Carrying capacity and ecological economics

When the tempest arose, "the mariners were afraid...and cast forth the wares that were in the ship into the sea, to lighten it of them" (Jonah 1:5 King James). This passage from the Book of Jonah anticipates a strategy many environmentalists recommend today. Nature surrounds us with life-sustaining systems, much as the sea supports a ship—a ship that is likely to sink if it carries too much cargo. Environmentalists therefore urge us to "keep the weight, the absolute scale, of the economy from sinking our biospheric ark" (Daly 1991a, p. 35).

This concern about the carrying capacity of Earth, reminding us of the fearful sailors on Jonah's ship, marks a departure from traditional arguments in favor of environmental protection. The traditional arguments did not rest on prudential considerations. Early environmentalists such as Henry David Thoreau (Shanley 1971) cited the intrinsic properties of nature, rather than its economic benefits, as reasons to preserve it. They believed that economic activity had outstripped not its resource base but its spiritual purpose. John Muir condemned the "temple destroyers, devotees of ravaging commercialism" who "instead of lifting their eyes to the God of the mountains, lift them to the Almighty dollar" (Muir 1912, p. 256). This condemnation was not a call for improved cost-benefit analysis. Nineteenth-century environmentalists, seeing that nature is full of divinity, regarded its protection less as an economic imperative than as a moral test.

By opposing a strictly utilitarian conception of value, writers such as Muir saved what little of nature they could from what Samuel P. Hays called the gospel of efficiency (Hays [1959] 1972). Today, however, environmentalists themselves often preach this gospel. They have developed contingent valuation methodologies to assign what they call shadow prices to intrinsic values. They construct on-line, integrated, multiscale, ecological economic models and assessments, using the results of interactive, interdisciplinary, adaptive, synthetic, multifactorial, multiscale, multifunctional, networked, computational, simulational, cross-cutting, externally funded research. They address uncertainties, vulnerabilities, and surprise scenario forecasts. Thus they adopt the very economic or utilitarian approach their predecessors deplored.

In this article, I question attempts by today's environmentalists, particularly those who identify themselves as ecological economists, to vindicate environmental protection on instrumental grounds. I cast doubt on hopes that the utilitarian logic of ecological economics is any more able than is the logic of mainstream economics to provide a strong foundation for the cause of environmentalism.

by Mark Sagoff

Mainstream versus ecological economics

Mainstream economists, such as James Tobin, Robert Solow, and William Nordhaus, typically state that nature sets no limits to economic growth. Trusting to human intelligence and ingenuity as people seek to satisfy their preferences and achieve well-being, these economists argue that people can "choose among an indefinitely large number of alternatives" (Barnett and Morse 1963). They believe that the earth's carrying capacity cannot be measured scientifically, because it is a function or artifact of the state of knowledge and technology.

Ecological economists, in contrast, believe that sources of raw materials and sinks for wastes (what they call natural capital) are fixed and therefore limit the potential growth of the global economy. They reject the idea that "technology and resource substitution (ingenuity)... can continuously outrun depletion and pollution" (Daly 1985, pp. 274–275). Growth faces limits, Herman Daly has written, and to "delude ourselves into thinking that growth is still possible if only we label it 'sustainable' or color it 'green,' will just delay the inevitable transition and make it more painful" (Daly 1993, p. 268).

We may also characterize the difference between mainstream economists and ecological economists with reference to the concept of the limiting factor. According to Daly and his coauthors, we have "entered a new era" in which "the limiting factor in development is no longer man-made capital but remaining natural capital" (Costanza et al. 1991, p. 8). Mainstream economists argue, however, that if there is a limiting factor in economic production, it is knowledge, and that as long as knowledge advances, the economy can expand. Where there is effective management, Peter Drucker has written, "that is, the application of knowledge to knowledge, we can always obtain the other resources" (Drucker 1993). He adds: "The basic resource—'the means of production,' to use the economist's term—is no longer capital, nor natural resources (the economist's 'land'), nor 'labor.' *It is and will be knowledge*" (Drucker 1993, p. 8).

The idea that knowledge is the key resource reflects theoretical and empirical results that Solow presented in the 1950s and summarized in 1970 (Solow 1956, 1957, 1970). According to Joseph Stiglitz (1990, p. 53) Solow found that economic growth depends "simply on the rate of (labor-augmenting) technological change," and that "most of the growth of the economy over the last century had been due to technological progress." Economists following Solow have adopted a standard model of growth that contains only two factors: knowledge and the labor to apply it. This model differs from the classical model of Ricardo and Malthus (Malthus [1836] 1989, Ricardo [1817] 1951) because "[natural] resources, the third member of the classical triad, have generally been dropped" (Nordhaus and Tobin 1972, p. 14).

Mainstream economists offer at least three arguments to show that knowledge and ingenuity are likely always to alleviate resource shortages. First, reserves of natural resources "themselves are actually functions of technology. The more advanced the technology, the more reserves become known and recoverable" (Lee 1989, p. 116). Recent examples of reserve-increasing technologies include the use of bacteria to leach metals from low-grade ore and the application of computer analysis to seismic vibrations to locate deposits of oil (Gianturco 1994). As a result of such advances, reserves of many nonrenewable resources have increased in recent decades, despite rising global consumption. Between 1987 and 1990, estimates of proven recoverable reserves of petroleum, for example, rose 11.4% and those of natural gas by 17.9% (WRI 1994).

