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Nature's Economy and the Human Economy

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Abstract Human beings and the human economy are entirely integrated into nature's economy—the biosphere and the ecosystems that comprise it. Society is therefore utterly dependent on the free services provided by ecosystems. But population growth, rising per capita consumption, and the use of environmentally malign technologies are steadily eroding those services. Projecting how long that process can continue without a global calamity depends on numerous uncertainties, many created by the existence of nonlinearities, thresholds, and lag times in ecological systems. A major problem is to determine how to allocate resources in various ways to solve the human predicament. Scientists have much of the information necessary for making those decisions, so the biggest problem is in the purview of social scientists. They must help to determine how best to move society from knowledge to action.

Keywords Economy · Ecosystems · Natural capital · Population · Consumption · Economic growth

The terms "Ecology" and "economics" have the same root in Greek, "Oikos" – house. Ecology can be considered the study of nature's house; economics is the study of a subsection of nature's house, the human house.

1 Nature's House

The part of our planet that harbors life—from a few kilometers below the surface to higher than Mount Everest in the atmosphere—is a system composed of all of Earth's organisms and the physical environments with which they interact. This "biosphere" is the largest unit of nature's house—in scientific jargon, an ecosystem. Smaller ecosystem units can be defined as the combined physical environment and the living elements in a single forest,

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a single aquarium, or even the inside of your gut (richly populated with bacteria and other microorganisms thriving in the warm, wet environment you provide) (Millennium Ecosystem Assessment 2003; Steffen et al. 2004).

Like all animals, plants, and microbes, people are parts of ecosystems. They interact with their physical environments, for example extracting oxygen from the atmosphere, returning carbon dioxide (CO_2) to it, and on a cool day warming the atmosphere while shivering in response to the temperature. People interact with other organisms by eating them (steak, wheat, spinach), being eaten by them (great white sharks, mosquitoes, the protozoans that cause malaria), or cooperating with them (many of the bacteria in human intestines, hunting dogs, other people).

The energy that drives ecosystems comes almost entirely from the sun; some of its rays are captured by green plants in the process of photosynthesis. The old saying that "all flesh is grass" is close to correct. Energy, which one can think of as stored work, travels one way through ecosystems. Although energy can neither be created or destroyed (first law of thermodynamics), each time some is used to do work, part of it flows to places from which it cannot be retrieved to do more work (second law of thermodynamics). When a steer eats grass, it will gain weight, but many times more than a pound of grass (dry weight) must be eaten to produce a pound of beef. Chewing, digesting, making muscle and fat, all require work, and all produce waste heat that cannot be harnessed to do anything useful. That is why more vegetarians can be supported on a given amount of crop production than people who pass the crops through cattle in order to yield steaks.

Unlike energy, materials can be and are recycled by ecosystems. The non-living nutrients that are required to build a photosynthesizing grass plant are taken from air and soil, and are returned to the non-living part of the ecosystem when the grass dies (or are returned in the feces, urine, and flatulence of a steer that ate the grass, or of a person who ate the steer, or when the body of steer or person decays). Materials such as carbon, nitrogen, and phosphorus move in gigantic global cycles (biogeochemical cycles) that involve many different organisms and many different chemical forms, and keep life on Earth going. Although ecosystems are simple in principle, in actuality they can be extremely complex.

Human beings evolved genetically and culturally in response to the ecosystems in which they participated and upon which they depended. We're still doing it, and our dependence is usually discussed by scientists in terms of the "ecosystem services" society receives (Holdren and Ehrlich 1974; Daily 1997). Those services are diverse, and include maintaining the gaseous quality of the atmosphere, moderating the climate and local weather, running the hydrological cycle that supplies fresh water, controlling floods and storm surges, generating and maintaining the soils essential to agriculture and forestry, controlling the vast majority of pests that could attack our crops, and supplying "ecosystem goods" such as fishes from the sea, timber, natural pharmaceuticals, and game and other wild foods.

2 The Human Economy

The "human house" depends on four kinds of capital for its functioning. The most familiar are human-made capital (also called reproducible or built capital) such as buildings, machine tools, vehicles, appliances, etc. Human capital is the skills and knowledge of the labor force. Both of those types of capital are carefully tracked by societies. Less well tracked is social capital, which is also less well characterized but can be defined as the values (positive or negative) embodied in social networks and institutions. The form of capital that concerns us most here is natural capital—the components of ecosystems—the "interest" flowing from

which is those ecosystem services just described. Natural capital generally is poorly valued or not valued at all, even though that capital is equally or more essential to human survival and welfare than other forms of capital. Many of the most devastating costs to humanity that are not captured in markets (externalities) are damages to natural capital (e.g., Dasgupta 2007).

