"COMMENTARY: COWBOYS, CORNUCOPIANS AND LONG-RUN SUSTAINABILITY"

by
Robert U. AYRES*

93/10/EPS

This working paper was published in the context of INSEAD's Centre for the Management of Environmental Resources, an R&D partnership sponsored by Ciba-Geigy, Danfoss, Otto Group and Sandoz AG.

* Professor of Environmental Economics, Sandoz Chair in Management and the Environment, at INSEAD, Boulevard de Constance, Fontainebleau 77305 Cedex, France.

Printed at INSEAD, Fontainebleau, France

COMMENTARY: COWBOYS, CORNUCOPIANS AND LONG-RUN SUSTAINABILITY

Robert U. Ayres

INSEAD

November 1992

Abstract

In the 1970's there was a lively debate on the relationship between natural resource availability and long-run economic growth. One side has been characterized as "neo-Malthusian". It emphasized the limited global "stockpile" of critical natural resources, from cobalt to petroleum, and the need to curb population and economic growth. The other side of the debate has been characterized as "cornucopian". It emphasized the creative powers of technology and free-markets to find substitutes for any and all scarce resources.

This paper argues that the original dichotomy was false. It did not adequately represent either the real positions of most conservative business and political leaders today. Nor did it reflect the currently emerging consensus among environmentalists. The former do not concern themselves with long-run issues at all, nor do they take a global view of the problems of mankind. Rather, they argue from the standpoint of short-run national (and corporate) interest. Environmentalists, on the other hand, do not fit the "neo-Malthusian" world-view, which emphasizes the role of natural resources (and land) as factors of production, and points to the limited supply of renewable resources and inevitable the exhaustion of non-renewables.

The most important scarcities, in the emergent environmentalist world-view, are largely outside the market domain: soil fertility, clean fresh water, clean fresh air, unspoiled landscapes,

climatic stability, biological diversity, biological nutrient recycling and environmental waste assimilative capacity. There are no plausible technological substitutes for these. The irreversible loss of species and ecosystems, and the buildup of greenhouse gases in the atmosphere, and of toxic metals and chemicals in the topsoil, groundwater and in the silt of lake-bottoms and estuaries, are not reversible by any plausible technology that could appear in the next few decades. Finally, the great nutrient cycles of the natural world — carbon, oxygen, nitrogen, sulfur and phosphorus — require that constant stocks in each environmental compartment and balanced inflows and outflows. These conditions have already been violated by large-scale and unsustainable human intervention.

Introduction

The early 1970's witnessed a vigorous debate between two well-defined intellectual positions. The debate became quite passionate. One side was the "neo-Malthusians", inspired by such best-selling prophets of doom as the Paddock's *Famine - 1975* [Paddock & Paddock 1967], Paul Ehrlich's *The Population Bomb* [Ehrlich 1968], E.F.Schumacher's *Small is Beautiful* [Schumacher 1973] and Barry Commoner's books *The Closing Circle* and *The Poverty of Power* [Commoner 1971, 1976][1]. The essential neo-Malthusian message gained immense (if temporary) prestige when it was computerized by Jay Forrester's Systems Dynamics Laboratory at MIT[2].

---

[1] Commoner's position was commonly viewed as "anti-technology", because he attributed virtually all environmental degradation to irresponsible misuse of technology. He disavowed opposition to economic growth *per se*, and once engaged in a public debate with Paul Ehrlich and Jon Holdren. I am indebted to Herman Daly for calling my attention to this.

[2] Forrester's first 5-variable world model (World 1) had relatively little impact, except on the Club of Rome, an international advocacy group, founded by Aurelio Peccei. Forrester immediately improved and polished the model, resulting in World 2 [Forester 1971]. Meanwhile, the Club of Rome commissioned the Systems Dynamics Laboratory to elaborate the World 2 model. The result was World 3 [Barney 1980].

The report of Forrester's group, originally entitled *Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*, and later just *Limits to Growth*, was published in paperback book form [Meadows *et al* 1972] and widely publicized[3]. The World 3 model received editorial page recognition in many newspapers, where the results were sometimes misleadingly presented as a collective output of MIT (or, MIT's "Megacomputer"). The book was translated into over 20 languages and sold over 4 million copies. It was even presented as a TV documentary in the Netherlands[4].

The Club of Rome became entranced with the apparent power and instant credibility of computer models and immediately commissioned several more "global models", of which the best known was that of Mesarovic and Pestel *Mankind at the Turning Point* [Mesarovic & Pestel 1974]. The neo-Malthusian view was summarized quite well in an official document of the Carter administration: *The Global 2000 Report to the President: Entering the Twenty-first Century*.

While the neo-Malthusians encompassed a considerable range of differences, some among them — such as Paul Ehrlich and Jon Holdren — tended to equate economic growth itself with pollution and environmental harm. A group of 30 well-known British scientists signed a manifesto called "A Blueprint for Survival" which began with the words "If we are to support the life-supporting capabilities of our all-important film of air, water and soil, *economic growth must be brought to a halt as rapidly as possible.*" The manifesto went on to say that "*continued industrial growth by itself will bring us to a condition to self-destruct within the lifetime of our grandchildren*" [quoted in Heilbroner 1972, p. 139].

---

[3] The detailed backup material was also published later by Meadows *et al.*, under the title *Dynamics of Growth in a Finite World*, Wright-Allen, 1974 [Meadows *et al* 1974].

[4] Allegedly more than a million copies of the book (in Dutch) were sold.