Second, advances in technology allow us not only to increase available reserves but also to employ substitutes for resources that may become scarce. When mainstream economists speak of substitutability, they generally refer to the substitution of one resource for another or "the ability to substitute away from resources that are becoming scarce" (World Bank 1992). As Solow (1973, p. 53) explains, "Higher and rising prices of exhaustible resources lead competing producers to substitute other materials that are more plentiful and therefore cheaper." Daly correctly ascribes to Nordhaus and Tobin the view "that in the aggregate resources are infinite, that when one flow dries up, there will always be another, and that technology will always find ways to exploit the next resource" (Daly 1991b, p. 108).

The third argument offered by mainstream economists is that the power of knowledge continually reduces the amounts of resources needed to produce a constant or increasing flow of consumer goods and services. "If the future is anything like the past," Solow writes, "there will be prolonged and substantial reductions in natural resource requirements per unit of real output" (Solow 1974, pp. 10–11). Knowledge increases the productivity of natural resources just as it increases the productivity of labor. For example, for transmitting messages, glass fibers not only substitute for but vastly improve upon copper cables. The transmission capacity of an optical fiber cable increased by an order of magnitude every four years between 1975 and 1992. Today, a thin cable using optical amplifiers and erbium-doped fibers powered by laser diode chips can carry 0.5 million phone calls at any moment. Computers become stronger as they grow smaller; the world's entire annual production of computer chips can fit into a single 747 jumbo jet (Herman et al. 1990). Moreover, energy requirements continually decrease per unit of economic output; for example, the amount of energy needed to produce a unit of household lighting has decreased manyfold since the time of candles and oil lamps. For reasons such as these, "virtually all minerals have experienced long-term declines in real prices during the last two generations" (Smil 1993, p. 57).

Reflecting on these trends, the World Resources Institute (WRI) questions the idea that shortages of nonrenewable resources will prove a limiting factor in the global economy. WRI (1994, p. 6) states: "Even without more resource-sparing policies...the cumulative effect of increasing reserves, more competition among suppliers, and technology trends that create substitutes suggests that global shortages of most nonrenewable resources are unlikely to check development in the early decades of the next century." WRI also dismisses "the frequently expressed concern that high levels of consumption will lead to resource depletion and to physical shortages that might limit growth or development opportunity." The evidence suggests that "the world is not yet running out of most nonrenewable resources and is not likely to, at least in the next few decades" (WRI 1994, p. 5).

Many mainstream economists are less convinced than Barnett and Morse (1963) that there are no natural resource limits whatever to economic growth. Some mainstream analysts have proposed careful models for measuring price trends (Hall and Hall 1984, Slade 1982a, b); others have explained how difficult it is to obtain measures of scarcity (Dasgupta and Heal 1979, Fisher 1979, Smith and Krutilla 1982); and many others have explored problems created by externalities and common property regimes (Ayres and Kneese 1969, Kamien and Schwartz 1982). Some ecological economists have tried to find common ground with mainstream economists with respect to residuals management (waste processing) and intertemporal equity (the due consideration of the interests of future generations; Page 1977). Other ecological economists have emphasized adaptive management approaches to particular environmental and resource problems (Common 1995, Holling 1978). Not every ecological economist may agree with Paul Ehrlich and Anne Ehrlich (1974) and Daly (1991b), moreover, that we confront an age of scarcity in the near or, at best, the medium term.

While both mainstream and ecological economics comprise a variety of positions, sometimes intersecting, in this article I single out for criticism a series of arguments that ecological economists, such as Ehrlich and Ehrlich, Daly, Robert Costanza, and Donnella Meadows (1992), have mounted against the growth model of neoclassical economics, as defended by Barnett and Morse, Nordhaus, Tobin, Solow, Stiglitz, and others. To show that these arguments fail is to prove neither that the standard model is correct nor that there are no ecological or resource limits to growth. In fact, the thesis that there are significant natural limits to growth remains intuitively appealing. Accordingly, we should subject arguments for that thesis to friendly criticism, if by this means they can be strengthened and improved.

Energy and entropy

In their dissent from the prevailing mainstream view, many ecological economists cite a theory put forward by Nicholas Georgescu-Roegen (1971), which depends on two premises to refute the standard model of economic growth. The first premise cites the second law of thermodynamics, which requires that in "entropy terms, the cost of any biological or economic enterprise is always greater than the product" (Georgescu-Roegen 1973, pp. 41–42). There is always an energy deficit. Second, the free or usable energy (what is called low entropy) that is used up to replace this deficit represents a fixed and dwindling stock. Because we are running down low-entropy terrestrial resources, ecological economists contend, "nature really does impose an inescapable general scarcity," and it is a "serious delusion to believe otherwise" (Daly 1979, p. 69).

The first premise is unexceptional: The global economy must consume energy. After running through its reserves of fossil fuel, it must therefore import power from some other source. The second premise, however, is controversial: Are energy resources limited to a fixed and dwindling stock?

