Economics of Natural Resource Scarcity: The State of the Debate

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Abstract

Whether economic growth can be sustained in a finite natural world is one of the earliest and most enduring questions in economic literature. Even with unprecedented growth in human population and resource consumption, humans have been quite adept at finding solutions to the problem of scarce natural resources, particularly in response to signals of increased scarcity. Because environmental resources generally are not generally traded on markets, however, scarcity signals for these resources may be inadequate, and appropriate policy responses are difficult to implement and manage. In the debate over the economic scarcity of natural resources, one significant change in recent years has been a greater focus on the ecosystem services and the resource amenities yielded by natural environments. The general conclusion of this paper is that technological progress has ameliorated the scarcity of natural resource commodities; but resource amenities have become more scarce, and it is unlikely that technology alone can remedy that.

Key Words: natural resource scarcity. environmental amenities. resource substitution.

JEL Classification Numbers: Q01, Q10, Q20, Q30, Q40, Q50

Contents

Introduction **4**

Brief Historical Overview **6**

Ecosystem Services and Resource Amenities **9**

Empirical Considerations **11**

- Resource Commodities 12
- Resource Amenities 31

Theoretical Considerations **34**

Summary and Conclusions **39**

References **42**

Economics of Natural Resource Scarcity: The State of the Debate

Jeffrey A. Krautkraemer[*]

Introduction

Whether economic growth can be sustained in a finite natural world is one of the earliest and most enduring questions in economic literature. In essence, the issue is whether technological progress and capital accumulation can overcome diminishing marginal returns to finite natural resources. The debate begins with the birth of economics as a separate discipline and continues to this day. Its intellectual roots still play a prominent and significant role. It is the topic of the two previous volumes on *Scarcity and Growth* published by Resources for the Future. While the general nature of the debate is unchanged, the focus and topics of discussion have evolved.

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[*] This paper will appear as Chapter 3 in the forthcoming RFF volume *Scarcity and Growth Revisited*. Until his untimely death in December 2004, Jeffrey A. Krautkraemer was a professor of economics in the College of Business and Economics, Washington State University, Pullman. Professor Krautkraemer also had been a Gilbert White Fellow at RFF and an Associate Editor of the *Journal of Environmental Economics and Management.* His primary research focuses were natural resource economics and relationships between economic growth and natural resources. Recent publications included a chapter on the economics of energy supply in *Encyclopedia of Energy* (Elsevier) and an article on natural resource scarcity in *Journal of Economic Literature*. Jeff's contributions to the environmental and natural resource economics literature, in particular on resource scarcity and on interactions between economic growth and the environment were widely respected and influential in the field. Even more importantly, he was a friend to pretty much everyone in the economics profession who knew him. He exemplified grace and kindness in the way he lived and worked, and the way he faced the illness that claimed his life. He will be keenly missed by the many, many people whose lives he touched and enriched.

The past two centuries have seen unprecedented growth in human population and economic well being for a good portion of the world. This growth has been fed by equally unprecedented natural resource consumption and environmental impacts, including conversion of large portions of the natural world to human use, which have prompted recurring concern about whether the world's natural resource base is capable of sustaining such growth. To some degree, this concern is supported by simple mathematics: exponential physical growth in a finite world eventually generates absurd results. For example, any positive population growth rate eventually has the population completely covering the face of the Earth and expanding rapidly into space; any positive growth rate for petroleum consumption eventually results in annual production that is greater than the mass of the Earth.

While exponential growth can be expected to lead to increasing resource scarcity, human creativity can ameliorate increased scarcity. Humans have been quite adept at finding solutions to the problem of scarce natural resources: finding more abundant substitutes for various natural resources, exploration for and discovery of new reserves, recovery and recycling of materials, and, perhaps most importantly, the development of new technologies that economize on scarce natural resources or that allow the use of resources that were previously uneconomical.

These responses are not automatic but are the result of purposeful activity in response to signals of increased scarcity. Successful outcomes are not guaranteed. Consequently, there has been a persistent tension between impending scarcity and technological progress. Recent decades have seen increasing concern about the environmental impact of population and economic growth. Because environmental resources—ecosystem services or "resource amenities"—are not generally traded on markets, scarcity signals for these resources may be inadequate, and appropriate policy responses are difficult to implement and manage.

This paper reviews the extensive scope of the debate over the economic scarcity of natural resources and assesses its current state. One significant change in recent years is a greater focus on the ecosystem services and the resource amenities yielded by natural environments—a shift from food, timber, coal, iron, copper, and oil to air and water quality, global climate, and ecosystem preservation.

The distinction between resource commodities and resource amenities is an important one. The answers to central questions regarding natural resource scarcity differ across the two types of natural resource goods and services. This paper discusses the nature of resource amenities and the significant management challenges they present. Then it reviews current empirical and theoretical findings. The general conclusion is that technological progress has ameliorated the scarcity of natural resource commodities, but resource amenities have become more scarce, and it is unlikely that technology alone can remedy that.

Brief Historical Overview

The scarcity and growth debate began in earnest with Thomas Malthus's observations on the fecundity of human nature and the relative stinginess of Mother Nature (Malthus 1798). Diminishing marginal returns was a cornerstone of classical economics and played an important role in his pessimistic view of the prospects for economic improvement. In this view, as more capital and labor inputs were applied to a fixed amount of land, the marginal product of capital and labor combined eventually would decrease and so would output per capita. Expansion of agricultural activity to previously uncultivated land was not a solution since the best agricultural land would be put into production first. Productivity could increase with technological improvements, but the pace of technological progress up to that time had been slow so this was not given great weight by Malthus and other classical economists of his time.

The other half of the Malthusian dilemma was mankind's propensity to reproduce. If wages were above a subsistence level, Malthus argued, then family size would increase.

Population growth combined with diminishing marginal returns would bring wages down to a subsistence level, or even below, and stem the population growth through malnutrition, famine, and delayed marriage. Malthus argued that population tended to increase geometrically while agricultural output increased arithmetically, so the demand for food would necessarily bump up against the ability to produce food, the end result being a subsistence standard of living for most of the population.

Malthus wrote at a time of great social upheaval. The English population was growing rapidly and the prices of basic foodstuffs had been increasing and were kept high by restrictions on grain imports. The enclosure movement had moved thousands from their traditional agricultural roles to cities, where many were unable to find work and lived on relief. Malthus could not have foreseen the rapid technological progress and the decline in fertility rates that would allow large portions of the world to avoid the Malthusian population trap. Some would argue that this is because human society has been living off its natural capital endowment, while others would argue that humankind's ingenuity in finding solutions to resource constraints has allowed it to prosper.

The nineteenth and twentieth centuries are punctuated with misgivings that adequate natural resources were not available to sustain economic growth. The mid-nineteenth century British economy was heavily dependent on coal for energy, and Stanley Jevons (1865) argued that as the cost of coal increased it would undermine economic activity. But shortly thereafter, petroleum displaced coal for many purposes.

In America, the conservation movement of the late nineteenth and early twentieth centuries was concerned with depletion of a broad range of natural resources, including minerals, forests, soil, and fisheries. Its focus was efficiency in a technological sense, based on the belief that private interests could not make the best use of current natural resources and conserve them for future generations. Instead, scientific management in the public interest was necessary to achieve "the greatest good for the greatest number."

The rapid growth of the United States economy following World War II spurred further concern about natural resources, particularly for defense purposes as the Cold War began. Resources for the Future was born, in part, as an outgrowth of the 1950–1952 President's Materials Policy Commission.

The first systematic empirical examination of historical trends, *Scarcity and Growth* (Barnett and Morse 1963) examined scarcity hypotheses for a variety of natural resources for the period 1870–1958. Except in the case of forests, the empirical evidence—discussed in more detail below—supported decreasing rather than increasing scarcity.

The second RFF volume on scarcity and growth (Smith 1979) appeared at a time of heightened concern about natural resources and the environment. Natural resource prices, especially energy prices, were increasing, and deteriorating air and water quality and other environmental problems had led to the enactment of a host of environmental legislation. The price increases began before 1970 and were exacerbated in the 1970s by the oil embargo and OPEC price increases. The Club of Rome published *The Limits to Growth* (Meadows et al. 1972), which predicted dire consequences by the early part of the twenty-first century unless population and economic growth were significantly curtailed. The tone of *Scarcity and Growth Reconsidered* was less optimistic than that of *Scarcity and Growth*, although overall it was cautiously optimistic, at least with respect to the availability of natural resource commodities. Environmental amenity values and the values of basic life support systems were mentioned as important, but the focus was still on productive resource inputs.

The most recent renewal of concern over natural resource scarcity began in the mid-1980s under the rubric of "sustainability" or "sustainable development." The term "sustainability" has powerful connotations even if its exact meaning cannot be pinned down. It has become a catch phrase in the current debate about the ability of the natural world to support both current and future population and economic activity. One key element in this renewal of the debate is the much greater focus on the resource amenities provided by the natural environment. The effects of current economic activity on the basic environmental life support systems now seem more critical than the availability of particular natural resource commodities.