Isaac Newton observed that action is accompanied by an equal and opposite reaction. This law of action and reaction seems to hold in the social sphere as well. By the mid-70's there was a growing suspicion that the neo-Malthusians had overstated their case[5]. Both the World 3 model, and the empirical basis of *Limits to Growth* were regarded with scorn by most academic critics, especially economists and physical scientists. A group at the respected Science Policy Research Unit (SPRU) at Sussex University, U.K. undertook a direct attack on the assumptions and conclusions of *Limits to Growth*. The most telling criticism of this group was that the simple models of Meadows *et al* utterly ignored the ability of a market economy to respond to perceived scarcities by technological substitution and "fixes".[6]

Resource economists also pointed out that, if natural resources were truly becoming "scarcer" in any meaningful sense (assuming resource markets to be competitive and resource firms to be well-informed and not myopic), then prices should be rising in real terms. Yet historical studies of resource prices over a long period of time have consistently showed the opposite: resource prices (with one exception: timber) have tended to decline over time, suggesting that technological improvements in resource discovery and extraction have consistently more than compensated for exhaustion[7]. According to this view, the sharp petroleum price increases in 1974 and 1979 were merely "blips" arising from special political circumstances. Steadily declining oil prices in the 1980's (up to 1988) would seem to confirm

---

[5] On the other hand, Malthus himself may have been somewhat misrepresented by the casual use of his name. An anonymous reviewer comments, justly, that "in fairness to Malthus, he never argued that substitutions or increases in productivity due to technological change were impossible; he merely pointed out that as population increased in was likely to stress, check and outpace such advances."

[6] The SPRU group went so far as to introduce new interactions and feedback loops into Meadows' World 3 model to reflect the missing market adjustment effects. The spectacular "crashes" that characterized the World 3 simulation runs duly disappeared. See *Models of Doom* [Cole *et al* 1973].

[7] In this connection, see two landmark publications by Resources for the Future, Inc. *Scarcity and Growth: the Economics of Resource Scarcity* [Barnett & Morse 1962] and *Scarcity and Growth Revisited* [Smith 1979]

this view, although recent events in the Persian Gulf (1990) are indicative of increased vulnerability, if nothing else.

In reaction to the fears of overpopulation raised by the Paddocks and Ehrlich (and others), Julian Simon argued in *The Economics of Population Growth* that population growth is a positive, rather than a negative factor [Simon 1977]. He elaborated this theme further in *The Ultimate Shortage* [Simon 1980, 1980a]. The expectations of food scarcity and mass famine in the third world during the 1970's were (temporarily) contradicted by reality. Although there have been episodes of drought and starvation in the 1980's, particularly in the Sahel region of Africa, they were local and attributable as much to civil wars in Uganda, Sudan, Ethiopia and Eritrea as to the weather. (On the other hand, could the frequency and intensity of civil conflict be an indirect reflection of increasing conflict over access to scarce and deteriorating arable land?) Simon did not consider such questions. He cited surveys carried out by Joginder Kumar, and later by the FAO, indicating that arable land has been increasing worldwide at somewhere between 0.7 and 1.0 percent per annum [quoted in Simon 1980, p.1432]. Per capita food production actually increased by 28% from 1948-50 to 1976, and increased on a year-to-year basis in all but 7 of those years [ibid p.1433]. (However, as pointed out later, these points do not support Simon's case as strongly as he supposes).

To anticipate arguments presented later, it might be pointed out here that even a long historical record of continuous improvement in the *aggregate* productivity of land does not imply that conventional agriculture can increase productivity or output indefinitely. For one thing, the gains in productivity that have kept world food production increasing as fast as (or slightly faster than) population, have not been achieved by sustainable means. The "Green Revolution" was achieved by a combination of monoculture, economies of scale, and synthetic fertilizer. Monoculture, depending on genetically selected "high yield" strains, requiring intensive use of synthetic fertilizers and pesticides, has also sharply accelerated the rate of topsoil erosion. Many areas that were made to bloom for a few years by means of irrigation using non-renewable underground water are already declining or exhausted and ruined by erosion and salination. Eventually the world will run out of "new lands" that can be exploited in this way.

Julian Simon took an extreme position. He argued that population growth is *not* the problem, but is actually beneficial because "human ingenuity" is unlimited. Most population experts strongly disagree. As demographer Nathan Keyfitz remarked "if that were so the inhabitants of squatter colonies in Mexico City or hungry cattle herders in the Sahel would be very creative" [Keyfitz 1991, p.16]. It seems self-evident that poverty *per se* does not stimulate productivity. But Simon, and others of his persuasion, argue that the problem of lagging growth and poverty is not excess population *per se* but wrong and perverse government economic policies. The relevance of policy – key to Simon's argument – deserves to be taken more seriously. I shall come back to it.

The power of human ingenuity and technological progress to overcome resource exhaustion was emphasized from a technological perspective, e.g. by Harold Goeller and Alvin Weinberg in *The Age of Substitutability*, which was based on a study of the various historical uses of mercury and the ways in which advancing technology has made alternatives available [Goeller & Weinberg 1976]. The most extreme version of this optimistic position was adopted by Herman Kahn and others at the Hudson Institute. Their study *The Next 200 Years* to celebrate the U.S. bicentennial (1976) was a very optimistic forecast of continued worldwide economic growth essentially unimpeded by resource constraints [Kahn *et al* 1976]. Indeed, Kahn *et al* took issue with the neo-Malthusians on all fronts, but attacked the "anti-growth" school with particular virulence. Kahn *et al* added a few caveats recognizing the possibility that unknown and unexpected environmental problems might modify their optimism, but they clearly considered this possibility unlikely.