If we ignore pollution problems, fossil fuels could subsidize the global economy for quite a while. According to John Holdren, "one sees no immediate danger of 'running out' of energy in a global sense.... At 1990 rates of use, resources of oil and natural gas would last 70 to 100 years," counting conventional sources only, and there is "a 1500-year supply of coal" (Holdren 1992, p. 165). The World Bank estimated in 1992 that, at present rates of extraction, known reserves of fossil fuels would last for 600 years. The World Bank concluded that "fears that the world may be running out of fossil fuels are unfounded" (World Bank 1992, p. 115).

The well-known problems associated with greenhouse gases, however, argue for a general conversion to nonpolluting energy sources, such as solar power and geothermal energy. These sources—which dwarf fossil fuels in the amount of energy they make available—seem so abundant that for practical purposes they may be regarded as infinite. Kenneth Townsend observes, for example, that "the spontaneous flow of energy on earth from low- to high-entropy states may be offset by solar flow" (Townsend 1992, p. 98). Georgescu-Roegen recognizes that it may be possible "to make greater use of solar radiation, the more abundant source of free energy" (Georgescu-Roegen 1973).

The sunlight continually reaching the surface of the earth—not including vast amounts diffused in the atmosphere—is unimaginably immense. At the equivalent of 1.73×10^{14} kilowatts (kW) of power, it represents an annual energy income or subsidy of 1.5×10^{18} kW hours, approximately 10,000 times the amount of energy the global economy now consumes (Dunn 1986). Even with today's technology, conversion efficiencies of sunlight to electricity are good—23% on sunny days and 14.5% on average annually for Luz solar trough systems (Brown et al. 1995, Pimentel 1994) and approximately 11% (with performance improving rapidly) for current advanced amorphous silicon, copper indium diselenide, and cadmium thin-film photovoltaic systems. Analysts who study the rapidly falling prices and increasing efficiency of solar energy tend to agree with Lester Brown of the Worldwatch Institute that "technologies are ready to begin building a world energy system largely powered by solar resources" (Brown et al. 1991, p. 48).

While photovoltaics currently enjoy the greatest interest, water, wind, and biomass also provide promising and cost-effective methods of harnessing the superabundant energy of the sun. Hydropower now supplies 24% of total world electrical-generating capacity (Gleick 1994). Rapid gains in capturing wind power have made it competitive with other energy sources; in California, for example, wind machines now produce enough electricity to meet the residential needs of a city the size of San Francisco. Energy plantations, using fast-growing plants to remove carbon from the atmosphere, may build on the Brazilian fuel-alcohol program (Rothman 1983).

One recent survey found that by "the middle of the 21st century, renewable energy technologies can meet much of the growing demand at prices lower than those usually forecast for conventional energy" (Johansson et al. 1993, p. 1). This survey brings together well-respected authorities who review enthusiastically the potential of hydropower, crystalline-and-polycrystalline-silicon solar cells, amorphous silicon photovoltaic systems, photovoltaic concentrator technology, ethanol and methanol production from cellulosic biomass, advanced gasification-based biomass power generation, wind energy, and various other power sources considered to be environmentally friendly. The survey also describes the exceptional prospects of nonsolar alternatives, such as tidal power, which captures gravitational energy, and geothermal power, which employs heat coming from the earth's core. The energy accessible to modern drilling technology from geothermal sources in the United States, for example, is thousands of times greater than that contained in domestic coal reserves (NAS 1987).

Amory Lovins, like others who study energy technology from the bottom up, has argued that advanced technologies are commercially available that can "support present or greatly expanded worldwide economic activity while stabilizing global climate—and saving money" (Lovins and Lovins 1991). Lovins writes that "even very large expansions in population and industrial activity need not be energy-constrained" (Lovins 1991, p. 95). If available geothermal, solar, and other sources of nonpolluting energy exceed global demand by many orders of magnitude, and if efficiency alone can greatly increase economic output with no additional energy inputs, it is not obvious how the second law of thermodynamics limits economic growth.

Rather than refute Lovins and other experts in their own terms (i.e., with arguments showing the limited potential of solar and other technologies), ecological economists tend to rebuke them *ad hominem*. "This blind faith in technology," Carl Folke and his colleagues (1994, p. 3) have written, "may be similar to the situation of the man who fell from a ten-story building, and when passing the second story on the way down, concluded 'so far so good, so why not continue?'" Another ecological economist writes that those unalertable to intractable scarcities "believe in perpetual motion machines" and "act as if the laws of nature did not exist" (Ehrlich 1994).

Complementarity of natural and human-made capital

Ecological economists attempt to refute the mainstream position not only by citing the second law of thermodynamics but also by arguing that "the basic relation of manmade and natural capital is one of complementarity, not substitutability" (Daly 1994, p. 26). Extra sawmills, for example, cannot substitute for diminishing forests, more refineries for depleted oil wells, or larger nets for declining fish populations. Daly (1990, p. 3) concludes that "material transformed and tools of transformation are complements, not substitutes."