Ecosystem Services and Resource Amenities

Natural resource commodities used to produce material goods and services are not the only economic services provided by the natural world. Other services include the basic life support systems of the earth: the air, fresh water, carbon, nitrogen, and nutrient cycles; the climate in which we live and to which the flora and fauna have adapted; the sinks where we deposit the waste products of production and consumption; and the ecosystems that support our agricultural and other economic activities. The natural world serves as a storehouse of genetic information and the original source of many of the world’s pharmaceutical products. It provides the “playgrounds” where many of us recreate and which we often observe with wonder. These goods and services are known by the term “resource amenities.” While “amenities” may not be the best appellation—they do include fundamental services—it does distinguish them from the use of natural resources in the production of the commodities more commonly treated as economic goods and services.

These amenity resources have played a role in the economic growth debate at least since the time of John Stuart Mill (1848), who observed:

> Nor is there much satisfaction in contemplating the world with nothing left to the spontaneous activity of nature; with every rood of land brought into cultivation, which is capable of growing food for human beings; every flowery waste or nature pasture ploughed up, all quadrupeds or birds which are not domesticated

> for man's use exterminated as his rivals for food, every hedgerow or superfluous tree rooted out and scarcely a place left where a wild shrub or flower could grow without being eradicated as a weed in the name of improved agriculture.

Environmental concerns are raised in both *Scarcity and Growth* and *Scarcity and Growth Reconsidered*, but they are secondary in both volumes.

The very title of John Krutilla's seminal 1967 paper, "Conservation Reconsidered," highlighted a new focus of conservation themes. While the initial research concerning resource amenities had concentrated on recreation and wilderness preservation rather than ecosystem services, the latter could easily fit within the same analytical framework. Krutilla made a compelling argument that technology was much better able to provide substitutes for resource commodities than for resource amenities; as a result, the relative value of resource amenities would increase over time. This, in turn, had important implications for development decisions, particularly when future values were uncertain and the loss of preserved environments was irreversible.

Many economic activities, from the extraction of resource inputs to the emission of wastes, damage resource amenities. Dams and water diversion projects provide water for irrigating crops. This greatly enhances agricultural production—40% of crop production occurs on the 17% of cropland that is irrigated (WRI 2000). However, upstream water withdrawals for irrigation reduce water availability downstream with potentially disastrous effects. The most extreme example may be the Aral Sea, whose volume dropped precipitously before the 1990s as a result of irrigation diversions; 20 of the 24 fish species in the lake disappeared as a result (WRI 2000). It is difficult to imagine any extractive use of natural resources that does not in some way affect natural resource amenities—from the potential environmental impacts of oil drilling on the pristine wilderness of the Arctic National Wildlife Refuge to the more general impact of carbon dioxide emissions on global climate.

A key aspect of ecosystems and the provision of resource amenities is the inextricable connections between the elements of an ecosystem. Commercial exploitation for natural resource commodities generally considers at most a few of the elements in the ecosystem. But the extraction of one element or the addition of excessive amounts of another can disrupt the entire balance of the ecosystem, with unforeseen consequences. Our understanding of ecosystems is incomplete, and there is much uncertainty about how they are affected by different uses and their ability to provide resource amenities over the long run. This complexity raises important questions about how property rights to the various elements of the ecosystem can be assigned and how all of the externalities of commercial exploitation can be internalized when some may not be identified in advance.

Resource amenities present significant management challenges for social institutions. The natural resources that provide these amenities are often open access resources, and many of the goods and services public goods. Consequently, one can expect far different outcomes than for natural resource commodities. The interdependence between natural resource commodities and natural resource amenities implies that natural resource and environmental policy cannot be concerned with single resources but must look at complete ecosystems and, indeed, the environment as a whole.

Empirical Considerations

In the “race” between technological progress and diminishing marginal returns in a finite natural world, the prospects for future generations depend upon which trend is proceeding at a faster pace. Many issues, then, boil down to a seemingly simple empirical question of whether technological progress can overcome diminishing marginal returns. Over the years, there have been technological pessimists and optimists, and that pattern continues to this day.

The empirical evidence to date for natural resource commodities is largely in favor of technological progress. The many predictions of impending doom have not come true—at least not yet. The discovery and development of new reserves, the substitution of capital, and technological progress in resource extraction and commodity production have led to generally downward sloping price trends for many natural resource commodities. If there is any systematic bias to past predictions of the future, it is an underestimation of the ability of technological progress to overcome natural resource scarcity. For example, petroleum supply forecasts have persistently overestimated the future price of oil and underestimated oil production (Lynch 2002). The picture is less clear for the amenity goods and services derived from the natural environment.

Resource Commodities

Three economic measures have been used as indicators of resource scarcity: price, extraction cost, and user cost. These three indicators are related through a basic first order condition for optimal resource extraction:

$$P = C_q + \lambda$$

where

P denotes the extracted resource price

C_q denotes marginal extraction cost

λ denotes the user cost

The user cost captures the nonextractive economic cost of current depletion, including the forgone regeneration for a renewable resource and the forgone future use of a nonrenewable resource. It also includes any contribution of the resource stock itself to the net benefit of extraction—for example, a more abundant resource stock may decrease extraction or harvest cost.

Barnett and Morse (1963) focus primarily on extraction cost. Extraction cost is computed as the amount of labor and capital needed to produce a unit of output. This measure is founded on the classical economics view that with diminishing marginal returns and finite natural resources, the cost of natural resource use should increase as demand increases and depletion occurs. The tendency toward increasing extraction cost can be offset by technological progress.

Data from the United States for the period 1870–1958 for agriculture, minerals, forestry, and commercial fishing are examined. During this period, population increased by a factor of four, annual output increased 20 times, and the output of the extractive industries increased about six times. This period of rapid population and economic growth should furnish a good test of the relative impacts of diminishing marginal returns and technological progress.

Agricultural output increased four times over this period, and the unit cost declined by one-half when both capital and labor are included and by one-third when only labor is included. The cost measure for agricultural production actually declines more rapidly after 1920. The economy became more mineral intensive over this period, with mineral resource use increasing 40 times. Even so, the unit extraction cost measure for minerals production declined significantly with an increase in the rate of decline after 1920. Commercial fishing also saw a decrease in extractive cost. Only forestry unit extraction cost increased, although both output and unit cost tended to level out after 1920. The conclusion is that the data do not support the strong scarcity hypothesis of increasing resource scarcity (Barnett and Morse 1963).

A weaker scarcity hypothesis is that economy-wide technological progress would make it difficult to discern increasing scarcity in the natural resource industries. This weaker hypothesis is tested by examining the movement of unit costs in the resource sectors relative to unit costs in nonresource sectors. The minerals sector shows a decline in unit cost more than one-half the decline in nonresource sectors. Agricultural cost declines from 1929 if only labor is used and is roughly constant if both capital and labor are used as input measures. Forestry, of course, still shows increasing resource scarcity. Table 1 provides a summary of the unit cost estimates in Barnett and Morse (1963).

The cost estimates for natural resource industries were updated to 1970 for *Scarcity and Growth Reconsidered*, and results for other regions were also included (Barnett 1979). The results were essentially the same: the agricultural, mineral, and extractive sectors continued to show a strong decline in labor per unit extracted. Labor plus capital declined, but at a slower rate. Others have found a statistically significant increase in extraction cost for United States coal and petroleum in the 1970s, although this could be due to the exercise of market power rather than changes in scarcity (Hall and Hall 1984). The decline in extraction cost for metals continued in the 1970s (Hall and Hall 1984). There is weak evidence that some natural resource prices increased relative to nonresource commodity prices during the period 1960–1970 (Barnett 1979).

Barnett also observes that *Scarcity and Growth* viewed environmental impacts as a more significant concern than increasing scarcity of resource commodities. Pollution abatement costs were about 2% of output at the time, which was viewed as relatively small. A more aggressive abatement policy, projected to increase costs to 3% of output by the year 2000, would reduce projected annual economic growth by less than 0.1% (Barnett 1979).

A shortcoming of the use of labor or labor–capital as the input measure is that it does not include other inputs that may be significant, including energy and environmental services. Some of the decline in labor and capital costs per unit of output occurred because energy was substituted for capital and labor. The output per unit of energy input in mining increased from 1919 to the mid-1950s and then declined to one-half of its peak (Cleveland 1991). In agriculture, output per unit of energy input decreased between 1910 and 1973 and then increased after energy prices increased in the mid-1970s to early 1980s. A similar pattern occurred in forestry.

Table 1

Unit Extraction Costs, 1870-1957

Labor-capital cost per unit output	1870–1900	1900	1910	1919	1929	1937	1948	1957
Non-extractive GNP	136	126	115	118	100	102	80	68
Agriculture	132	118	121	114	100	93	73	66
Minerals	211	195	185	164	100	80	61	47
Agriculture relative to GNP	97	94	105	97	100	91	91	97
Minerals relative to GNP	155	155	161	139	100	78	76	69
Labor cost per unit output								
Nonextractive GNP	162	137	121	126	100	103	83	69
Agriculture	151	130	130	115	100	92	66	53
Minerals	285	234	195	168	100	96	65	45
Sawnlogs	59	65	67	108	100	104	88	90
Agriculture relative to GNP	93	95	107	91	100	89	80	77
Minerals relative to GNP	176	171	161	133	100	93	78	65
Sawn logs relative to GNP	36	47	55	86	100	101	106	130

Unit cost index numbers, 1929 = 100.