Kahn *et al* acknowledged four "worldviews" ranging from the extreme neo-Malthusian to the extreme "technology/growth enthusiast" (or "cornucopian"), with two intermediate positions, namely the "guarded pessimist" and the "guarded optimist". Of course, it is simply not the case that all reasonable worldviews fall neatly on a scale between neo-Malthusians and cornucopians. The world is too complex for that. Another and equally valid simplification is Boulding's characterization of the "endless frontier" or "cowboy economy" as contrasted with the "spaceship economy" [e.g. Boulding 1966]. These two extremes can be described in terms of the same basic dimensions as Kahn's four. But, while there is some overlap, the Boulding archetypes cannot be regarded as a compromise between (or "linear combination" of) Kahn's.

Obviously there is some similarity between the "cornucopian" position and the "endless frontier". But the former is an expression of technological optimism, whereas the latter is a description of obsolete social attitudes mainly found in North America and a few other places like Australia, Amazonia and Siberia. The "endless frontier" worldview is based on a combination of history and mythology. The differences between the two positions really emerge most clearly in terms of their respective implications for the role of government. Both "cowboys" and cornucopians of the Kahnian stripe tend to be political conservatives. However, the cowboys see government as an active, interventionist ally (e.g. the "cavalry") in taming and exploiting the wilderness and in capturing new territories. The cornucopians in general, see the role of central government as limited to macro-economic policy and defense. They emphasize the ability of price-signals in unfettered free-markets to call forth technological solutions to environmental and even social problems.

Arguably, there is even more of a similarity between the "spaceship economy" and the "neo-Malthusian" position. At first glance, the two may even appear identical. Yet the emphasis in the "spaceship" is on mutual cooperation and conservation. The emphasis in the neo-Malthusian scenario is on restraint, austerity and government-imposed equity. Perhaps I am overstating the distinction somewhat to make the point. But it is an important one. Kahn *et al* characterize the neo-Malthusians — their ideological opponents — as technological pessimists. But the "spaceship" mentality is not necessarily technologically pessimistic (though Boulding himself was referring to the Earth itself as a spaceship, to most people a spaceship symbolizes the most advanced technologies known to man).

The technological optimists have been running things, by and large, in recent years. There are a great many examples — too many to explain away as "exceptions" — where technological over-optimism has actually created new environmental problems far more serious than necessary and more serious than the ones that technology set out to solve in the first place. The cases of Chernobyl and Lake Aral are now well-known. The Aswan dam in Egypt is much less beneficial than original proponents expected. It may yet prove to have been a comprehensive environmental and economic disaster, due to a combination of evaporative water loss reducing the water available downstream, loss of the annual infusion of fertile silt, and the spread of Bilharzia. Unsustainable desert agriculture in not limited to the former Soviet Union or the Third World: it is practiced in California, Arizona, Texas, and much of the U.S. high plains. The destruction of Amazonian or Costa Rican rain forests to produce paper pulp, charcoal for iron-smelting, or grassland for cattle-grazing is already an ecological disaster.[8]

[8] It is also likely to be viewed as an economic disaster, in the long run, because national accounting methodology misleadingly treats extractive revenue as if they were ordinary income, rather than capital depletion. [See Repetto *et al* 1991]

The difference between the emerging breed of environmentalists ("spacemen") and the older breed of neo-Malthusians is that the latter mostly failed to see that the environment itself is a limited resource. Neo-Malthusians mainly emphasized potential scarcities of resources — especially agricultural land — as inputs to the economic process[9]. In this, they usually under-estimated the potential for technological substitutions and "fixes". The "spacemen", on the other hand, tend to focus much more on the environment as a finite, dynamic, interdependent and vulnerable set of interactive subsystems (the atmosphere, the hydrosphere, the biosphere) with which human life and economic activity are tightly linked[10].

There are many, including myself, who believe that given a reasonably free market technology can generally be depended upon to find a substitute for almost any scarce material resource input (except energy itself). However, there are no plausible technological substitutes for climatic stability, stratospheric ozone, air, water, topsoil, vegetation — especially forests — or species diversity. Degradation of most of these is irreversible. In every case, total loss would be catastrophic to the human race, and probably lethal. Although technology can create (and money can buy) many things, it cannot create a substitute for the atmosphere or the biosphere. Technological optimism, in this regard, is simply misguided.

Population growth and food production

The relationship between population growth and economic growth is still very controversial, at least from the perspective of underlying causality and resulting policy

---

[9] In this regard, Commoner was clearly an exception. Indeed, his major concern was with environmental degradation. His policy prescriptions, unfortunately, were more moral and political than economic. He distrusted free markets (and economists) and tended to blame capitalism for environmental problems.

[10] See, for example, *Gaia: A New Look at Life on Earth* [Lovelock 1979]; *The Global Possible* [Repetto 1985]; *Sustainable Development of the Biosphere* [Clark & Munn 1986]; and *Managing Planet Earth* [Scientific American Special Issue 1989].

implications. Julian Simon notwithstanding, there is good reason to believe that population is already too high in many areas, but population growth continues. Economic growth measured in conventional terms barely keeps pace, and in the poorer countries much of what appears to be growth is due to unsustainable exploitation of natural resources. If growth were measured properly to take into account degradation of irreplaceable environmental assets, the appearance of growth might well be illusory [Repetto *et al*, op cit]. There is some deceleration of population growth, especially in Latin America, China and India. But there are still a number of Asian and African countries where each woman bears six or more children during her years of fertility. A number of countries — Nigeria and Malaysia among them — even continue to officially encourage population growth.

Human population, in the last analysis, depends on food production. The worlds fisheries are already mostly over-fished and cannot be expected to yield more fish protein than they do at present, barring major changes in management of the resource. Food production is essentially coincident with agriculture. Since Third World population is almost sure to double (or more) in the next fifty years, and at least a billion people are already malnourished, agricultural production will have to increase by more than a factor of two, and probably a factor of three. It is difficult to see where this increased output can come from. In fact, per capita food production has actually *declined* since 1980 in many countries.