Those externalities are one signal that human beings have overpopulated Earth and that present patterns of behavior are not sustainable. Three elements of natural capital show this especially dramatically. One is deep, rich agricultural soils, which are mostly generated on a time scale of centimeters per century and in many areas are being eroded away at a rate of meters per century. The second is groundwater, especially "fossil" groundwater (that accumulated during ice ages), which over much of the planet is being withdrawn from aquifers at far above recharge rates. The third is biodiversity: the plants, animals, and microorganisms that are the working parts of ecosystems, and whose populations and species are being exterminated at a rate unprecedented in the roughly 7 million years of human history.

These are, of course, intertwined problems because ecosystems are held together by webs of interactions. Soils are produced by the interactions of wind, water, and organisms with rocks. Thanks to the actions of the dominant animal on the planet, *Homo sapiens*, global climate (including wind and water flows) is changing at a rate unprecedented in the past ten millennia, since humanity took up farming. Soils are themselves complex ecosystems. They are not mere crushed rock—fertile soils are incredibly chemically complicated structures, teeming with life. A ton of soil contains about 100 million billion microbes, some 100,000 times the number of stars in our galaxy. Worms, fungi, and a myriad other soil organisms are essential to creating and preserving soil fertility. That fertility, in turn, is essential to agriculture and forestry, which supply that dominant animal with food and timber.

But ecosystem services are increasingly faltering under the assault of increasing numbers of people, growing levels of per capita consumption, and the use of environmentally destructive technologies. Humanity is already running short of water in many areas (Postel et al. 1996; Gleick 2007). Opportunities for diverting more of the hydrologic cycle to human uses tend to be limited and expensive. Climate change and loss of biodiversity are changing patterns of water flow. For example, about 30% of the Parc Nacionale des Volcans in Rwanda was deforested in the 1960s for a failed pyrethrum scheme. The wooded volcano park served as a gigantic sponge that soaked up rainfall and metered it out in stream flow, providing about 10% of the nation's agricultural water. The deforestation led to the drying up of some of the streams, hurting farmers.

In a world where most major habitats have been either destroyed or fragmented by human activities (one quarter of the global land surface has been converted to crop systems, about half has been seriously disturbed by humanity, and all of it has been modified by human activities), climate change constitutes a special threat to biodiversity. Organisms occur in smaller populations than before, exposing them to a greater threat of extermination (rather than evolutionary adaptation to new conditions). Other organisms that cannot adapt but whose populations could migrate to stay within a suitable climate envelope, are prevented from doing that, either because the change is too rapid or because of barriers created by habitat fragmentation due to human settlement and agricultural conversion. Ironically, biodiversity could help save itself. Growing forests is one way to *reduce* the rate of climate change because it removes the greenhouse gas (GHG) CO_2, the principal cause of climate change, from the atmosphere.

3 Allocating Responsibility for Damaging Life-support Systems

Land-use change and climatic disruption are just examples of the assault on ecosystem services now being generated by humanity. That assault threatens the very existence of industrial civilization—a threat that is often referred to as "the human predicament." How does one allocate responsibility among various societies and aspects of the human enterprise for this assault? Scientists generally use the simple I = PAT formula (Ehrlich and Holdren 1971; Ehrlich and Ehrlich 1990). I is the total Impact of a human group, P is Population size, A is Affluence, measured as per capita consumption, and T is a grab-bag term for the Technology employed to supply the consumption, along with the economic, social, and political arrangements of the supply system. A society's total impact is the product of these three factors. This formulation immediately calls attention to an important aspect of the relationship between human economies and nature's economy. It was once considered that the most important population problem was growth in poor countries with high birthrates. I = PAT shifted attention to the problem centered in the rich countries because their "A" factors were as much as 20 times greater than those of the poor.

Population statistics are easy to obtain, produced by governments. Although they are of variable quality, they generally present a pretty good summary of the demographic situation. The A and T factors present greater difficulties. For example, some forms of consumption are more environmentally damaging than others—buying a Degas painting is more ecologically benign than purchasing an executive jet. Worse yet, in many cases no detailed comparisons of impacts have been made, and how one would aggregate across different technologies is not clear. In the face of these problems, environmental scientists tend to use per capita energy use as a surrogate for $A \times T$. Almost all environmentally damaging activities involve energy use, and the damage is generally highly correlated with the amount used. Flying an executive jet uses a lot more energy than enjoying a Degas hung in your living room. Energy use statistics also tend to agree with other estimates of the damage done by societies.

