the first time ever, moreover, carrying capacity has been exceeded globally. Furthermore, human population pressure is reducing carrying capacity directly through the unsustainable use and consequent destruction of natural habitat and agricultural land (Brown, 1988; Ehrlich and Ehrlich, 1988).

The human population has indirect impacts on carrying capacity as well. The magnitude of these impacts can be evaluated as the product of three interacting, multiplicative factors, of which population size is one. The other two factors are per-capita consumption of resources (a measure of affluence) and some measure of the environmental damage generated by technologies used to provide each unit of consumption (Holdren and Ehrlich, 1974). Indirect impacts are causing global environmental changes that themselves influence the number of people Earth can support. Of these changes, the greatest potential consequences for carrying capacity appear to reside in anthropogenic changes in the global climatic system.

Population growth thus contributes to a widening gap between the quantity of resources, especially food, needed by the human population and the amount that can be extracted from the planet. In the following, we discuss the reduction in carrying capacity that can be expected to result from direct human impacts on resources and the environment and from our indirect impacts on the climatic system.

DIRECT HUMAN IMPACTS

The Stanford Carrying Capacity Project has estimated that the human population now uses directly, coopts, or has destroyed approximately 40 percent of global net primary productivity on land, the basic food supply of all terrestrial animals (Vitousek *et al.*, 1986). Humanity is not only exercising increasing control over this global food supply, but is also undermining the capacity of photosynthesizing organisms to produce it.

The direct human impact on carrying capacity is especially evident on marginal land at both extremes of the moisture gradient. Arid and semi-arid regions, particularly in Africa, are suffering severe degradation through desertification. A total of 27 million hectares of land -- an area the size of the state of Colorado -- completely lose economic utility each year because of excessive human impact (UNEP, 1987). Waterlogging and salination lead to 200-500 thousand hectares of irrigated land coming out of production annually (Goldsmith and Hildyard, 1984). The carrying capacity for human beings of all this land is essentially reduced to zero. When land deteriorates to this extent in poor countries, its inhabitants are forced either to join masses of displaced peasants in swelling urban slums or to migrate onto other marginal land where the cycle repeats itself.

Similarly, partly in response to population pressures, human beings are moving in ever greater numbers into tropical moist forests (TMF), where rapid deforestation and unsustainable agricultural practices render this land economically useless as well (Raven, 1988). Population growth among traditional shifting cultivators also threatens TMF by accelerating the slash-and-burn cycle to the point that the forest lacks time to recover between cuttings (Ehrlich et al., 1977).

Currently, only about half of Earth's original 16 million km^2 of TMF remains, and this is being severely disturbed (through intensive logging and slash-and-burn agriculture) or completely cleared at an annual rate of roughly 200,000 km^2 (Myers, 1988). Unless these patterns change, in 40 years relatively undisturbed TMF will be restricted to scattered fragments on steep hillsides and a few "islands" in Amazonia, the Congo basin, and Southeast Asia.

Such wholesale destruction of ecosystems reduces or eliminates services they once provided to people living both within and far from them. In addition to undergoing severe soil erosion, some badly deforested regions (where evapotranspiration is greatly reduced) suffer locally drier climates. In the Panama canal area, as in some other tropical regions, there has been a steady decline in rainfall associated with the removal of most of the forest cover (Myers, 1988). Reduction in the recycling of water within the ecosystem may thus set up a positive feedback system which accelerates the loss of TMF.

The recent catastrophic flooding in Bangladesh can be attributed in part to massive deforestation in the Himalayas (Swaminathan, 1988), a phenomenon closely tied to population growth. The consequences of the loss of tropical biodiversity on carrying capacity are even more widespread. Industrialized countries rely heavily upon tropical species for genetic material needed for the maintenance and improvement of strains of crops now in production (Myers, 1983) and for the development of new crops that could improve diets of human populations in the tropics (Ehrlich and Ehrlich, 1981).

Even more threatening than these direct effects of the human population on local and regional carrying capacities are human impacts that operate by changing global systems indirectly. The most important of these (but far from the only one) involves exacerbation of the natural long-term trend of interglacial warming.

GLOBAL WARMING

Anthropogenic climate change has been a matter of deep concern among environmental scientists for more than two decades (Bryson and Wendland, 1968; Ehrlich, 1968; Ehrlich and Ehrlich, 1970; SCEP, 1970; Ehrlich et al., 1977). The consensus among atmospheric scientists now is that the increased injection of greenhouse gases into the atmosphere due to human activities has already committed the planet to a warming of at least 1° or 2° Celsius (Abrahamson 1989). Furthermore, there seems to be little prospect of curbing future emissions sufficiently to prevent an average temperature rise of 3° to $4^{\circ}C$, or even more. To put this into perspective, consider that the average temperature of the Earth during the last ice age was only $5^{\circ}C$ cooler than it is today (Schneider, 1988)!

While the climatic effects of such a warming cannot be predicted with accuracy, computer models indicate that among the more likely results will be a decrease in water availability in the world's major grain belts. In addition, it is agreed that climate change will occur at a rate unprecedented in recorded history -- possibly 10 to 50 times faster than the average natural rates of change following the last ice age (Schneider, 1988).