Agricultural productivity has increased dramatically in recent decades, in part due to the "green revolution". But there are clear indications that further increases in the use of chemical fertilizers and pesticides will not have commensurate impacts on output in the future. For instance, data gathered by the U.S. Department of Agriculture indicates that for the first 40 pounds of nitrogen applied per acre of Iowa cornland, production increased by 27 lbs per lb of N. However, for applications above 160 lb/acre, increases in corn output averaged just 1 lb per lb of N [Brown 1974]. A number of countries already use more than 200 lb of fertilizer per acre. The potential for further increases in output in some of the developing countries is still significant, but more and more countries have essentially reached the saturation point. (Also, it is important to bear in mind that synthetic nitrogen fertilizers are manufactured by an endothermic process of nitrogen fixation that utilizes a fossil fuel, natural gas, as the source of energy).

Moreover, the sort of energy-intensive mono-culture of cereal grains that yields the greatest output per acre is also unsustainable in the long run for other reasons. In the first place, it reduces the genetic diversity of the crop, thus increasing vulnerability to pest or disease mutations. This vulnerability leads to increasing use of toxic chemical pesticides, which (in turn) tends to breed disease resistant pests. Since 1950 (when there were no more than 10 resistant species of insects and mites) the number of resistant species has multiplied 50-fold [Georghiou & LeBaron 1991]. The number of resistant plant pathogens has increased roughly in the same proportion.

Fresh water for irrigation is extremely scarce in the more arid parts of the world, especially the Middle East. For example, Israel has now largely exhausted the available water resources of the West Bank of the Jordan River, and Palestinian claims to water will be difficult to meet. Stories of environmental degradation due to unwise irrigation schemes are commonplace. The rapid decline in fertility and salinization of the area around Lake Aral, in central Asia, is but one case in point. In fact, it is estimated that 36% of the irrigated land in India has been degraded by salinization, along with 27% of U.S. irrigated land, 20% in Pakistan and 15% in China [Postel 1989, Table 2]. Worldwide, 24% of irrigated land has been damaged already. In the United States, a large part of the high plains area is irrigated by pumping water from a non-renewable ("fossil") source, the Ogalalla aquifer. It has been half depleted over much of the area under which it lies. The Colorado River basin is in water deficit: consumption exceeds annual flow by 5% and water tables have fallen drastically in southern areas, like Phoenix and Tucson [ibid]. Mexico, which is entitled to a share of this water, currently gets virtually none.

Arable land is limited. Most of the good land is already in use. A small but significant percentage is actually abandoned each year, due to salt buildup or erosion. While the area of cultivated land has actually increased modestly in the past few decades, this small increase has mostly been at the margin. Much of it was at the expense of tropical forests or dry grasslands (as in the USSR). Worse, wind and water erosion are carrying away more and more precious topsoil[11], and salt is building up in some of the newly irrigated lands. Although some erosion can be tolerated (because soil is continuously being created by weathering and decay of vegetation), actual losses far exceed the tolerable limit. Whereas 2 tons/acre is probably renewable, continuous wheat cultivation results in erosion losses of over 10 tons/acre, while for corn the figure is close to 29 tons/acre — or ten times the rate at which topsoil is replaced by natural weathering processes. Due to such practices, 300 million hectares has become "strongly degraded" during the last four decades, which means it is irreversibly damaged and no longer arable. Another 900 million hectares is "moderately degraded", which means it has sharply reduced productivity [Brown & Wolf 1984].

Another growing problem for agriculture (and the biosphere) is the buildup of toxic materials such as lead and cadmium, from industrial effluents, in river-bottoms and delta lands. The problem is already acute in such places as the Rhine-Schelde estuary in Holland or the Hudson-Raritan bay in the U.S. Bacteria, fungi, and other micro-organisms are able to metabolize many of these elements and convert them into organic forms (e.g. methyl mercury

---

[11] It is estimated that a third to half of the topsoil that was present when European colonists came to North America has already been lost [Brown 1978; Brown & Wolf 1984]. The rate of loss has been curbed somewhat since the "dustbelt" years 1930's, but bad practices are still commonplace and may even be increasing.

or triethyl arsenic) that can be taken up by plants. Thence, they enter the animal food chain by way of grazing animals. In the Netherlands, where much of the land area is irrigated by canals carrying river-water, and dairy farming is extremely intensive, the rising levels of toxic metals in the soil have caused alarm. The problem is that the metallic toxins are taken up by the vegetation (mainly grass), and thence metabolized into cows milk and thence to the human food supply. Once the soil is contaminated in this way, there is no plausible cost-effective way to de-contaminate it. The choice will be to stop using this very productive land for agriculture, or to tolerate increasing dietary intakes of cadmium, lead, mercury and other toxic metals.

A related problem is the buildup of contaminants of various kinds in ground water used for drinking by animals and humans alike. Here, the recycling capacity of the biosphere works against us. Not only are toxic metals a growing problem in some regions, but viruses, nitrates and phosphates (from fertilizer) and chlorinated organics are being found virtually throughout the biosphere. The worst of these problems are currently found in the most heavily industrialized regions of the developing countries. However, there is every reason to expect the problem to spread as rapidly as the adoption of fertilizers and pesticides in lass developed countries. (It should be noted, by the way, that commercial phosphate fertilizers contain significant trace quantities of cadmium and other toxic metals, so that heavy, sustained use of fertilizers contributes to the toxic buildup in soils).