As John Holdren has shown, the United States could potentially reduce its energy use through efficiency improvements to about a quarter of today's level while *increasing* the quality of life. Holdren has developed an optimistic (or, as he calls it, "best plausible") scenario for the population-energy-environment future. It is shown in Table 1. Why do we call this an optimistic scenario? First of all, it shows population peaking around the middle of this century and then declining. That implies changes in attitudes and government policies, further improvement in the situation of women, and making family planning more widely available. Second, it projects that total human energy use in 2100 could be 23 terawatts ($TW = 10^{12}$ W)—down from 27 TW in 2050. That's still a lot of energy, and it's not clear that Earth's ecosystems can sustain being assaulted with over 20 TW for almost a century. At the same time, 23 TW is much, much better than the 57 TW projected under a "business as usual" scenario in which humanity continues to more or less ignore its environmental peril. Third, the Holdren scenario shows the gap between the rich and the poor disappearing by 2100 as the two groups converge on a per capita energy use of 3 kW ($kW = 10^3$ W).

This means much greater efficiency would be achieved among both rich and poor, with the poor extracting much more quality of life from roughly three times their 2000 energy use, and the rich also improving the quality of their lives but using less than half as much energy as they did a century before. The US actually would drop its per capita energy use from about 11 to 3 kW. That implies deployment of many technologies already in hand but not in wide use or as well developed as they might be. As the table also illustrates, the carbon efficiency of the global economy (roughly the amount of carbon in the form of CO_2 from

Table 1 Holdren's optimistic scenario

	2000	2050	2100
Population (billions)	6.1	9.0	7.5
GDP/person (year 2000 $)			
Industrial	23,000	43,000	70,000
Developing	3,000	22,000	70,000
GDP (trillion year 2000 $)	45	225	525
Energy use (TW)[a]	14	27	23
Carbon emissions (GtC)[b]	6.4	6.9	2.8

[a] TW = 10^{12} W
[b] GrC = Gigatons (10^9 tons) of carbon, as the weight of the carbon itself in CO_2

burning fossil fuels emitted to the atmosphere per unit of GDP) would increase some 25-fold, through switching to non-carbon-emitting technologies and sequestration of CO_2.

Whether all this will happen remains to be seen, but Holdren has convincingly shown it is possible to limit humanity's impact to 23 TW 90 years from now. Whether energy use and other human activities between now and then will cause a collapse of life-support systems that will make the scenario irrelevant remains to be seen, as does whether a civilization with a 23 TW level of energy use can be sustained.

Since the population and affluence factors are both increasing, and almost all societies, including the richest, seem determined to keep the A factor rising, the prospects for reaching a sustainable society do not seem bright. To some degree, of course, this depends on what one wishes to sustain. Some analysts, especially environmental scientists, look to sustaining or restoring resource stocks—humanity's supply of natural capital. Others, especially economists, look to sustaining human well-being. They put more weight on the possibilities for substituting for natural capital. Recent work, however, indicates that these two approaches may not be far apart in their conclusions, which involve enough uncertainty to suggest a risk-averse approach (precautionary principle) (Arrow et al. 2004; Ehrlich and Goulder 2007).

4 The Dimensions of Uncertainty

Much of the critical uncertainty is grounded in the characteristics of nature's economy. Ecosystems tend to react in a non-linear fashion to perturbation; that is, the response of the system may not be proportional to the forcing applied to it. Two degrees Celsius of global heating might just melt some ice, raise sea level a few dozen centimeters, increase the frequency of droughts and the strength of hurricanes, generally lengthen growing seasons in temperate zones, and so on. It might also generate a rapid positive feedback in the form of releasing additional carbon dioxide (CO_2) and methane (another potent greenhouse gas), from arctic permafrost and shallow northern seas. That could speed the system to an additional four or five degrees Celsius of heating that might be sufficient to flip the climate into a regime not seen in the history of our species. The results could include drying up major grain-growing areas, flooding large areas of land and most coastal cities, killing off much of the oceans' productivity (in part by acidification caused by increased CO_2 absorption), and, by changing oceanic circulation, putting Europe into a relative deep freeze.

Nonlinearities often arise from the existence of thresholds. Fertilizer runoff can go down a river for decades until suddenly a fertilization threshold is crossed and a "dead zone" appears in the ocean off the river's mouth. Passenger pigeons could be hunted for decades and

gradually declined in numbers. Then their numbers, while still high, dropped below the threshold above which they could form the huge colonies required for successful reproduction, and they plunged to extinction. New flu virus strains can be generated in bird-pig-people interactions in Asia until suddenly one capable of causing a pandemic emerges and kills tens of millions of people. Larger and larger, ever more vulnerable human populations press ever closer to the natural reservoirs of human disease until an AIDS virus or some other deadly pathogen successfully transfers into *Homo sapiens*.

Time lags are also characteristic of ecosystem responses. GHGs released today will influence climate centuries in the future. It can take years for insect pests to evolve resistance to pesticides. Introduced organisms can remain obscure for years before exploding to pest status. Global heating may go on for decades, and then water flow under the west Antarctic ice sheet could cross a threshold, suddenly allowing the entire mass to slip into the ocean and raise sea level by meters in months or less. Societies have accumulated nuclear weapons over more than a half-century; if after such a time lag, a number of them were suddenly used, the damage to nature's economy (to say nothing of the human economy) could well be catastrophic.