This degree and pace of change will inevitably cause major disruptions in world agriculture. Shifting climate belts will require major adjustments in irrigation and drainage systems at a cost of as much as $200 billion worldwide (Postel, 1987). Farmers will have to switch to drought-resistant crops where possible, thereby incurring reduced yields (drought-tolerant grains have an average yield less than half that of corn; Brown, 1988). Drought-reduced harvests, like those of the late 1980's, can be expected to occur with greater frequency and severity.

Northward migration of temperature/rainfall belts that are favorable for grain production may at first glance appear beneficial to agriculture in regions like Canada and the northern part of the Soviet Union, where low temperatures and growing season frosts are limiting factors. But in many of those areas, thin, infertile soils will severely constrain productivity (Jenny, 1980).

Similarly, an increase in carbon dioxide concentration may enhance potential productivity, but it is doubtful that this will yield a net benefit in the face of so many other limitations. Higher temperatures and more CO_2 may unfavorably change relationships between crops and their pollinators, competitors, or pests. Finally, the unwillingness of governments to take many of the steps necessary to deal with nearly certain and unprecedented change will result in considerable delay and exacerbate the socio-economic problems involved in making adjustments.

Humanity has few options in making such adjustments to the projected greenhouse warming. The negative impact of climate change on global carrying capacity is not likely to be offset by increased agricultural yields through bringing more land into production nor through increased fertilizer use. The potential for increasing the world's cultivated area is slim -- the land area planted in grain worldwide has actually declined by about 7 percent since 1981 (Brown, 1988), due mainly to three changes: abandonment of deteriorated land; conversion of cropland to nonfarm uses, especially in densely populated regions; and set-asides in the United States.

The primary prospect for expanding food production thus rests with the potential for increasing yields through more intensive cropping, increased fertilizer use, or development of more productive strains. While it is still unclear how much higher yields can be raised (within economic constraints -- inputs are limited by costs), no marked increases are foreseen in the near future as each of these avenues is approaching saturation under current economic conditions (Brown, 1988).

Global warming will also cause a rise in sea level due first to thermal expansion of the oceans and later to the melting of ice caps in polar regions where the projected temperature rise is expected to be most dramatic. The predicted sea-level rise of as much as 1.4 to 2.2 meters by the end of the next century (Jacobson, 1988) will not only decrease food production through flooding of agricultural land, but will also displace millions of people from their homes and livelihoods. Damage to fisheries from inundation of wetlands that support them will adversely affect the nutrition of people who are heavily dependent upon that food resource.

Coupled with land subsidence due to natural processes and the extraction of oil and groundwater, sea-level rises in some localities will be much higher than the average. Low-lying, fertile, and sometimes heavily populated deltas (eg., the Brahmaputra/Ganges and Nile deltas) are likely to be submerged first. In Bangladesh and Egypt alone, an estimated 46 million people may be threatened by flooding (Jacobson, 1988).

Much larger areas of coastal land will become unsafe for human habitation because of the threat of storm surges carrying far inland. Developed countries, though more capable of resisting the rising seas, will not be immune. Holland may have to flood some of its reclaimed agricultural land with Rhine

River water to prevent saltwater intrusion into groundwater supplies (Schneider, 1988). In Florida, much of the Everglades will be lost (with deleterious effects on fisheries), aquifers will be salinized, and large areas will be made much more vulnerable to storm damage. The increased frequency and severity of natural disasters (eg., drought, storms, and flooding) associated with global warming, at a time when ecosystems are already stressed, will further reduce Earth's carrying capacity by decreasing the land area suitable for agriculture and human habitation.

An increased frequency of drought would also render food production less predictable, thereby reducing carrying capacity. Such reductions would be very serious, inasmuch as humanity is unable to feed itself adequately under current production and distribution systems.

A study by the Alan Shawn Feinstein World Hunger Program at Brown University (Kates et al., 1988) estimated that, even if food were equitably distributed (and nothing diverted to livestock), the all-time record food production of 1985 could have provided a minimal vegetarian diet to about 6 billion people, a number projected to be exceeded within the next decade. The same global harvest, allowing a diet with about 15 percent animal products, could feed some 4 billion people. A diet consisting of 35 percent animal products, similar to that consumed by most North Americans and West Europeans today, could be provided to only about 2.5 billion people -- less than half of today's population. These estimates assume a 40-percent loss of the food harvested to pests and wastage before consumption, an

FAO estimate which may be somewhat high. But even if that figure were 20 percent, it would not permit anything but an adequate vegetarian diet for today's population.

MODELING GLOBAL CHANGE AND FOOD SECURITY

To examine the possible effect of climate change on food production, we constructed a simple global model (for details, see Daily and Ehrlich, 1989) which simulates population growth, annual agricultural output, annual consumption, and the frequency and severity of unfavorable weather patterns such as occurred in 1988. The model determines the amount of food available for consumption (production plus carry-over stocks) in each year over a 20-year period. For all runs of the model, we assumed that average increases in grain production would keep up with population growth (1.7 percent annually). In years with favorable weather, we assumed that a surplus of 50 million metric tons of grain was produced. We then varied the frequency and severity of unfavorable weather patterns.