Source: Barnett and Morse (1963), Tables 6, 7, and 8.

The period between *Scarcity and Growth* and *Scarcity and Growth Reconsidered* saw considerable study of the dynamics of natural resource use. These theoretical developments pointed out the shortcomings of extraction cost as an indicator of resource scarcity. Extraction cost is an inherently static measure; it does not capture future effects that are important for indicating natural resource scarcity. In addition, extraction cost captures information about only the supply side of the market. If demand is growing more rapidly than extraction cost is declining, then extraction cost will give a false indication of decreasing scarcity. The opposite also is possible—extraction cost could increase even as technological progress develops substitutes for most of the uses of a particular resource.

The other two economic measures of resource scarcity—price and user cost—do incorporate information about the demand for the resource and, at least to the extent possible, expectations about future demand and availability. For this reason they are generally preferred as indicators of resource scarcity (Brown and Field 1979; Fisher 1979). The resource price would "…summarize the sacrifices, direct and indirect, made to obtain a unit of the resource (Fisher 1979)," since the price would capture both user cost and the current extraction cost. User cost would be the best measure of the scarcity of the unextracted resource. For most of the twentieth century, natural resource commodity price trends have been generally flat or decreasing. This is particularly true for mineral prices. Since these are nonrenewable resources, one might expect they would be more subject to increasing scarcity and therefore increasing prices. However, mineral prices have been generally declining over the twentieth century (Sullivan et al. 2000). Figures 1 through 4 show the long-term price curves for copper, lead, petroleum, and natural gas.

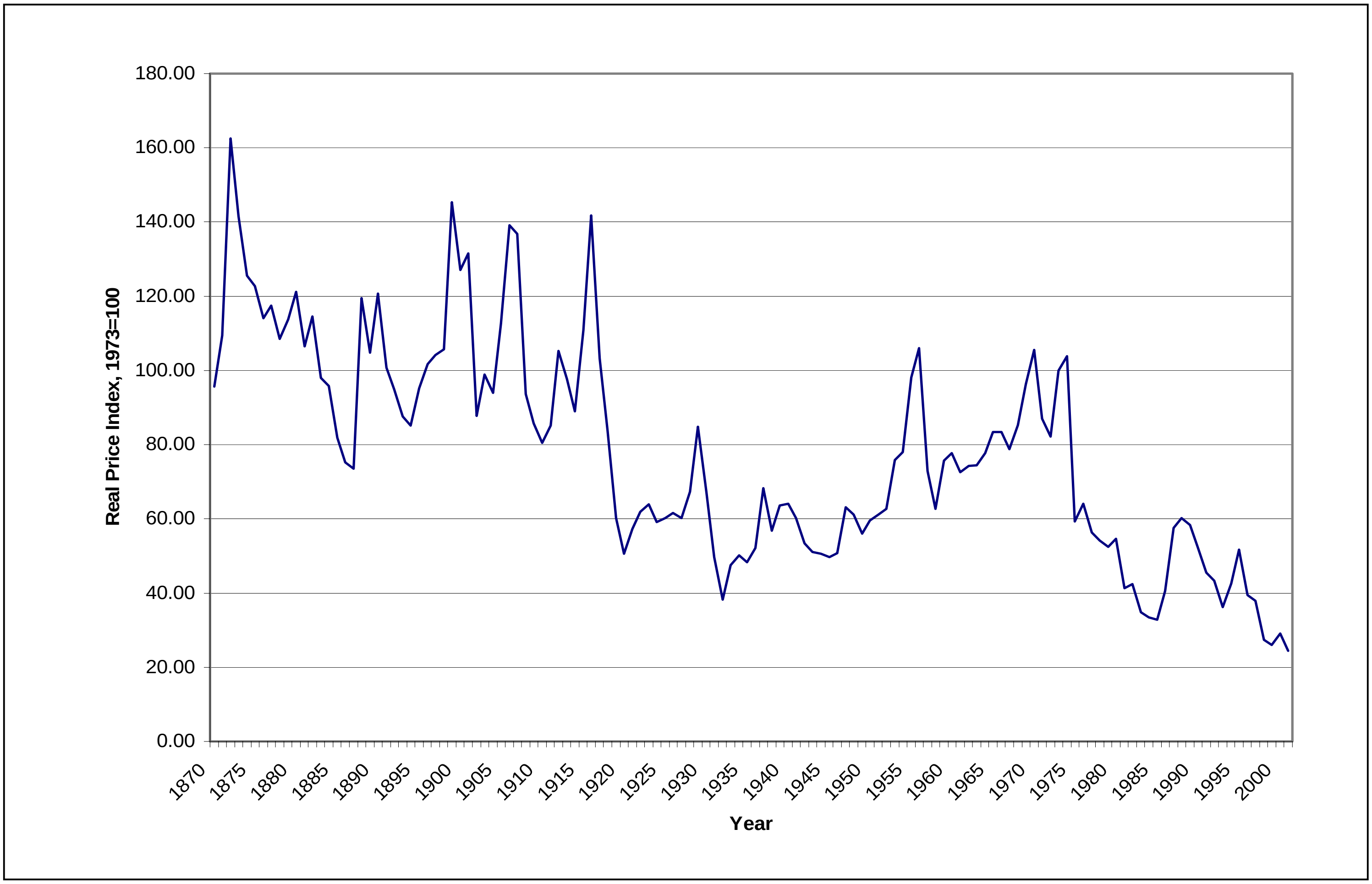

Figure 1—Real Price of Copper, 1870-2001

Source: Manthy (1978) for 1870-1973; USGS *Mineral Commodities Summaries*, for 1967-2001. The two series differ slightly for the period 1967-1973 so an average of the two is used; the general trend is unaffected.

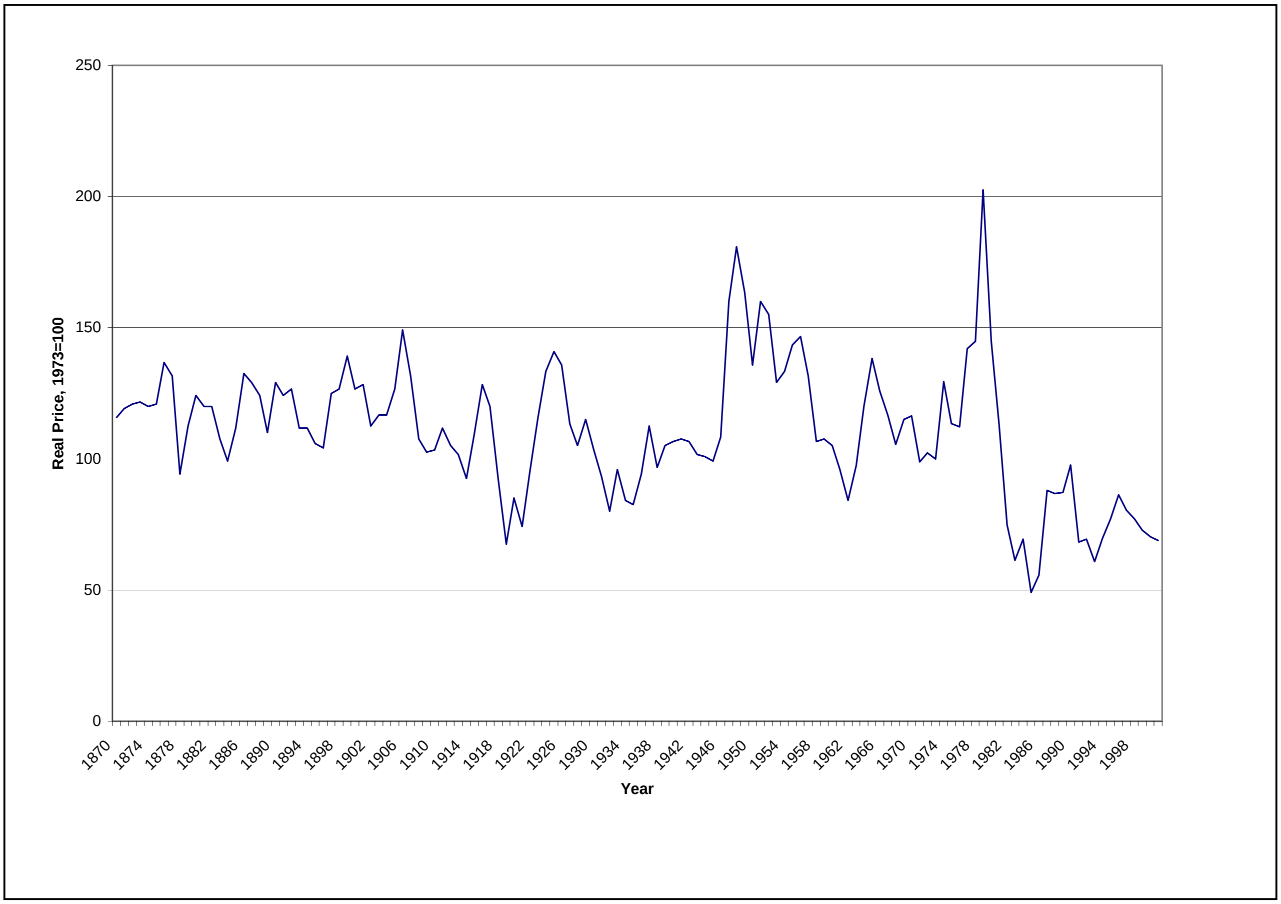

Figure 2—Real Price of Lead, 1870-2001

Source: Manthy (1978) for 1870-1973; USGS *Mineral Commodities Summaries*, for 1967-2001. The two series differ slightly for the period 1967-1973 so and average of the two is used; the general trend is unaffected.