The problem with this argument, however, is that it fails to respond to the underlying contention of the mainstream model "that increasing resource scarcity would always generate price signals which would engender compensating economic and technological developments, such as resource substitution, recycling, exploration, and increased efficiency in resource utilization" (Clark 1991, p. 320). The examples Daly offers, indeed, seem to support the mainstream position. The use of solar energy increases when prices for petroleum rise. As prices for lumber or seafood increase, silviculture and aquaculture rapidly supplement and even underprice capture or extractive forestry and fishing. Food prices in general stand at historical lows because of continuous and continuing improvements in the science and practice of agriculture (Heifner and Kinoshita 1994).

The standard model of economic growth assumes that human knowledge and ingenuity can always alleviate resource shortages so that natural capital sets no limit on economic growth. One may say that the standard model holds that knowledge can substitute for resources, then, in the sense that ingenuity can always find a way to get around scarcity—for example, by extending reserves, by substituting between resource flows, and by improving efficiency. This model does not imply, of course, that nets can replace fish, saws replace trees, or that the economy can do without resources altogether. As Solow (1992, pp. 8–9) summarizes: "It is of the essence that production cannot take place without the use of natural resources. But I shall assume that it is always possible to substitute greater inputs of labor, reproducible capital [e.g., technology], and renewable resources for smaller direct inputs of the fixed resource."

Daly concedes, in effect, that silviculture and aquaculture do alleviate scarcities just as mainstream economists would predict. When he considers what he calls "cultivated natural capital," including "agriculture, aquaculture, and plantation forestry," he writes that "[c]ultivated capital does substitute for natural capital proper in certain functions—those for which it is cultivated..." (Daly 1994, p. 30).

The facts bear out this optimism. Tree plantations worldwide "spread rapidly during the 1980s, rising from 18 million hectares in 1980 to more than 40 million hectares by 1990" (WRI 1994). The 1990s may become known as the decade of silviculture, as millions of hectares of land go into new industrial tree plantations each year, and trees are genetically engineered for various properties including rapid growth. During the 1990s, China plans to plant almost 60 million hectares of tree farms, for example, and India now plants four trees for every one it commercially harvests (WRI 1994).

The progress of aquaculture may be gauged from the fact that two of the top ten species harvested in the world today, silver carp and grass carp (Brown et al. 1995), are farmed fish. Supplies of other species, such as salmon, are rising, and prices falling worldwide (Lord 1994). "We must realize that what is happening to the salmon industry in Europe now is similar to what happened in the chicken industry decades ago," the trade journal *Fish Farming International* reports. "Salmon is becoming a low-cost food, and we shall just have to find ways to live with this" (Hempel 1994, p. 23).

What kinds of scarcities, then, limit economic growth? Daly (1994) suggests the limiting factor may be the earth itself—the stone, clay, and sand from which bricks are made. Speaking of timber used in construction, he writes: "Of course, one could substitute bricks for timber, but that is the substitution of one resource for another, not the substitution of capital for resources" (Daly 1994, p. 26). He then speaks enigmatically of the "inability of trowels and masons to substitute for bricks" (Daly 1994).

To understand Daly's argument, one must place it in the context of Aristotle's discussion of the four causes: material, efficient, formal, and final (Aristotle Apostle translator 1975). The material cause in the example Aristotle uses, a statue of a horse, consists in the bronze of which the statue is made. The tools the sculptor applies to the materials are the statue's efficient cause. The formal cause consists in the idea, plan, image, or design—in short, the knowledge—that guides the sculptor. And the final cause is the reason or purpose—to celebrate a victory or pay off a debt—that led the sculptor to make the statue.

Daly has asserted his basic premise in clear and precise Aristotelian terms: "[T]he agent of transformation (efficient cause) and the substance being transformed by it (material cause) must be complements" (Daly 1991c, p. 36). Daly's examples—nets and fish, sawmills and trees, oil drills and oil reserves, trowels and bricks—illustrate the complementary relation between efficient and material causes, or, as he says, "the main relation between what is being transformed and the agent of transformation...." (Daly 1991c).

Daly thus forcefully asserts what mainstream economists would never have thought of denying: one "cannot substitute efficient cause for material cause" (Daly 1995). At the same time, he offers no argument to refute the principle that mainstream economists assert and defend: The formal cause of production (i.e., design, knowledge, innovation, and ingenuity) can always overcome shortages in resources or materials. Thus, while mainstream economists know, for example, that harpoons and whales are complementary, they point out that advances in knowledge and invention have compensated for shortages of resources such as whale oil for uses such as lubrication and lighting. Similarly, while refineries cannot substitute for petroleum reserves, mainstream economists assert that human knowledge and ingenuity can find substitutes for petroleum—for example, by harnessing the inexhaustible resources of the sun. Nature need not limit economic growth, they propose, as long as knowledge increases and the sun shines.

The question of scale

When ecological economists speak of the limits of growth or caution that growth is unsustainable, they use the term *growth* in an idiosyncratic sense. "*Growth* refers to the quantitative increase in the scale of the physical dimension of the economy, the rate of flow of matter and energy through the economy, and the stock of human bodies and artifacts...." (Folke et al. 1994, p. 7). Daly adds: "*Scale* refers to the physical volume of the flow of matter-energy from the environment as low-entropy raw materials and back to the environment as high-entropy wastes" (Daly and Townsend 1993, p. 2).