In summary, while it is true that agricultural productivity has increased notably in some Third World areas (the "green revolution"), one cannot safely extrapolate such gains indefinitely. Increased outputs have been achieved up to now by selectively breeding high-yield races of cereal grains, requiring increasing use of (and dependence on) energy-intensive synthetic fertilizers. A further consequence has been increasing vulnerability to pests (due to monoculture and lack of genetic diversity). To double or triple total output by vastly multiplying inputs of fertilizers, pesticides and irrigation water would sharply increase the present rates of erosion, salination and desertification, unless (and probably, even *if*) strong countermeasures are taken. Barring an unlikely technological breakthrough in genetic engineering, further increases in agricultural productivity will be much more difficult to achieve. They will certainly require more sophisticated technologies and still higher levels of industrial inputs, including erosion control. Thus, increasing agricultural productivity certainly depends on increased industrial productivity and general economic growth.

Exhaustibility of natural and environmental resources

The matter trapped in the earth's gravitational field does not dissipate, at least beyond the earth's atmosphere. To an extremely good approximation, the stocks of each chemical element can be considered fixed.[12] Resource exhaustion cannot mean physical disappearance of matter from the earth *per se*. It can mean, and is usually taken to mean, a change of form, from desirable to undesirable. "Useful" forms (or combinations) of elements, such as fossil fuels and metal ores are being used up and converted into "useless" (e.g. worn out) or even harmful forms or combinations (e.g. wastes and pollutants).

The apparent anthropocentrism of terms like "useful" or "harmful" need not worry us unduly. As Georgescu-Roegen correctly (and usefully) pointed out, the conversion from useful to useless can be described in neutral thermodynamic language: it corresponds exactly to increasing *entropy*. Useful materials can be regarded, in essence, as stocks of *low entropy* [Georgescu-Roegen 1971]. As the materials are degraded by use, entropy increases. Another

[12] To be strictly accurate, there is a small leakage of hydrogen from the top of the earth's atmosphere, where water vapor is ionized into hydrogen and oxygen. On the other hand, there is a apparently a significant annual net addition of metallic substance from meteorites and of water vapor and some other light elements (notably carbon) in the form of small comets [Frank 1990]. The earth is probably increasing slightly in mass, albeit very slowly.

way of characterizing the change in form is in terms of decreasing *distinguishability* — hence separability — and increasing *homogeneity*.

Notwithstanding arguments about the magnitude of the reserve, there can be no doubt that high quality natural resources are being dissipated. The fact of dissipation is indisputable. It is creating a number of environmental problems, including the buildup of toxic heavy metals in a number of environmental "sinks", including river bottom sediments and estuaries. From the standpoint of natural resource exhaustion, it is occurring at a rate that is open to argument, but is not zero. The size of the stockpile of "economically recoverable" reserves of fossil fuels and metals is not precisely known (or knowable) but it is finite.

Economic recoverability varies over time, of course. Up till the present time, at least, technological progress and economies of scale have more than compensated for price increases that would be expected to accompany declining natural resource stockpiles. In a landmark study, some years ago, Barnett & Morse demonstrated that the real costs of capital and labor inputs needed to produce both agricultural and mineral industry products in the U.S. declined overall from 1870 through 1960 [Barnett & Morse 1962]. Moreover, the rate of cost decrease actually increased sharply during the second half of this period. Both of these results seem to contradict the neo-Malthusian "scarcity" hypothesis. Later work has confirmed that the trends seen by Barnett & Morse prior to 1960 continued more or less unabated through the 1970's, in spite of the so-called "oil shock" of 1973-74 [Smith 1979].

The question arises: can we safely assume that the historical trend of increasing resource consumption, together with declining costs and prices (in real terms), can or will continue indefinitely, for all natural and environmental resources? Granted, as Kahn and others point out, the reserve-to-production ratio is not a reliable measure of approaching exhaustion for mineral resources.[13] Nevertheless, the answer to this question is definitely 'no'. That is, it is *not* safe to assume that technological improvements will continue forever to compensate for natural resource scarcity on a finite earth. Let us now reconsider the meaning of exhaustibility.

Consider, first, the more familiar kind of exhaustible resources, namely those consisting of convenient chemical combinations that facilitate conversion to useful forms of energy or further separation to extract valuable materials. Petroleum is the prime example. It is the most economically important single natural resource in the world today. U.S. production of petroleum peaked in 1969-70 and has declined since then. Declining output (despite higher prices) has been accompanied by declines in estimates of recoverable reserves. Production in the Soviet Union, currently the world's largest producer, probably peaked in 1987 or 1988.

One by one, the most promising oil-producing regions of the world have been or are being explored, including polar regions and continental shelves. The frequency of discovery of large new fields has diminished sharply. It is increasingly probable that the largest pools of oil have already been discovered. A larger and larger fraction of the remaining oil reserves are in the territories of a few under-populated middle-Eastern countries, with correspondingly increasing risks of armed conflict. These facts are clearly incompatible with increasing worldwide use of and dependence on petroleum products, especially for transportation purposes. This trend is clearly unsustainable for more than a few more decades at most.

Technological optimists point out that tertiary recovery has not yet been widely practiced (and that it might be feasible to capture carbon dioxide from electric power plants and pump it into old oil or gas wells, thus increasing recoverability at the same time). True, petroleum can

[13] In fact, for oil this ratio has hovered around 20 years since the 1920's, if not earlier [e.g. Graf 1924]. Because mining firms do not find it worthwhile to invest in exploration once their proved reserves reach a certain point, this fact is probably a better measure of the relevant discount rate than it is of recoverable reserves *per se*.

be replaced by synthetic fuels from tar sands, oil shale or coal[14]; or, perhaps methanol can be produced from natural gas. To be sure, some technology for using synfuels is already in existence. But even on a very large scale, there is no reason to suppose that synfuel costs could ever be even remotely competitive with current costs of extraction and refining. The process is inherently more complex and energy intensive than the present one[15]. Some large-scale pilot plants been built and found to be even more expensive, in general, than engineers expected. Thus, while we need not fear that liquid fuels would become unavailable, we must realistically expect them to be considerably more costly -- even without making any allowance for environmental damages. The long historical trend of declining resource prices will almost certainly be reversed within a few decades, at most. The concomitant global trend toward increasing total and per capita use of petroleum products (and, by extension, other extractive resources) is clearly unsustainable. Similar, though not identical, arguments can be made for a number of other extractive resources.