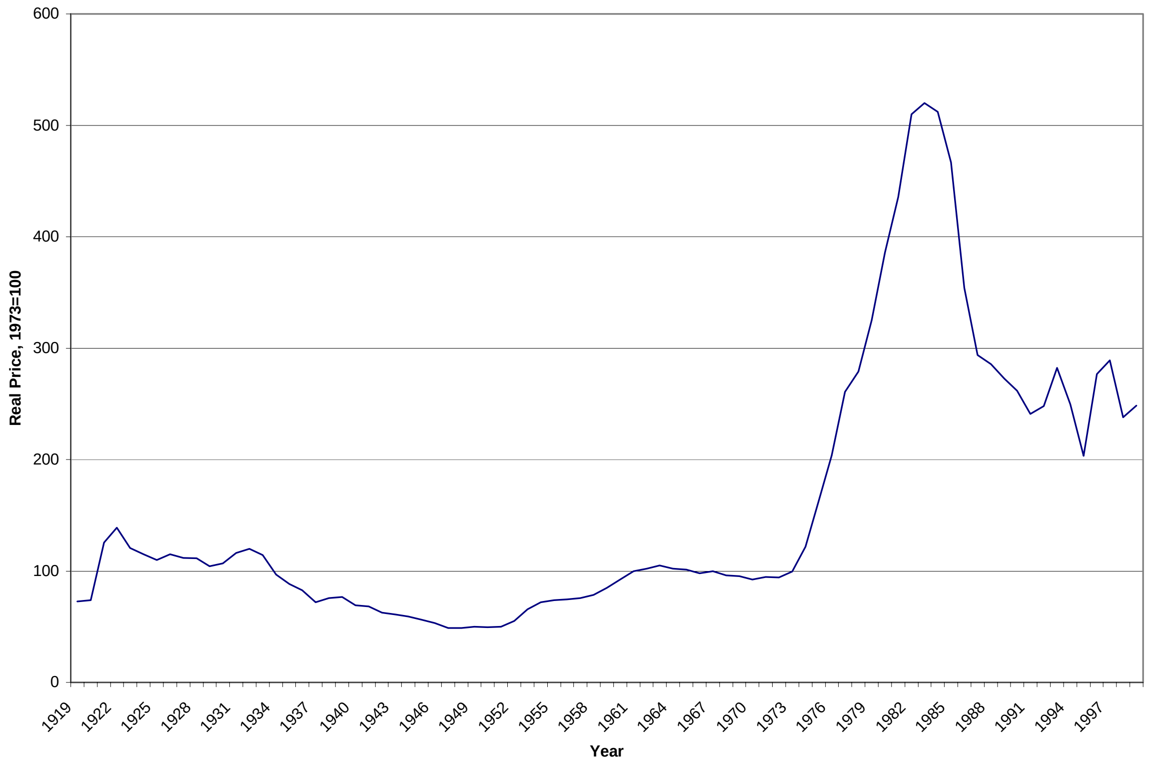

Figure 3—Real Price of Natural Gas, 1919-1999

Source: Manthy (1978) for 1919-1973; Energy Information Agency, Department of Energy, *Annual Energy Review*, for 1968-1999. The two series differ slightly for the period 1968-1973 so and average of the two is used; the general trend is unaffected.

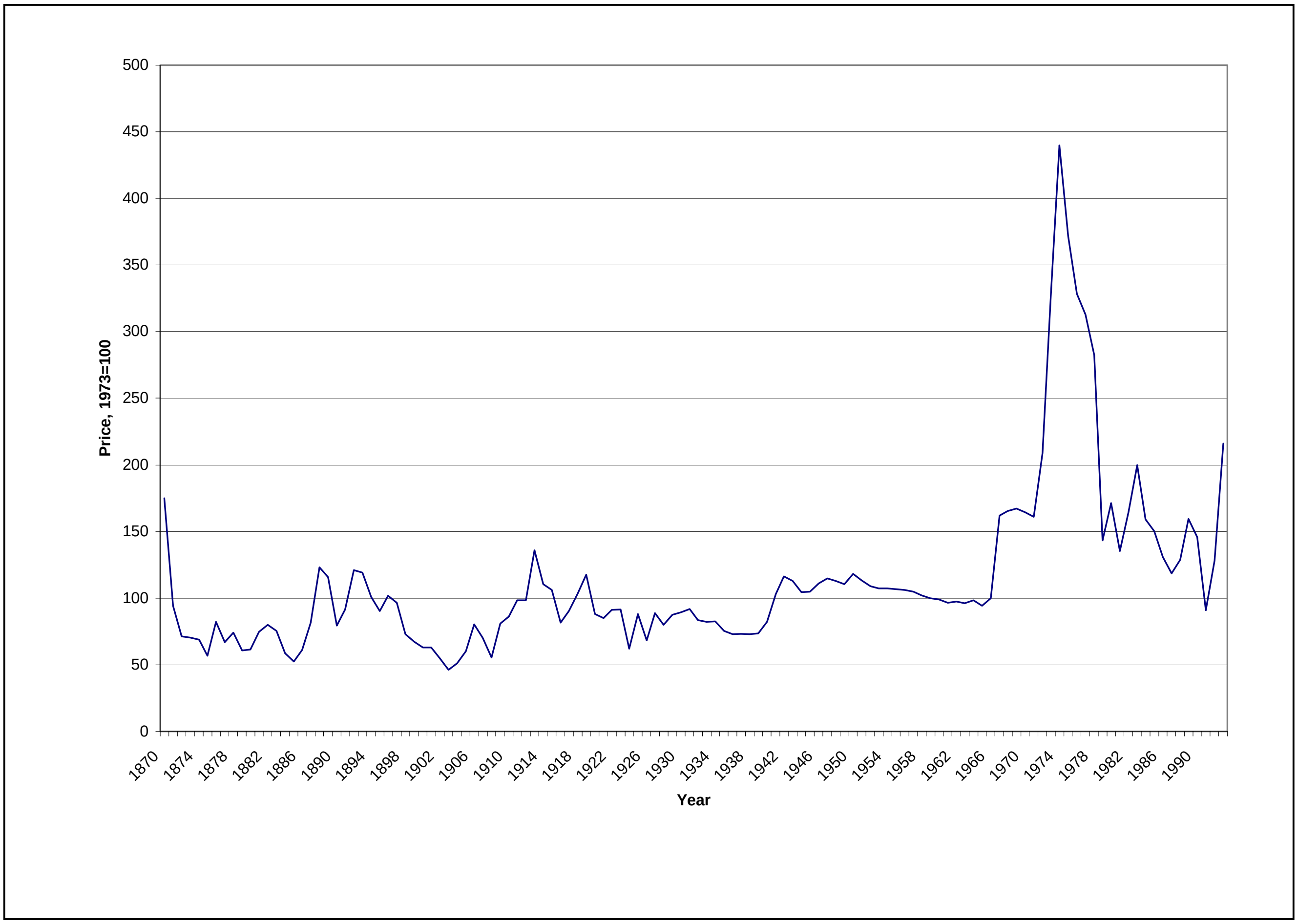

Figure 4—Real Price of Petroleum, 1870-2000

Source: Manthy (1978) for 1870-1973; Energy Information Agency, Department of Energy, *Annual Energy Review*, for 1949-2000. The two series differ slightly for the period 1949-1973 so and average of the two is used; the general trend is unaffected.

An exception to this downward trend for nonrenewable resource prices is the period from 1945 until the early 1980s. Over much of this period, many nonrenewable resource prices—copper, iron, nickel, silver, tin, coal, natural gas, and a mineral aggregate—show an upward trend (Slade 1982). Almost all minerals prices rose in the 1970s, particularly after the 1973 oil embargo. This seems to match the U-shaped price curve that would occur as depletion exerted enough upward pressure on price to overcome the downward force of technological progress (Slade 1982). By all appearances at the time, it seemed likely that nonrenewable resource prices would continue to increase.