Ecological economists distinguish between the terms *growth* and *development*. Economic growth, "which is an increase in quantity, cannot be sustainable indefinitely on a finite planet"; economic development, in contrast, "which is an improvement in the quality of life...may be sustainable" (Costanza et al. 1991).

With respect to development, we must ask how ecological economists propose to measure improvement in the quality of life. If they adopt an economic measure, such as utility, preference-satisfaction, or macroeconomic indicators of prosperity, then what they mean by *development* simply collapses into what mainstream economists mean by *growth*. If they propose some other measure, they strike their tents as economists and set out on the high seas of moral philosophy.

What ecological economists mean by *growth*—an increase in physical scale, quantity, or volume—has no analogue in mainstream economic thought. While *growth* is not a scientific term in mainstream economics, it is used generally to refer to the rate of increase of gross domestic product, defined as the value of everything the economy produces in a year at then-current prices. Quantitative increase in the physical dimension of the economy is neither necessary nor sufficient for economic growth in the conventional sense, which has to do with the value of production rather than the physical size of whatever is produced or consumed. If ecological economics possesses a central thesis, it is that the "term 'sustainable growth' when applied to the economy is a bad oxymoron" (Daly 1993, p. 267). Whatever ecological economists say about sustainability, however, has no apparent implications for what mainstream economists mean by *growth*.

If energy consumption or carbon emissions may serve as indicators of economic *scale* or *quantity*, as ecological economists use these terms, we can see that the scale of an economy may not vary with gross domestic product. Between 1973 and 1986, energy consumption in the United States, for example, remained virtually flat while economic production expanded by almost 40% (Brower 1992). In Japan, gross domestic product per capita has doubled—from approximately $8000 to $16,000—since 1973 with no increase in per capita emissions of carbon dioxide. Primary energy demand in the United Kingdom in 1990 was less than it was 16 years earlier, although the gross domestic product grew (UK DoE 1990). Since 1973, France and West Germany have decreased per capita emissions from fossil fuels as their economies have expanded. In France between 1973 and 1991, the economy grew by approximately 30% while per capita emissions declined by approximately 40% (Moomaw and Tullis 1994). Although emissions sometimes increase with gross domestic product, no general relation holds between growth in the conventional sense and the scale ecological economists believe is unsustainable.

Ecological economists assert that economic growth, as they define it, is unsustainable because it stresses the carrying capacity of the earth. Economic growth in the conventional sense, however, bears no general relation to environmental stress. Societies with large gross domestic products, such as Sweden, protect nature, while nations in the former Soviet bloc with much smaller gross domestic products, such as Poland, have devastated their environments. The Scandinavian countries use their affluence to help countries with smaller economies, like Poland, clean up the environmental mess they have made.

In impoverished nations, as consultant in environment and development Norman Myers observes, people may "have no option but to over-exploit environmental resource stocks in order to survive," for example, "by increasingly encroaching onto tropical forests among other low-potential lands" (Myers 1994, p. 128). The poorest of the poor, Myers writes, are often the principal cause of deforestation, desertification, soil erosion, and extinction of species (Myers 1993). It is the absence of economic growth rather than its presence, then, that is a principal cause of rain forest destruction, desertification, erosion, and loss of biodiversity.

No one believes that economic growth is likely to lead automatically to environmental protection. This article has found no reason to agree with the contention of ecological economics, however, that growth in the sense of greater gross domestic product is unsustainable because it necessarily strains natural limits and leads automatically to resource depletion and ecological demise.

The scale or size of an economic activity, moreover, if measured in terms of the volume or quantity of the flow of matter-energy through it, seems to be a useless concept because it bears no clear relation to environmental quality. The physical quantity of detergents used to do laundry, for example, may be the same whether or not those detergents contain phosphates; the ecological consequences, however, are likely to be vastly different. Similarly, a 12-ounce can of hair spray that uses chlorofluorocarbons is likely to damage the environment much more than a 12-ounce can that substitutes a harmless propellant. Because quantities of water exceed those of any other material in our industrial metabolism, the most efficient way to limit scale might be to cut back on water, but no one believes we would thereby greatly protect the environment. One would cry over a gallon of spilled mercury but not over a gallon of spilled milk.

Presumably, ecological economists know that some forms of throughput are worse than others even in the same quantities or amounts. If ecological economists were to discriminate, however, on some basis other than quantity alone among kinds of throughput that harm the environment, they would find themselves embarking on a path at the end of which mainstream economists (e.g., economists at the World Bank) are waiting for them. Rather than decry throughput in general, measured vaguely in terms of quantity, mainstream economists believe some pollutants and practices are worse than others. As a result they address well-defined problems, such as chlorofluorocarbon loadings, rather than the size or scale of throughput as a whole. These economists reject the idea that the dose alone makes the poison; accordingly, they adopt a case-by-case approach that looks for regulatory solutions to specific market and policy failures.