Under our most "optimistic" scenario, unfavorable climatic events occurred on average once every five years and caused a 5 percent reduction in grain harvest, roughly the magnitude of the climate-caused drop in 1988. Under our most "pessimistic" scenario, the mean time between unfavorable climatic events was 3.3 years, and each event caused a 10-percent drop in grain production below the trend.

In order to simulate the feedback between availability of food and population size, it was assumed that a food deficit of one metric ton of grain resulted in two incremental deaths.

Roughly three people are supported by each ton of production now, but about one third of all grain is fed to animals, so compensation is theoretically available by consuming more grain directly.

Actual death rates might, of course, be raised further than this indicates. In the real world, undernutrition occurs mainly among the poorest people, perhaps the bottom quarter or fifth of the population. This group bears the brunt of any deficits, while the rest usually can maintain adequate diets (although probably at higher prices). Because of the disproportionate burden on the poor, disease and hunger may take a heavier toll on them than our all-or-nothing simplification suggests.

Results of the model suggest that the optimistic scenario (a 5 percent reduction in grain harvest on average twice per decade) would not lead to complete depletion of world grain stocks, though world food security would be threatened. These reductions would have little effect on overall population growth. Under the pessimistic scenario (10 percent reductions on average three times per decade), however, severe deficits in grain stocks occur about twice per decade, each causing the deaths of between 50 and 400 million people.

Weather patterns that might cause such drops include, for instance, repeats of the 1988 North America/China drought event, with the same or greater severity, or totally different patterns involving other areas. In short, we have not incorporated the question of the pattern of crop failures that would lead to declines in grain production. We also have not considered compensatory actions such as bringing set-aside land in the

United States back into production, conversion from feed to food crops, or the general intensification of agricultural activity that would result from increased demand for food, except to the degree they are subsumed in our "constant average increase" assumption.

We have also perhaps been pessimistic in not incorporating the possibility of increases in production because of technical innovations stimulated by famines. On the other hand, some of our implicit assumptions about carrying capacity are optimistic. We have not, for example, incorporated additional drops in harvest due to social breakdown related to famines, the spread of disease through malnourished (and thus immune-compromised) populations, or inappropriate aid programs that damage the agricultural sectors of recipient nations.

Indeed, most of our basic assumptions could be considered very optimistic. For instance, agricultural production is no longer keeping pace with population growth in Africa or Latin America. Furthermore, we have assumed that (climatic change aside) production can be kept growing for two decades more in spite of massive erosion of topsoil, increased waterlogging and salinization in irrigated areas; dropping water tables; deforestation leading to regional drought and flooding; desertification; accelerating conversion of land to non-agricultural uses, and so forth.

The model is, of course, simply an aid to thinking about the possible consequences if short-term climatic change were to cause drops in grain production of a magnitude roughly comparable to those known to have been caused before, and considering the rest of the system to be essentially "surprise free." Our results are not predictions, they are simply indications of the nature of problems that may occur if the global warming leads to an increased frequency and severity of climatic events deleterious to agriculture.

CONCLUSIONS

The population-food system has no "fail-safe" backup mechanisms designed into it, even if climates should remain very favorable to food production. We depend upon the statistical "cushion" that adverse weather and unusual pest outbreaks do not occur everywhere at once. To the degree that global food production becomes more concentrated (as in North America), humanity becomes more vulnerable. There is no time to be lost in moving towards population shrinkage as rapidly as is humanely possible; the momentum of population growth ensures that human numbers cannot start to decline as a result of reduced fertility in less than half a century under any realistic assumptions.

Not only is population control required, but governments and societies must bend their efforts to reduce the rate of global climatic change (Ehrlich, 1988). The 1988 drought spurred the United States Congress into action, but bills first introduced in 1988 were still under debate in the spring of 1989 when the prospect of another drought-reduced harvest in North America seemed very real. Concerted action to start reducing the emission of greenhouse gases is needed now because a) the resistance to implementing changes is so great, and b) the lead time on many effective actions will be a decade or more. The problem is especially acute, since leaders in the rich nations have largely failed to realize the magnitude of the changes necessary if the warming is to be significantly slowed. Action in rich nations is needed also to ensure that poor nations will have some chance to develop through use of their indigenous energy resources (Ehrlich and Ehrlich, 1989).

For the indefinite future, Homo sapiens will face major challenges in supplying everyone with adequate diets. Production must be increased while at the same time curbing the destruction of irreplaceable soils, overdrafts of "fossil" groundwater, and the destruction of biodiversity. Much more effort should go into reducing wastage of food between field and stomach, strengthening the agricultural sectors of poor nations in ways that promote their food security, and improving the equity of food distribution. Even if all of these daunting ecological, economic, social, and political tasks can be tackled simultaneously, there is no guarantee of success.

Only one element of carrying capacity -- food -- has been examined in this paper, and many of the complex interactions in the population-food-climate complex have not even explored. Nonetheless, our preliminary analysis suggests that there is no room for complacency whatsoever.

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