But minerals prices did not continue to increase. The economy responds to price increases in a variety of ways: substitutions are made; research and development produce resource-saving technologies; new reserves are discovered and developed; new methods for recovering resources or reducing the cost of using lower-quality reserves are found, and so on. As a result, most mineral prices have declined since the early 1980s, and some of these declines are substantial (see Figure 5). Increases in total factor productivity in mining exceeded the increases in manufacturing as a whole (Humphreys 2001; Parry 1999). The price declines occurred even as some of the environmental externalities associated with resource extraction have been internalized.

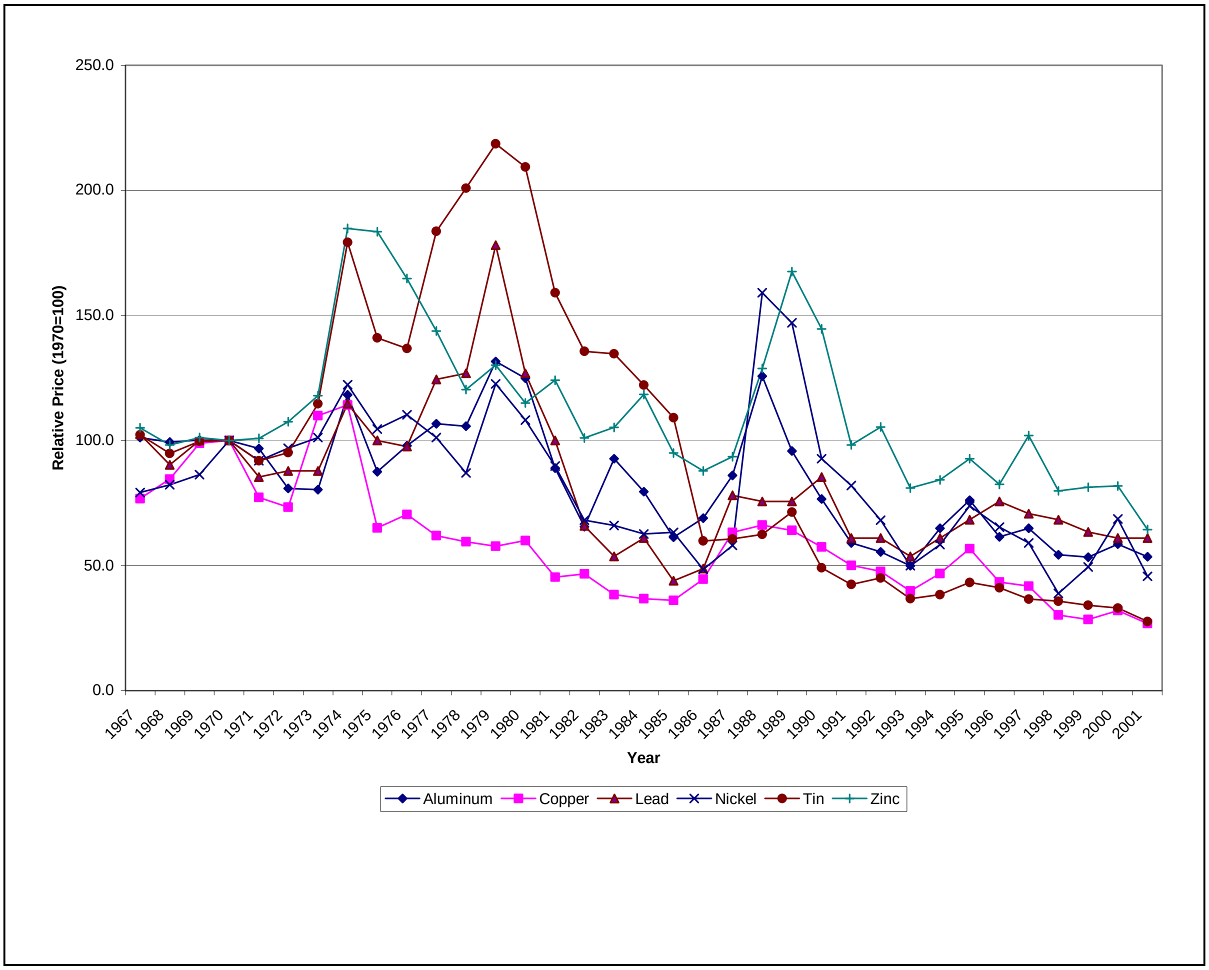

Figure 5: Selected Minerals Prices, 1967-2001

Source: United States Geological Service, *Minerals Commodity Summaries*.

The significant decline in the mineral resource intensity of total output after the mid-1970s provides evidence of the ability to substitute away from inputs that have become more costly (Tilton 1989). The development of the solvent extraction-electrowinning (SX-EW) method for refining copper ore is one example of the effect of technological progress. This process reduces costs greatly by eliminating smelting and refining, and this allows the economical use of much lower grade copper ore, including material that was left behind by previous mining operations (Tilton and Landsberg 1999; Bunel 2001). The price of copper increased in the late 1980s but has since declined substantially to well below its 1979 level, overcoming previous concerns about the future demand for and cost of extracting copper (Brobst 1979; Goeller, 1979).

The real prices of fossil fuels also declined from peaks in the early 1980s (see Figure 6). Petroleum is particularly instructive. Consumption and consumption per capita declined in North America and Europe in the early 1980s following the oil price spike of 1979. Consumption increased slowly after the mid-1980s as real oil prices fell, but consumption per capita remains below its 1980 level in both the United States and Europe. Total consumption in North America is now slightly above its previous peak in 1978, while European total consumption is still below its previous peak in 1979. Consumption declines in the developed world were offset by increasing consumption in the Asian Pacific region, particularly by a doubling of consumption in China in the 1990s.

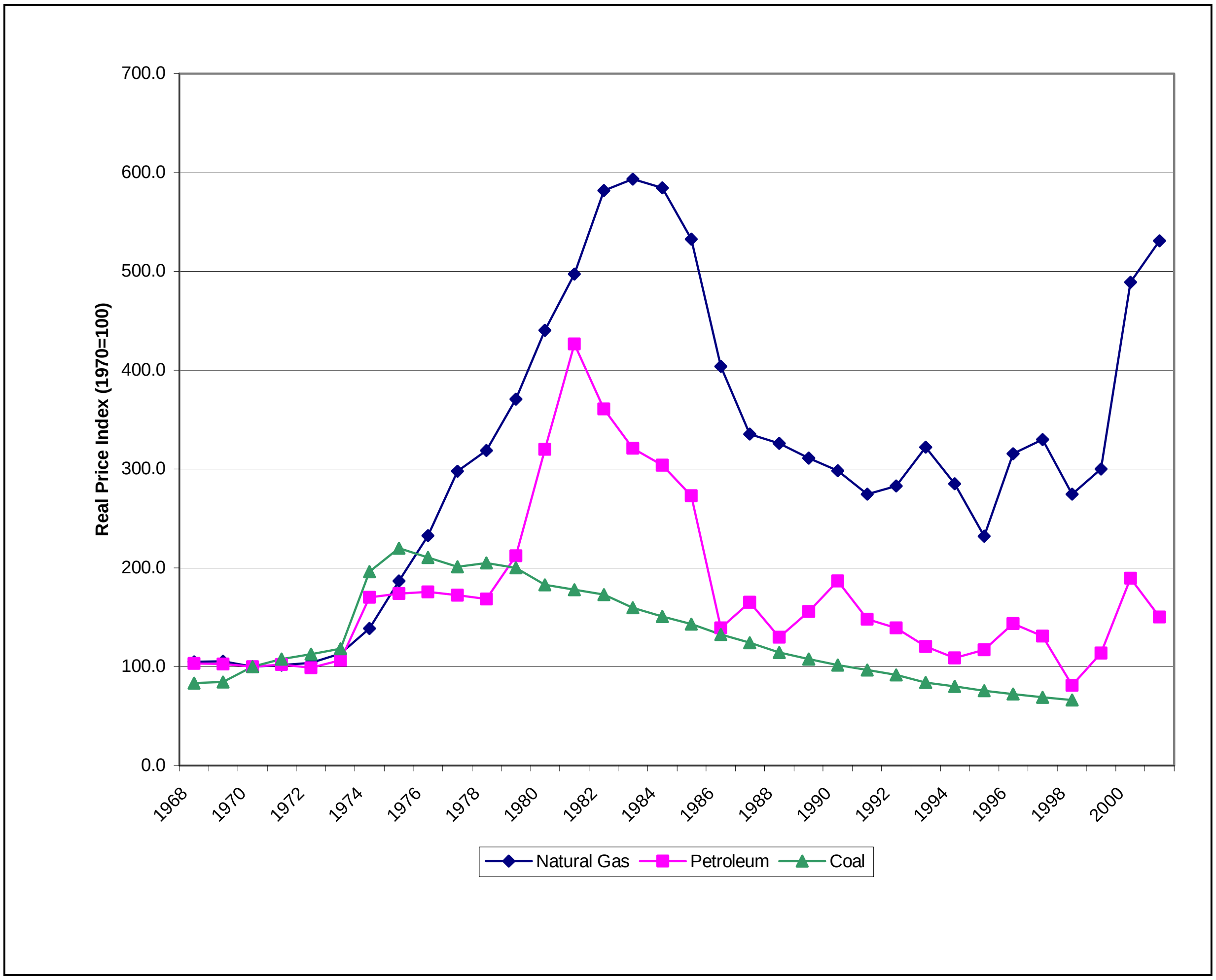

Figure 6: Fossil Fuel Prices, 1968-2001

Source: Energy Information Agency, *Annual Energy Review*.