If ecological economists were to relativize the concept of scale to kinds of throughput, they would also confront the problem of identifying and dealing with the pollutants, practices, and policies that are particularly harmful to the environment. They would have to decide which economic activities create risks greater than benefits, which externalities markets fail to price, and so on. If ecological economists conceded that water vapor is not as destructive as chlorofluorocarbons, in other words, even though industry releases a much greater quantity of the former, they would have to move on as economists to risk-benefit analysis, the pricing of externalities, and the correction of market failures. Thus, the ecological economics paradigm would simply collapse into that of mainstream economics.

Co-opting nature

To give empirical content to theoretical arguments about why the global economy can no longer grow, ecological economists often refer to what one describes as the "best evidence" (Goodland 1993) that economic expansion has reached its natural limits—an estimate by Peter Vitousek and his colleagues (1986, p. 372) that "organic material equivalent to approximately 40% of the present net primary production in terrestrial ecosystems is being co-opted by human beings each year." Vitousek and his colleagues (1986, p. 372) also state that "humans now appropriate nearly 40%...of potential terrestrial productivity." Commentators conclude: "If we take this percentage as an index of the human carrying capacity of the earth and assume that a growing economy could come to appropriate 80% of photosynthetic production before destroying the functional integrity of the ecosphere, the earth will effectively go from half to completely full during the next...35 years" (Rees and Wackernagel 1994, p. 383).

The argument that total net primary production limits gross domestic product or economic growth rests on two premises. First, the total amount of net primary production on which the global economy draws is fixed or limited by nature. Second, as economies grow, they must appropriate relatively more net primary production. Ehrlich and Ehrlich, for example, cite the scarcity of net primary production to refute the "hope that development can greatly increase the size of the economic pie and pull many more people out of poverty" (Ehrlich and Ehrlich 1990). They call this idea "insane" because of "the constraints nature places on human activities" (Ehrlich and Ehrlich 1990). Such an expansion of economic activity, Ehrlich and Ehrlich contend, "implies an assault on global NPP [net primary production] far beyond that already observed" (Ehrlich and Ehrlich 1990).

Vitousek and his colleagues (1986) calculated the assault of the global economy on global net primary production in terms of three separate percentages. First, they estimated the percentage of terrestrial net primary production that people directly consume and, second, the percentage they co-opt. By the term *co-opted net primary production*, Vitousek and his colleagues mean "material that human beings use directly or that is used in human-dominated ecosystems by communities or organisms different from those in corresponding natural communities" (Vitousek et al. 1986, p. 370). The amount of net primary production that "flows to different consumers and decomposers than it otherwise would" amounts to 42.6 petagrams (Pg) of net primary production or approximately 19% of the terrestrial total. The 40% figure mentioned earlier—the one constantly cited—is the third percentage that Vitousek and his colleagues calculated. It refers to the percentage of net primary production that "human beings have 'co-opted' and potential NPP [net primary production] lost as a consequence of human activities."

Vitousek and his colleagues (1986) calculated that the amount of net primary production people directly consume as food is equal to 0.91 Pg of organic material annually. They estimated the combined consumption of plants by livestock and of wood by human beings at 4.4

Pg of dry organic material annually, resulting in a total of approximately 5.3 Pg of direct annual consumption of terrestrial net primary production by humans and their chattel.

The amount of direct consumption, a little more than 5 Pg of biomass, is less than the 15 Pg of organic material that Vitousek and his colleagues (1986), using data collected in the 1970s, estimated is produced annually on cultivated land. We may conclude from the figures cited that, even by 1979, farmers produced much more biomass than people and livestock directly consumed. This conclusion is consistent with expert opinion, which estimates that world agriculture produces enough oil seeds and grain today to provide a vegetarian diet adequate in calories and protein for twice the world's population (Waggoner 1994).

Relying on 1970s data, Vitousek and his colleagues (1986) calculated actual, not potential, net primary production; however, subsequent data suggest global net primary production need not be fixed at 1970s levels but may greatly increase, for example, in response to cultivation. For instance, in developing countries, wheat yields per acre doubled from 1974 to 1994, corn yields improved by 72%, and rice yields by 52% (Anderson 1995). The potential for further increases is enormous. US farmers now average approximately 7 tons of corn per hectare (t/ha), but when challenged, as in National Corngrowers Association competitions, they have tripled those yields (Waggoner 1994). Varieties of rice developed recently are expected to boost average rice yields dramatically above the present 3.5 t/ha, with a conjectural biological maximum of approximately 15 t/ha (Anderson 1995).

Vitousek and his colleagues recognized that the net primary production output of cultivated land may exceed that of natural ecosystems—but when it does, "the amount of potential NPP [net primary production] co-opted by human beings increases" (Vitousek et al. 1986, p.372). The amount of net primary production farmers co-opt, then, becomes an artifact of the amount they create, not an indicator of a natural limit on productivity.