Natural resource exhaustion has a straightforward interpretation in entropic terms. But separability, or ease of recovery for human (industrial) purposes, is not the only important aspect of inhomogeneous aggregations of matter. The true "limits to growth" are more subtle. One of the limiting constraints is the degradation of the waste assimilative capacity of the biosphere and interference with its ability to stabilize the climate and recycle essential nutrients — along with toxic ones. Thus, the ability of the environment to neutralize or recycle chemical wastes into nutrients is also a kind of natural resource. (Environmentalists have used the term "assimilative capacity").

---

[14] Coal, oil shale and tar sands reserves are enormous, of course.

[15] Petroleum refining, today, results in a loss of about 10% of the energy content of the fuel. By comparison, coal-conversion processes would be only about 50% efficient in the same terms. In other words, to produce the same energy-content of finished fuels about 80% more crude fuel would have to be produced. This would also increase the carbon-dioxide emissions by a comparable amount.

Similarly, without going into excessive detail, the ability of the environment to protect itself from damaging UV radiation (via the ozone layer in the upper atmosphere) is another kind of resource. The ability of the environment to sustain a relatively constant temperature level between the freezing and boiling points of water is still another kind of natural resource.[16] In short, there are a number of system *functions* that can only be regarded as *resources*. These resources are, clearly, finite and vulnerable to human interference. While it can be argued that these functions are potentially renewable (hence, not technically *exhaustible*), they can be irreversibly destroyed, if not actually consumed. In the next section, the self-organizing character of natural bio-geochemical cycles is considered in greater detail as an exhaustible resource.

Sustainability of biogeochemical cycles

The earth is not just a static aggregation of chemical elements. It is much more. It is a dynamic *system* of physical and chemical processes (some biological, some geochemical, and some biologically assisted). This system is *self-organizing*. That is, it maintains itself in a dynamic *pattern* of continuous changes, within a stable envelope. (The envelope is sometimes called a "strange attractor", invoking the analogy of an invisible gravitational mass around which various bodies orbit). Some features of such a stable self-organizing system are actually predictable, at least in a probabilistic sense. Every living organism has this character. In certain respects, the earth system as a whole is like an individual organism: it is maintained in a stable state, far from chemical or thermodynamic equilibrium, by a steady supply of external energy from the sun.

[16] It is noteworthy that in a chemical equilibrium state the earth's atmosphere would consist mainly of carbon dioxide (as is the case for both Venus and Mars), whence the "greenhouse effect" would keep the earth's temperature well above the boiling point of water.

The existence of an oxygen-nitrogen atmosphere is sufficient evidence of the non-equilibrium character of the system. The oxygen atmosphere is maintained by a cyclic system of enzyme-catalyzed chemical reactions, sustained by a continuous flow of energy from the sun. The most important of these reactions, by far, is photosynthesis. There are similar biologically sustained (or assisted) cycles for water, nitrogen, sulfur, phosphorus, calcium, potassium, chlorine, iodine and others. All of these chemical cycles are both essential to the existence of life. Most of the endothermic chemical reactions needed to close the cycles are driven by living organisms.

The importance of the nutrient cycles to maintaining the conditions for life -- including human life -- arises partly from their role in stabilizing temperature, humidity, salinity, acidity (pH) and other climatic conditions,[17] and partly from their ability to convert toxic waste products from one form of life back into nutrients for another form of life. For instance, oxygen is a waste product of photosynthesis, but it is toxic to anaerobic organisms yet essential for animal and plant respiration. Carbon dioxide is a waste product of animal respiration, but essential for plants. Similarly, ammonia (or ammonium ions) are essential plant nutrients, yet toxic to most higher animals, and so on.[18]

Any disturbance to the bio-geochemical cycles is *ipso facto* a threat to survival. A materials cycle consists of a sequence of transformation processes and reservoirs or compartments. It can be represented schematically as **stocks** linked by **flows**. The condition for stability

[17]It is this capability (still a subject of scientific dispute) that has inspired the *Gaia* theory of Lovelock, Margulis and others [Lovelock 1972, 1979, 1982, 1988].

[18]The micro-organisms that recycle many of these essential nutrients, especially trace metals, are also capable of metabolizing toxic metals, like arsenic, cadmium, mercury and lead, converting them into chemical forms (such as methyl, dimethyl and ethyl) that are taken up "by mistake" by plants and thus introduced into the food chain of higher animals, including man. In this instance, the recycling capability of the biosphere works against us. The devastating consequences of this recycling capability have been demonstrated in recent decades with respect to mercury ("Minimata disease"), cadmium ("Itai-itai" disease) and chlorinated pesticides (DDT, chlordane, Lindane, etc.)

is easily stated: the stocks in each compartment, or reservoir, must remain constant (at least on the average); and, for this condition to be met the inflows into each compartment must be balanced exactly (on the average) by the outflows. If this condition is **not** met, the stock in some compartment must increase, at the expense of the stock in some other compartment. If the cycle does not re-stabilize, somehow, it will collapse.