Developments in computer technology and directional drilling, neither of which was predicted in *Scarcity and Growth Reconsidered*, have substantially lowered exploration and development costs and enhanced recovery from existing reserves. Discovery and development costs in the United States are one-third of what they were 20 years ago (*Economist* 2001). World proved petroleum reserves increased from 660 billion barrels at the end of 1980 to 1,009 billion barrels at the end of 1990. Even though consumption from 1991 to 2000 was approximately 250 billion barrels, proved reserves at the end of 2000 stood at 1,046 billion barrels. The United States produced 28 billion barrels of oil in the 1990s, but its proved reserves dropped by only 4.1 billion barrels (British Petroleum 2001).

Because there is a finite amount of oil in the ground, production cannot increase indefinitely; it must reach a peak, then eventually decline to zero. Hubbert (1969) argued that because of the production technology, the relationship between production and time would trace out a bell-shaped curve with a positive exponential growth rate for production in the early years and an exponential decline to zero. The area under this curve would be determined by the amount of recoverable petroleum. This notion and an estimate of the total availability of reserves led Hubbert (1969) to predict a peak in oil production in the lower 48 United States around 1970.

This prediction was right on target, although the peak was higher than forecast. However, the actual decline in production in subsequent years as been slower than forecast. Production in 2000 was about one-half of peak production rather than the predicted one-third. Technological developments have increased the recovery of oil from existing reserves and allowed exploitation of deposits that previously were uneconomical. World production was predicted to peak between 1990 and 2000, depending upon whether the low or high end of estimated reserves was correct. Actual production has not followed a bell-shaped curve. It reached a temporary peak in 1979, fell in the early 1980s, and began a slow rise through the late 1980s and 1990s. A similar pattern holds for U.S natural gas production, which Hubbert predicted to peak in 1980. This demonstrates that production is not fixed by the production technology but can be altered by market conditions and technological innovations (Cleveland and Kaufman 1991).

Other major natural resource sectors show increasing productivity and declining prices. Malthus's prediction about population and food supply was inaccurate: food production has exceeded population growth. For much of the last two centuries, the increase in food production was the result of bringing more land under cultivation and farming existing land more intensively. The substitution of tractor power for draft animals made more agricultural production available for human consumption—in the 1920s, the production from about one-quarter of United States cropland was used to feed draft animals (Johnson 2002).

Corn yield per hectare was relatively constant from 1800 to 1930, when hybrid corn was introduced. Corn yield had increased about 50% by 1950; it tripled between 1950 and 1984. Wheat yields per acre in the United States were relatively constant from 1800 to 1950 and then more than doubled between 1950 and 1984 (Johnson 2002). Average cereal grain yields in the United States during 1996-1998 were 22% higher than during 1986–88; the increase in cereal grain yields for the world was a little lower at 17% (World Resources Institute 2000). The increases in agricultural productivity have increased food availability and lowered prices. The prices of maize, rice, soybeans, wheat, and beef are about one-half of their 1960 levels (WRI 1998). See Table 2 and Figure 7.

Table 2

Real Commodity Prices, 1960–1995

	1960	1965	1970	1975	1980	1985	1990	1995
Agricultural								
Maize	100	122	111	126	83	78	52	50
Rice	100	106	97	146	110	55	52	52
Sorghum	100	120	113	136	98	82	57	55
Soybeans	100	122	105	109	93	73	56	49
Wheat (US)	100	98	78	118	86	71	48	53
Beef	100	115	146	83	108	88	72	45
Fish Meal	100	157	140	97	125	73	74	74
Mineral								
Aluminum	100	90	91	73	83	62	67	62
Copper	100	183	172	84	93	63	81	75
Gold	100	94	83	207	491	269	223	187
Iron Ore	100	86	71	69	71	70	56	41
Lead	100	153	126	96	131	59	84	55
Manganese Ore	100	83	52	72	52	49	80	40
Nickel	100	102	144	128	115	91	112	88
Silver	100	136	160	221	648	202	109	99
Tin	100	170	138	143	220	159	57	49
Zinc	100	121	99	138	89	96	127	73
Fossil Fuels								
Coal	100	88	100	222	199	157	116	88
Natural Gas	na	na	100	187	440	532	298	232
Petroleum	na	na	100	174	320	273	187	117
Forest Products								
Malaysian Logs	90	94	100	87	158	103	103	125
Plywood	na	na	100	65	92	75	86	119
Sawnwood	103	104	100	71	79	64	76	89
Woodpulp	na	na	100	138	105	86	115	101

Sources: Food, mineral, and forest product data are from WRI (1998). The fossil fuel data are from the Annual Energy Review, Energy Information Agency, Department of Energy, (http://www.eia.doe.gov). Prices are expressed as percent of the 1960 or 1970 price, depending upon data availability.

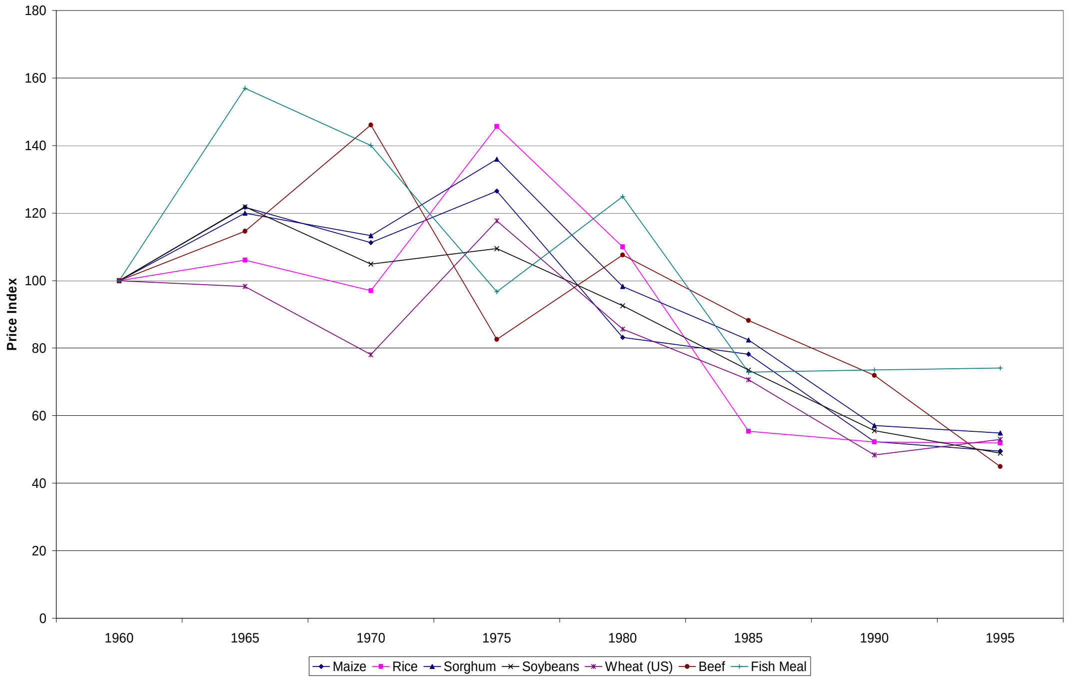

Figure 7: Selected Food Commodity Prices, 1960-1995

Source: (WRI 2000)

Worldwide fiber production from forests has increased 50% since 1960. Timber production in North American and Europe is primarily from secondary-growth forests, and the forested area in developed countries has actually increased in the last two decades (WRI 2000). Forest products have not shown the same general downward price trend, but neither is there a significant upward trend—see Table 2 and Figure 8.

Marine fishery production increased six-fold since 1950, primarily through extending fishing to relatively unexploited areas, although aquaculture has increased to more than 20% of the total fish harvest (WRI 2000). But many older fisheries are producing much less as a result of over-fishing; it is estimated that 75% of fisheries have been over-harvested. One sign of this is the increase in the catch of low-value species while the catch of some high-value species has declined. The prospects for increasing harvest from existing fisheries are not good (WRI 2000). The harvest from capture fisheries has reached a peak, and growing production from aquaculture threatens capture fisheries as feedstocks are diverted from natural to commercial production.

The user cost or rental value of a natural resource is the best measure of the marginal value of the resource stock in place. Unfortunately, information about user costs or rental values is not generally available. Many natural resource stocks are not traded or traded infrequently, and even those that are traded are seldom traded as just resource stocks. Nevertheless, there have been several efforts to construct time series of user cost, and most empirical tests of the behavior of nonrenewable resource prices have found that user cost has fallen rather than increased over time (Krautkraemer 1998). An important exception is the stumpage value of Douglas fir timber from 1940 to 1970 (Brown and Field 1979).