It is important to see that rising yields do not imply the co-option of more land but, in fact, may free land to return to nature. Between 1950 and 1989, the global output of major food crops rose by 160%, more than keeping pace with world population (Brown et al. 1995). Most of the increase is attributed to improved yields, not to the use of more land. As a result of greater yields, the United States now idles 50 million acres of farmland in conservation reserves, and the nation is far more forested than a century ago, while remaining a major net food exporter (Crosson 1994). Other industrialized nations, also net agricultural exporters, have seen farms revert to forest (WRI 1994). The most telling examples of net primary production appropriation Vitousek and his colleagues present (e.g., the "6 Pg of organic material [that] is consumed each year in fires associated with shifting cultivation"; Vitousek et al. 1986) arise not as a result of economic growth but from human activity associated with absence of economic growth, or its opposite, destitution (Myers 1993). Displaced peasants, driven by political and economic deprivation, are responsible for nearly three-fifths of current tropical deforestation (Myers 1994). This picture suggests that, for the environment, destitution is far worse than economic development.

A similar doubt attends the second premise of the argument: net primary production and gross domestic product are related, so as economies grow they must co-opt more and more organic matter. The great engines of economic growth—the service sector, information, communication, medical technology, education, and finance—do not draw heavily on net primary production. Why then should net primary production limit economic growth?

As early as 1864, pioneering conservationist and environmentalist George Perkins Marsh observed that humanity had long since completely altered and interfered with the spontaneous arrangements of the organic and inorganic world (Marsh [1864] 1965). Other authorities agree that the landmass of the globe has been thoroughly co-opted (Riabchikov 1975, Study of Critical Environmental Problems 1970)—as Vitousek and his colleagues (1986) define that term—for more than a century. If this is the case, however, then either there is no covariance between net primary production appropriation and increases in gross domestic product or there has been no economic growth in the last century.

The precautionary principle

Ecological economists correctly point out that both ecological and social systems are complex, even chaotic, and that events in each—much less those that result from the interplay of the two systems—are inherently unpredictable (Folke et al. 1994). Ecological economists argue that mainstream economics "lacks any representation" of the evolutionary nature of these systems and the nonlinear causation that is characteristic of them (Christensen 1991).

We may distinguish two contradictory responses to this perceived failure of mainstream economics. First, ecological economists promote their own linear or Newtonian models, relating what they call natural and man-made capital, throughput and ecological stress, and economic growth and net primary production co-option. The arguments examined in this article suppose that within these pairs, each term varies with or complements the other in the simplest arithmetic way—so that economic growth, by filling up the world as cargo weighs down a ship, exceeds the carrying capacity of the earth.

Second, ecological economists propose a "precautionary principle" as one way "to deal with the problem of true uncertainty" (Costanza 1994). This principle recommends that society establish "safe minimum standards...for protecting Earth's life-support systems in the face of virtually inevitable unpleasant surprises" (Ehrlich 1994, p. 49).

That the inevitable unpleasantness should nonetheless be a surprise reflects a belief, implicit in the writings of ecological economists, that nature is essentially benign—a loving mother cradling us with life-support systems. Ecological economists worry that technology may upset the womb-like processes with which nature coddles us. The chief problem, as they understand it, is uncertainty. So far, nature's free gifts have sustained humanity, but as economies grow, we can no longer be certain of her continued largess.

Mainstream economists also recognize uncertainties and surprises. They start, however, with the intuition that for almost all individuals of any species, nature is quite predictable. It guarantees a usually quick but always painful and horrible death. Starvation, parasitism, predation, thirst, cold, and disease are the cards nature deals to virtually every creature, and for any animal to avoid destruction long enough to reach sexual maturity is the rare exception rather than the rule (Williams 1988). Accordingly, mainstream economists reject the idea, implicit in ecological economics, that undisturbed ecosystems, such as wilderness areas, offer better life-support systems than do the farms, suburbs, and cities that sometimes replace them. Without technology, human beings are less suited to survive in nature than virtually any other creature. At conferences, we meet in climate-controlled rooms, depend on waiters for our meals, and sleep indoors rather than alfresco. Nature is not always a cornucopia catering to our needs; it can be a place where you cannot get good service.

Mainstream economics, in subdisciplines involved with risk assessment, risk-benefit analysis, and decisions under uncertainty, identifies environmental hazards and recommends precautions against them. The Montreal Protocol (adopted in 1987 and strengthened in 1990), which controls chlorofluorocarbon emissions, illustrates one success of this mainstream approach. But in doing so, conventional economists call attention to unpleasant events that are entirely predictable in the absence of technologies that co-opt and alter the natural world. They also focus on specific problems, such as ozone depletion and greenhouse emissions, rather than call for safe minimal standards in general. A huge literature within mainstream economics responds to those problems associated with global climate change (Cline 1994, Nordhaus 1994, Schelling 1992). Ecological economists might dispute this literature on technical grounds, but they cannot say it ignores scientific findings.

When ecological economists urge us to maintain a safe minimum standard or, as what they call an insurance policy, a number of unco-opted ecosystems and an adequate reserve of natural resources, questions arise as to which threatened life-support processes or systems and which resources in particular require protection. It is difficult to see how economists can address this question except with conventional cost-benefit analysis. In the context of radical uncertainty, there are many ways to cut back on the scale or size of economic activity. Which make the most sense? A current debate in Congress centers on the national helium reserve. Helium, presumably, is not the kind of natural capital that requires special protection. What, then, is and why?