If the natural nutrient recycling system is not continuously in balance -- at least, on the average -- there must be a buildup in some reservoir(s) and a compensating decline in another. The buildup would be harmful to the organisms for which that chemical combination is toxic, while the decline would be harmful to the organisms for which that combination is a necessary input. Thus, although there are undoubtedly self-regulating mechanisms (negative feedbacks) in the system that enable it to recover from small perturbations, a large enough perturbation of the stable chemical cycling system could cause an irreversible collapse of the system.

Two essential points need to be emphasized. One is that every closed cycle (water, carbon/oxygen, etc.) is an inherently non-equilibrium phenomenon, in the sense that it can only be maintained by a continuous flow of available (free) energy from the sun.[19] This statement is an obvious consequence of the second law of thermodynamics (the entropy law), which states that entropy increases in every irreversible process in an isolated system. A self-sustaining perpetual motion machine (**perpetuum mobile**) is impossible because it would violate this law.

---

[19] The importance of "self-organizing" dissipative systems far from thermodynamic equilibrium and maintained in a steady state by a continuous flow of free energy, has been particularly emphasized by Prigogine and his co-workers [e.g. Prigogine *et al* 1972; Nicolis & Prigogine 1977]. Living organisms, themselves, are self-organizing dissipative systems of this type. It is important to note that the surface of the earth itself is a dissipative system far from thermodynamic equilibrium, both in terms of chemical composition and temperature. An "equilibrium" world would have a completely different chemical composition [e.g. Lovelock 1979]. The atmosphere would probably consist almost entirely of carbon dioxide. There would be no free oxygen or nitrogen in the atmosphere. The atmospheric pressure would be far higher than it is on our earth. If there were any liquid water, the quantity of salts dissolved in the oceans would probably be about four times as high as it actually is. Such a planet would be much more acid (pH<<2) and much hotter than the actual earth (more like Venus); it could not support life as we know it.

Similarly, a self-sustaining materials cycle is impossible for the same reason. There can be no doubt that the biosphere is an essential actor in the carbon/oxygen, nitrogen, sulfur and phosphorus and other nutrient cycles.

The second point that needs to be understood is that any system far from equilibrium must be stabilized by a control system consisting of "negative feedbacks" to compensate automatically for natural perturbations, such as fluctuations in the solar constant. The control mechanisms for the natural nutrient cycles, and the earth's chemical composition and climate are not yet understood in detail. It is certain, however, that the system is highly non-linear. (This is guaranteed by the existence of feedbacks). The controls must be fairly robust to account for the relative stability of the nutrient cycles, surface temperatures, acidity and chemical composition over the last few hundred million years. On the other hand, feedback controls can always be overwhelmed by a large enough perturbation. (This must have occurred, for instance, 1960 million years ago when the dinosaurs became extinct).

A common characteristic of non-linear dynamic systems far from equilibrium is multiple branches or "attractors". It is possible under certain circumstances for a system to "flip" from one of these attractors to another. How big a perturbation would it take? Because we don't know the stabilizing mechanisms for the climate or the various cycles in detail we *cannot* know how big a perturbation it would take to move to another quasi-stable state, or even to begin an irreversible slide toward the true equilibrium state, which would not sustain life. We can reasonably assume that anthropogenic perturbations small compared to observed fluctuations in the past will not destabilize the system. However, with respect to some materials (such as greenhouse gases) the perturbations attributable to human industrial activity in the next century could easily exceed any historical counterpart. This is a very dangerous situation.

In fact, it is increasingly clear that all of the (formerly) stable natural cycles, especially those for carbon, nitrogen, sulfur and phosphorus, have already been seriously disturbed by human intervention, especially by the large-scale combustion of fossil fuels and large-scale use of nitrogen and phosphate fertilizers. It is also clear that acidification has become a major problem, at least in northern Europe, where the alkaline carbonate buffering capacity of the soils is relatively low [Alcamo *et al* 1986].

Conclusions

There is an urgent need for much more research on the links between the biosphere and the geochemical cycles. An integrated model of these cycles is also needed. The stabilizing and destabilizing mechanisms in the system must be identified and characterized. The stability properties of the integrated system must be investigated.

This research will take time, perhaps decades. It was pointed out above that self-organizing systems tend to change continuously within relatively stable envelopes. Yet when external forces interfere with stability (e.g. by unbalancing the fluxes in the system) a different kind of behavior can occur. Given that the bio-geochemical system is non-linear and complex, the dynamic behavior of such systems can be "chaotic". Some of the behavioral characteristics of the system, that were formerly predictable (in the probabilistic sense), can become unpredictable. We may not, be able to ascertain the limits of safety for human interference, even in principle. Yet the magnitude of anthropogenic disturbance is growing, decade by decade.

In the circumstances, it is hard to avoid the conclusion that the *only* prudent course of action is to reduce anthropogenic interference with natural processes. While it cannot be accomplished overnight, the goal of both economic development and environmental protection policy over the next few decades must be to stop those activities that are most likely to interfere with natural climatological and nutrient cycling processes.

References

[Alcamo et al 1986] Alcamo, Joseph, Leen Hordijk, J. Kamari, P. Kauppi, M. Posch & E. Runca, *Integrated Analysis of Acidification in Europe*, Research Report (RR-86-2), International Institute for Applied Systems Analysis, Laxenburg, Austria, March 1986.

[Barnett & Morse 1962] Barnett, Harold J. & Chandler Morse, *Scarcity & Growth: The Economics of Resource Scarcity*, Johns Hopkins University Press, Baltimore, 1962.

[Barney 1980] Barney, Gerald (Study Director), *The Global 2000 Report to the President*, Technical Report (Volume 2), Council on Environmental Quality/U.S. Department of State, Washington DC, 1980.