Finally, disrupting ecosystems is fraught with possible irreversibility's. The Antarctic ice sheet can't be restored on a time scale of interest to society. Long-lived toxic or hormone-mimicking chemicals released into the environment cannot, in general, be recaptured. Species (and many population) extinctions are forever. Furthermore, knocking one population out of an ecosystem may irreversibly change the entire structure of the system.

5 Human Barriers to Sustainability

Since these problems with nature's economy need to be fixed by the human economy if it is to remain functional, one widely misunderstood aspect of the latter impedes such resolution: the rate at which the environmental future is discounted. Human beings generally discount the future—enjoy your prized bottle of wine or take that vacation today. If you wait a month you might be dead. Most people would rather be given $95 today than $100 in a year—something sometimes referred to as the "time value of money." Politicians in democracies have very high discount rates in certain areas; anything they could do that won't have a positive impact until they're out of office is usually not seen as an attractive option.

Long-term interest rates generally reflect the time value of money, and recently have been 5% or a little less. Economists have tended to adopt similar rates when discounting future benefits, such as the benefit to future generations of preserving pollinators or of trying to limit the flux of greenhouse gases into the atmosphere to limit climatic disruption. At that discount rate, it doesn't make sense to pay very much today to obtain those benefits, and that is widely stated. But in fact the selection of such high discount rates is likely a serious error for technical reasons. It assumes, for example, that future generations will be much richer than the present one. If they are going to be poorer (a real possibility given the present assault on nature and the likely costs of dealing with environmental deterioration), the discount rate should be negative. People should be willing to pay more today to preserve things their descendants otherwise might not be able to afford.

Another key problem for nature's economy is the belief in the minds of most people, including most decision makers, that the physical economy must grow in perpetuity. Smart economists know this is impossible, but growth continues in both rich countries (where it is mostly fueled by wasteful overconsumption) and poor countries (where certain kinds of growth are essential and a form of investment). There is no serious discussion of the possibility

of redistribution to help either the poor or nature's economy. Furthermore, in order to keep growth going, more and more resource wars are being triggered, from the Israel–Arab 1967 war over water to America's present adventure in Iraq, where the fundamental issue is Iraq's vast oil reserves. These wars both have roots in nature's economy (e.g., in the distribution of natural capital) and direct effects on it, which in the future could be very serious, especially if resource wars go nuclear.

Perhaps the most ominous aspect of the state of nature's economy is the multiplicity of threats that it faces. This presents another substantial problem for the human economy. How should society allocate its funds and efforts to preserving natural capital as opposed to meeting other needs? Should it concentrate on stopping population growth and starting a slow decline toward a sustainable level? Or to halting greenhouse gas emissions? To inventing "consumption condoms?" To restricting the release of myriad novel chemicals whose threat is largely unknown, or to finding ways to protect populations and species from extinction? All of those would deal with some of the most important threats to natural capital that humanity faces. But the situation is made more difficult by the myriad uncertainties that surround them—about how serious they are and about what is required to deal with them satisfactorily. Should people put a giant sun shield far out in space, at incredible cost, to stave off the heating of Earth, despite the uncertainties of the results and the other possible uses for the same funds? Solving this problem amounts to calculating how to make the opportunity costs of assigning funds to each problem more or less equal. And all that neglects dealing with poverty, health care needs, decaying human-made infrastructure, and so on.

At least substantial information exists on which to base judgments of effort allocation. As a general rule, scientists have more than enough knowledge of the state of nature's economy to know the directions in which the human economy should be steered to change the "collision course" that human beings and the natural world are on, according the 1993 *World Scientists' Warning to Humanity* (Union of Concerned Scientists 1993). So a key issue today is how to change human behavior so we get on with the job. And that is in the realm not of the natural sciences but of the social sciences. Social scientists must answer crucial questions such as how to deal with the maldistribution of power that underlies much of the behavior of the human economy that threatens nature's economy. World-class economists are beginning to look at these issues, but are not well supported by the discipline as a whole, which is heavily focused on sophisticated mathematical treatments of problems not likely to provide answers of practical importance to solving the human predicament. The few political scientists, sociologists, anthropologists, and psychologists who are concerned about that predicament are often unappreciated minorities within their disciplines.

It has been suggested that a *Millennium Assessment of Human Behavior* might be organized that could jump-start a needed reassessment by the social science community of its goals and organization (Ehrlich and Ehrlich 2004; Ehrlich and Kennedy 2005). We have empirical evidence that societies can quite unexpectedly change course when the time is ripe (consider the change in race and gender relations in the United States from 1948 to 1978; the collapse of the Soviet Union in the 1990s). To preserve the features of nature's economy on which humanity depends, the help of social scientists is needed to ripen the time.

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