To add more than a footnote to the vast literature about climate change, ecological economists must argue for something other than better cost-benefit analysis, smaller discount rates, or more attention to market failures and environmental externalities. To distinguish themselves from everyone else, ecological economists must identify threatened forms of natural capital that require special protection because they are the limiting factors in economic development or impose on the carrying capacity of the earth. The World Bank (1992), representing the mainstream position, has described its view of the causes of ozone depletion, the greenhouse effect, and tropical deforestation and recommended solutions. If the precautionary principle and the appeal to safe minimal standards are to add anything to the discussion, they must offer specific recommendations beyond those of the mainstream risk-benefit approach.

According to Costanza (1994), however, the way the precautionary principle is to be applied is uncertain. The precautionary principle, he concedes, "offers no guidance as to what precautionary measures should be taken" (Costanza 1994). The principle instructs us to save resources we might need and to avoid decisions with potentially harmful ecological effects. But "it does not tell us how many resources or which adverse future outcomes are most important" (Costanza 1994, p. 399).

Conclusions

This article has criticized five principal theses concerning the carrying capacity of the earth. These theses have been asserted by many ecological economists. The first thesis asserts that entropy limits economic growth. On the contrary, the entropy law shows only that economic growth requires abundant and environmentally safe sources of energy. Whether these sources exist is a question better answered by engineers than by economists. The engineering literature, especially with respect to solar power, suggests that safe, abundant, and inexpensive new sources of energy have already been found.

Second, mainstream economists believe and history confirms that knowledge, ingenuity, or invention—the formal causes of production—find ways around shortages in raw materials, either by increasing reserves, substituting between resource flows, or making resources go further. In reply, ecological economists answer that tools of transformation—the efficient causes of production—are complementary to and therefore cannot substitute for the material causes. While true, this reply is irrelevant.

Third, ecological economists define economic growth in terms of the physical dimensions of throughput, which, as they point out, cannot expand indefinitely. This definition tells us nothing, however, about growth as mainstream economists understand that term, having to do with the value rather than the physical dimensions of production. The concept of throughput, moreover, is too amorphous to be measured. Its relation to environmental deterioration therefore cannot be determined.

Fourth, ecological economists

calculate that 40% of net primary production moves through the human economy, or in some way is coopted by or subject to human purposes. This calculation is said to represent the extent to which human beings and their effects fill up the world, as cargo might fill a ship. This argument rests on two premises: First, that total net primary production is fixed or limited in nature and, second, that economies, in order to grow, must co-opt correspondingly more organic matter. Both premises are false.

Finally, ecological economists offer a precautionary principle that counsels us to play it safe, but little instruction as to what this means. As a historical matter, however, human beings have found it safer to control and manipulate nature than to accept it on its own terms.

The central principle of ecological economics—the concept of carrying capacity—fails to show that economic growth is unsustainable. Ecological economists are unable to point to a single scarcity of natural capital that knowledge and ingenuity are unlikely to alleviate. Moreover, the so-called carrying capacity of the earth for human beings is not a scientific concept and cannot be measured by biologists. It is an elastic notion and depends on social, economic, technological, and cultural progress and practices (Schneider 1985).

Environmentalists a century ago pointed to the intrinsic rather than to the instrumental value of the natural world. Like Thoreau, they found heaven not only above their heads, but under their feet. They thought of nature as a divine mystery; the term *natural capital* would have been lost on them. If a leaf of grass, as Walt Whitman wrote in "Song of Myself" in his work *Leaves of Grass*, is no less than the journeywork of the stars, there is no need to conjecture about its medicinal benefits.

E. O. Wilson (1980) has correctly said that the destruction of biodiversity is the crime for which future generations are the least likely to forgive us. The crime would be as great or even greater if a computer could design or store all the genetic data we might ever use or need from the destroyed species. The reasons to protect nature are moral, religious, and cultural far more often than they are economic.

To this reasoning, ecological economists may reply that morality and prudence teach the same lesson, so that one is likely to reinforce the other. Morality and prudence, however, teach different lessons. Morality teaches us that we are rich in proportion to the number of things we can afford to let alone, that we are happier in proportion to the desires we can control rather than those we can satisfy, and that a simpler life is more worth living. Economic growth may not be morally desirable even if it is ecologically sustainable.

Prudence, in contrast, teaches that as long as you can get away with it, "More is more"—to quote the immortal words of Miss Piggy, a puppet diva created by Jim Henson. Advances in technology may one by one expunge the instrumental reasons for protecting nature, leaving us only with our cultural commitments and moral intuitions. To argue for environmental protection on utilitarian grounds—because of carrying capacity or sources of raw materials and sinks for wastes—is therefore to erect only a fragile and temporary defense for the spontaneous wonder and glory of the natural world.

We might, then, take a lesson from the mariners introduced at the beginning of this article. When lightening the ship of its cargo failed to overcome the danger—the tempest only worsened—they looked for a moral rather than a physical explanation of their plight. They found it: Jonah confessed his crime in fleeing from God's commandment. When the sailors transferred Jonah from the ship to the whale, the seas became calm. Today, we are all aware that the seas may rise up against us. Like the mariners, however, we might consider not just the weight of the cargo but also the ethical compass of our biospheric ark.

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