[Boulding 1966] Boulding, Kenneth E. ''Environmental Quality in a Growing Economy'', in: Garrett(ed), *Essays from the Sixth RFF Forum*, Johns Hopkins University Press, Baltimore, 1966.

[Brown 1974] Brown, Lester R. with Erik P. Eckholm, *By Bread Alone*, Praeger Publishers, New York, 1974.

[Brown 1978] Brown, Lester R., *The Worldwide Loss of Cropland*, Worldwatch Paper (24), Worldwatch Institute, Washington DC, October 1978.

[Brown & Wolf 1984] Brown, Lester R. & Edward C. Wolf, *Soil Erosion: Quiet Crisis in the World Economy*, Worldwatch Paper (60), Worldwatch Institute, Washington DC, September 1984.

[Clark & Munn 1986] Clark, William & R.E. Munn, *Sustainable Development of the Biosphere*, Technical Report, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1986. [Cambridge University Press]

[Cole et al 1973] Cole, H.S.D. et al (eds), *Models of Doom: A Critique of the Limits to Growth*, Universe Books, New York, 1973.

[Commoner 1971] Commoner, Barry, *The Closing Circle*, Alfred Knopf, New York, 1971.

[Commoner 1976] Commoner, Barry, *The Poverty of Power*, Bantam Books, New York, 1976.

[Ehrlich 1968] Ehrlich, Paul, *Population Bomb*, Ballantine, New York, 1968.

[Forester 1971] Forester, James V., *World Dynamics*, Wright-Allen, Cambridge MA, 1971.

[Frank 1990] Frank, Louis A. (with Patrick Huyghe), *The Big Splash*, Avon Books, New York, 1990.

[Georgescu-Roegen 1971] Georgescu-Roegen, Nicholas, *The Entropy Law & the Economic Process*, Harvard University Press, Cambridge MA, 1971.

[Georghiou & LeBaron 1991] Georghiou, George P. & H.M. LeBaron, Title missing, *American Scientist*, November-December 1991 1991 :507.

[Goeller & Weinberg 1976] Goeller, H. & Alvin Weinberg, "The Age of Substitutability", *Science* **191**, February 1976.

[Graf 1924] Graf, G.E., *Erdol, Erdolkapitalismus, und Erdolpolitk*, Urania-Verlags GmbH, Jena, Germany, 1924.

[Heilbroner 1972] Heilbroner, Robert, "Growth & Survival", *Foreign Affairs* **57**(1), October 1972 :139-153.

[Kahn et al 1976] Kahn, Herman, William Brown & L. Martel, *The Next 200 Years - A Scenario for America & the World*, Wm. Morrow, New York, 1976.

[Keyfitz 1991] Keyfitz, Nathan, "Population & Development Within the Ecosphere: One View of the Literature", *Population Index* **57**(1), Spring 1991 :5-22.

[Lovelock 1972] Lovelock, James E., "Gaia as Seen Through the Atmosphere", *Atmospheric Environment* **6**, 1972 :579-580.

[Lovelock 1979] Lovelock, James E., *Gaia: A New Look at Life on Earth*, Oxford University Press, London, 1979.

[Lovelock 1982] Lovelock, James E., *Gaia: A New Look at Life on Earth*, Oxford University Press, London, 1982. 1st Paperback edition.

[Lovelock 1988] Lovelock, James E., *The Ages of Gaia: A Biography of Our Living Earth*, Oxford University Press, London, 1988.

[Meadows et al 1972] Meadows, Dennis et al, *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*, Universe Books, New York, 1972.

[Meadows et al 1974] Meadows, Dennis et al, *Dynamics of Growth in a Finite World*, Wright-Allen Press, Cambridge MA, 1974. [Distributed by Productivity Press]

[Mesarovic & Pestel 1974] Mesarovic, M. & E. Pestel, *Mankind at the Turning Point - The Second Report to the Club of Rome*, E.P. Dutton/Readers' Digest Press, New York, 1974.

[Nicolis & Prigogine 1977] Nicolis, Gregoire & Ilya Prigogine, *Self-Organization in Non-Equilibrium Systems*, Wiley-Interscience, New York, 1977.

[Paddock & Paddock 1967] Paddock, Paul & William, *Famine - 1975*, Little, Brown, Boston, 1967.

[Postel 1989] Postel, Sandra, *Water for Agriculture: Facing the Limits*, Worldwatch Paper (93), Worldwatch Institute, Washington DC, December 1989.

[Prigogine et al 1972] Prigogine, Ilya, Gregoire Nicolis & A. Babloyantz, "Thermodynamics of Evolution", *Physics Today* **23**(11/12), November/December 1972 :23-28(N) & 38-44(D).

[Repetto 1985] Repetto, Robert (ed), *The Global Possible: Resources, Development & the New Century*, Yale University Press, New Haven CN, 1985.

[Repetto et al 1991] Repetto, Robert et al, *.COSTA RICA* . (Unpublished), 1991.

[Schumacher 1973] Schumacher, E.F., *Small Is Beautiful: Economics as Though People Mattered*, Harper Colophon, Harper & Row, New York, 1973.

[Simon 1977] Simon, Herbert A., "What Computers Mean for Man & Society", *Science* **195**(4283), March 18, 1977.

[Simon 1980] Simon, Julian, "Resources, Population, Environment: An Oversupply of False Bad News", *Science* **208**, June 27, 1980 :1431-1437.

[Simon-a 1980] Simon, Julian, *The Ultimate Shortage*, Princeton University Press, Princeton NJ, 1980.

[Smith 1979] Smith, V. Kerry (ed), *Scarcity & Growth Revisited*, Johns Hopkins University Press, Baltimore, 1979.