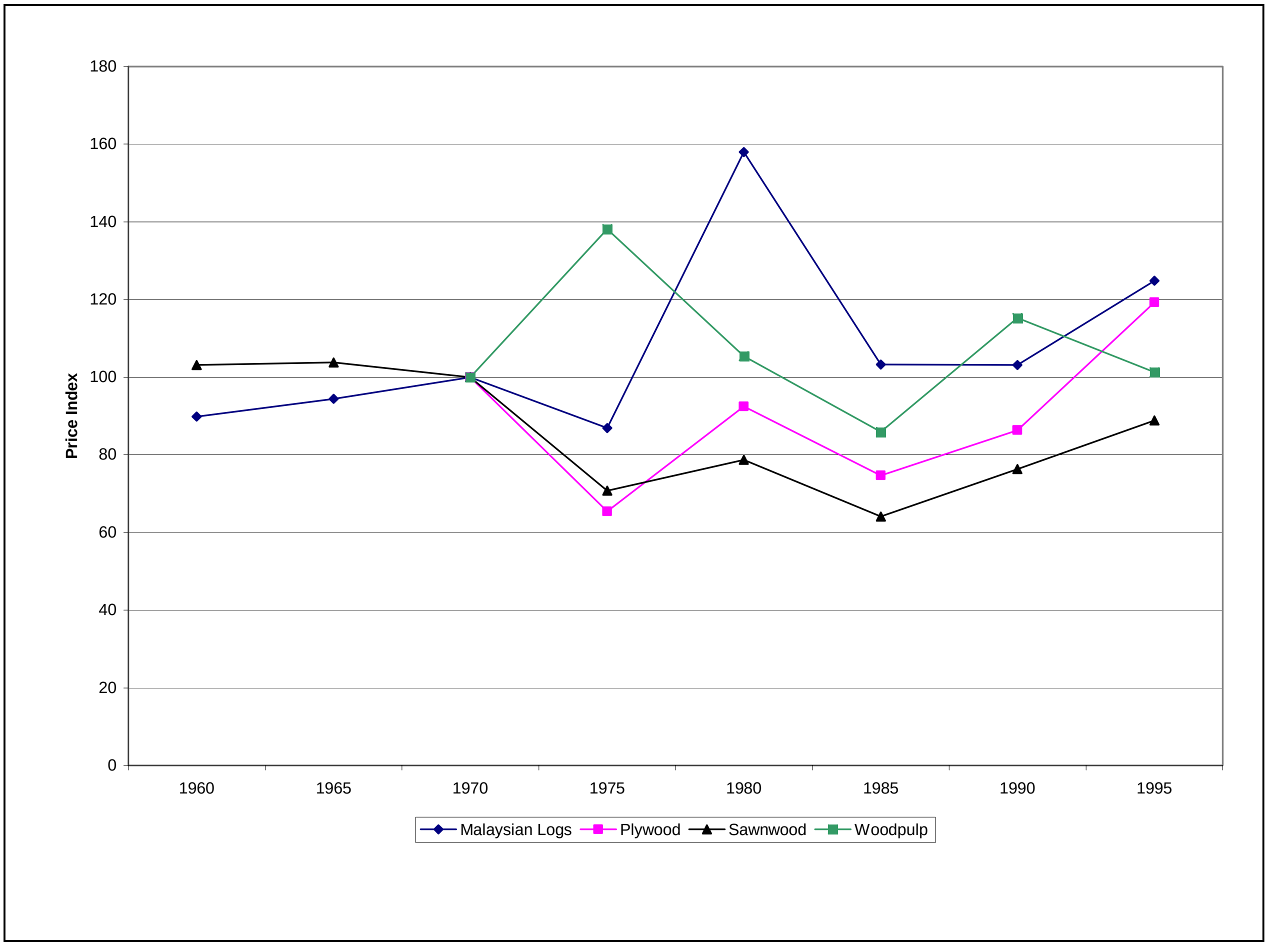

Figure 8: Selected Wood Prices, 1960-1995

Source: WRI (2000).

Resource Amenities

It is much more difficult to evaluate the scarcity of natural resource amenities. These goods and services are not generally traded on markets, so price and cost data are not available. An alternative is to look at physical measures of scarcity, but even here the data are much sparser than the data for natural resource commodities. In addition, while physical measures of natural resource commodities can be made across relatively homogeneous resources—million metric tonnes of lead, copper, and zinc; barrels of petroleum; trillion cubic feet of natural gas—the same cannot be done with natural resource amenities. A hectare of forestland in the northeastern United States is not the same as a hectare of forestland in the Amazon River basin or the temperate rainforests of Alaska. The use of aggregate data can mask significant local problems.

Environmental policies have achieved some success in conserving certain amenity values in recent years, particularly in developed countries. The United States has reduced emissions of criteria air pollutants in the United States, quite substantially in some cases (WRI 1998), and water quality in the United States and Europe is generally improved (WRI 2000). These successes involve environmental factors that most directly affect human well being and are more visible than the loss of services from degraded ecosystems. Some natural environments have been better protected and preserved, but there also are reasons for alarm. A commitment to institutional innovation, not just technological innovation, will be crucial for the efficient management of environmental resources.

Conversion of land from its natural state to human use, or degradation of land from human use, is a primary reason for the loss of ecosystem services. The nineteenth and twentieth centuries saw a significant increase in human use of land; 40% to 50% of land has now been transformed or degraded. In addition, humans appropriate 8% of the primary production of the oceans and as much as 35% of primary production from the continental shelf in temperate zones

(Vitousek et al. 1997). Impacts from human use of the land can extend far from where the use occurs. Nitrogen from fertilizer in runoff water has created a large “dead zone” in the Gulf of Mexico at the mouth of the Mississippi River.

The 40% to 50% conversion figure is consistent with data on forestlands. Current forestlands are just over half of the world’s original forestland (53.4% in 1996); frontier forests (relatively undisturbed intact forest ecosystems) comprise only 21.7% of original forestland, and about 40% of the frontier forests are threatened, meaning human activities are likely to result in significant loss of ecosystem integrity (WRI 2000). Worldwide, almost 6000 tree species are threatened. Forestlands provide a variety of ecosystem services. They filter pollutants from air and water; regulate the flow of runoff water, thus controlling floods, preserving soil, and reducing silt in rivers and seacoasts; sequester carbon and buffer temperatures; and provide habitat to a wide variety of species. These services are lost when forestlands are converted to other uses.

Land conversion has reduced biodiversity, although the degree is difficult to measure because the number of species is not known and there is no single measure of biodiversity. Indeed, the rate of loss of species is usually estimated from the rate of loss of habitat. These estimates generally put the loss of species at 100 to 1000 times the rate that would have naturally occurred (Vitousek et al. 1997). It is relatively easy to identify species whose existence in particular areas has been endangered by habitat conversion, including grizzly bears, wolves, wild Pacific salmon, and sage grouse in the western United States alone.

Global climate change induced by atmospheric accumulation of carbon dioxide resulting from fossil fuel consumption and deforestation is another avenue through which humans can have a significant impact on ecosystem services. The atmospheric concentration of carbon dioxide has increased steadily since industrialization, from 286–288 parts per million in 1860 to 367 ppm in 1998 (WRI 2000). The current concentration is the greatest in the past 420,000 years.

The atmospheric concentration of methane has increased 151% since 1750 (IPCC 2001). The global average surface temperature has increased about 0.6 degrees centigrade (1.1 degrees Fahrenheit) and the 1990s were the warmest decade on record (IPCC 2001). While global temperatures and climate vary naturally, a consensus has developed that most of the warming over the last half century have been the result of increased greenhouse gases (IPCC 2001). Changing climate will damage many ecosystems if it occurs more rapidly than they can adapt. A meta-analysis of 143 studies found “a significant impact of global warming is already discernible in animal and plant populations (Root et al. 2003).

Alaska already seems to be experiencing significant changes. Because the average temperature in much of Alaska is close to the freezing point of water, increased temperatures can have a significant impact. Permafrost is melting and causing buildings and roads to sag, sea ice has thinned significantly, and warmer temperatures have allowed beetles to destroy spruce forests (Egan 2002). Coral reefs are also vulnerable to warmer temperatures because they thrive at temperatures just below the maximum temperature they can survive.

A recent study by the United Nations Development Programme, United Nations Environment Programme, World Bank, and World Resources Institute attempted a comprehensive, qualitative analysis of the state of the world’s major ecosystems. The study evaluated the capacity of several types of ecosystems—agricultural, coastal, forest, freshwater, and grassland—to provide a variety of services: food and fiber, water quantity, water quality, biodiversity, carbon storage, shoreline protection, woodfuel, and recreation. Each ecosystem was evaluated for the condition and direction of changing capacity for providing the various ecosystem services (WRI 2000).

The results, while not bleak, are ominous. With five types of ecosystems and eight types of services, there are 40 possible outcomes each for condition and changing capacity, and it was possible to assess 24 of these. Six of these categories were found to be in good condition, 12 in fair condition, five in poor condition, and one in bad condition (biodiversity in freshwater ecosystems). More disturbing, the capacity was declining in 18 of these 24 categories, mixed in three, and increasing in only one (two were unassessed). “Overall, there are considerable signs that the capacity of ecosystems to continue to produce many of the goods and services we depend on is declining” (WRI 2000).

Theoretical Considerations

The empirical data for natural resource commodities do not suggest increasing scarcity. However, past successes are no guarantee of future success. Population and economic growth will continue to increase the demand for natural resource commodities and, more importantly, place additional stress on natural environments. Increasing scarcity of a natural resource commodity generally triggers a variety of responses that, at least to some extent, ameliorate that scarcity. By their very nature, the same is not as true for resource amenities—these goods and services are not generally traded in markets so there is no price signal to trigger a response. Detection of the problem is much more difficult and the response depends upon collective action. Even if one is optimistic about the future availability of resource commodities, it is possible to be pessimistic about the future availability of resource amenities.

Even if natural resource commodities are becoming more scarce, it may be possible to sustain economic production using lower levels of resource inputs to produce equivalent levels of goods and services. This may be achievable through technological progress or the substitution of other more plentiful inputs. The question of what mechanisms can sustain an economy dependent upon an essential nonrenewable resource was examined with highly stylized optimal growth models in the 1970s, and the results were an important theme in *Scarcity and Growth Reconsidered* (Stiglitz 1979; Daly 1979).

In a simple depletion model, if technological progress increases the output obtained from a given resource input, it is akin to having a growing resource stock. If the economy is patient enough to give technological progress the time to increase the effective resource stock, then positive economic growth is sustained (Stiglitz 1974).

The effect of capital accumulation and capital–resource substitution is similar. In a simple capital growth model, capital accumulates as long as its marginal productivity is greater than the rate of time preference; the economy moves to a steady state where the marginal productivity of capital is balanced against impatience. In a growth model with both capital and a nonrenewable resource, the marginal product of capital depends upon the flow of the nonrenewable resource input. Capital productivity decreases as capital accumulates and the resource input declines. Exactly what happens to capital productivity depends upon how readily capital services can be substituted for the natural resource input. A measure of the substitutability of one input for another is the elasticity of substitution. The elasticity of substitution measures the percentage change in the ratio of the marginal product of the two inputs relative to a percentage change in the input ratio and is captured graphically by the curvature the production isoquants (Stiglitz 1979).

If the elasticity of substitution between capital and the resource is less than one, the ability to substitute capital for the natural resource input is relatively limited. In this case, the average product of the resource is bounded above, so there is a finite limit on the production that can be obtained: sustained output is not possible. If the elasticity of substitution is greater than one, the substitution possibilities are greater and economic growth can be sustained even as the resource input declines to zero. However, if capital productivity falls below the rate of time preference, the economy will decline. If the elasticity of substitution equals one, then the economy can be sustained only if capital’s output share is greater than the resource’s output share. In this case, the limiting value of capital productivity is zero, so an economy with a positive rate of time preference is too impatient to sustain growth through capital accumulation (Dasgupta and Heal 1974).

The ability to substitute capital for a natural resource, then, is a critical question in the current scarcity and growth debate. It is relatively easy to find examples where capital can substitute for the use of a natural resource. For example, insulation and thermal pane windows reduce the energy needed to maintain indoor temperatures. The redesign of products like milk and beverage containers that allows the same services to be obtained with less material input can be seen to substitute human capital services for plastic and aluminum. New technologies can replace one resource with another more abundant resource, as fiber optics have replaced copper for telecommunications. The mix of goods produced in the economy can shift from more to less resource intensive commodities. The energy used to produce one dollar of gross domestic product was reduced by almost one-half in the United States between 1949 and 2000, with most of that reduction coming after 1970, although total energy use tripled as population doubled and per-capita GDP increased (Energy Information Agency 2002). World primary energy use per dollar of GDP has declined by more than 25% since 1970 (Smith 2002) and at an annual rate of 1.7% during the 1990s (Darmstadter 2002*)*. The use of materials per unit of GDP has declined about one-third since 1970 (Wernick et al. 1996).

The ability to overcome natural resource commodity constraints through substitution and technological progress implies it is not necessary to extract all productive resource commodities from natural environments in order to sustain a standard of living. The opportunity cost of protecting natural environments is lower the greater the availability of close substitutes for resource commodities. Indeed, when the loss of resource amenity values is taken into account as a cost of extraction, this added cost may warrant using other substitutes or developing new technologies earlier than would otherwise occur. Preservation of the Arctic National Wildlife

Refuge is more sensible if petroleum substitutes are readily available than if petroleum is essential to continued economic well being.

The ability to substitute capital for natural resources is limited by physical laws of nature. It simply is not possible to produce an ever-expanding level of material output from an ever-decreasing quantity of material input. No amount of capital–resource substitution or technological progress can overcome that constraint. The same is true of energy—the amount of work obtained cannot be greater than the amount of the energy expended as an input. Recycling durable nonrenewable resources can increase the life of a given resource stock, but 100% recovery and reuse is not practical, so the process cannot continue indefinitely. Consequently, sustaining the economy ultimately must rely on renewable natural resource inputs. It is even more difficult for capital substitution and technological progress to overcome the loss of amenity goods and services from the environment.

The importance of the rate of time preference points to the equitable treatment of future generations as a major impetus for natural resource and environmental conservation. A positive social rate of time preference implies that future generations are not given the same weight in the social welfare function as the current generation. This can be construed as mistreatment of future generations simply because they live in the future, and it can be especially harsh when the economy’s only asset is a finite quantity of a nonrenewable resource

However, good things also can happen with the passage of time, and a positive rate of time preference does not necessarily imply the current generation is better off than future generations. This is clear from a simple capital growth model when the initial capital stock is relatively small. Production and consumption will increase over time as the economy accumulates capital. A zero rate of time preference, or equal weighting of generations, would require the first generation—which has the lowest utility—to make even greater sacrifices to increase the well-being of future generations who already would be better off. Consequently, the same present value criterion can give markedly different relative treatments of earlier and later generations depending upon the technological context. As a result, technological pessimists and technological optimists can differ markedly over the ethical treatment of future generations.

The role of the social rate of time preference becomes even more complex in a world with both physical and natural capital. While the direct effect of a lower discount rate is to increase the accumulation of natural resources, there are indirect effects that can lead to even more rapid resource and environmental depletion. A lower rate of time preference can spur economic activity, increasing the demand for natural resource inputs (Scott 1955), or increase the demand for land development over land preservation (Rowthorn and Brown 1995). Because many extractive industries are capital intensive, a lower discount rate can increase investment in extractive capacity, which allows more rapid resource extraction (Farzin 1984). This can even result in less permanent preservation of natural environments, particularly for open-access natural resources.

Perhaps a more effective way of preserving natural resource and environmental assets for the future is to ensure that all of the contributions those assets make to economic productivity are taken into account. Efficient asset accumulation requires equal marginal rates of return across assets. The marginal return to an asset includes the marginal value of any contribution to well being. An environmental asset can contribute to economic well being through the utility function, the production function, and through biological or ecological growth functions. For example, the marginal return to preserved forestland includes the value of water filtration, erosion and sediment control, carbon sequestration, habitat, and recreational and aesthetic services.

The problem for environmental assets is that most, if not all, of their productive contributions are social returns that are not appropriated through the marketplace. If the returns to the environmental asset are not captured, they will be ignored, regardless of the social rate of time preference. Unless market failures are corrected, a lower rate of time preference could lead to more rapid depletion of environmental assets through greater accumulation of other assets. An individual may want to invest in a portfolio of assets, including a healthy environment for their children or grandchildren, but they cannot individually purchase environmental assets for their bequest. The state of the environment depends upon everyone’s investment, not just the investment of a particular individual.

An appropriate remedy for this problem is policies that ensure that all of the returns to the natural resource assets are taken into account, not necessarily that the discount rate is reduced. Of course, the proper accounting for environmental services is not a trivial task, and placing quantity constraints on the use of the environment may be a practical alternative. Forest preserves, roadless areas, agricultural conservation reserve programs, areas off limits to mining, habitat conservation areas, shoreline preservation, and development setbacks can all make sense on the basis of efficiency as well as intergenerational equity. Such set-asides also are consistent with optimism about the ability of technological progress to continue to provide an adequate supply of natural resource commodities.

Summary and Conclusions

Empirical evidence does not indicate a significant increase in the scarcity of natural resource commodities. Indeed, the historical evidence is that expansion into previously undeveloped lands and technological progress have enabled the human economy to avoid the Malthusian trap and to maintain adequate supplies of food, forest, and mineral products even as population and economic output increased substantially.

Population and economic growth into the next century will greatly increase the demand for natural resource commodities. Even though population growth has slowed, a population of six billion growing at 1% adds the same number of people as three billion people growing at 2%. The desire for a higher living standard in the developing world places additional demands on technological progress to prevent increasing scarcity of natural resource commodities. The historical success of adaptation to increased demand for these commodities is by no means a guarantee of future success. Little arable land remains to expand agricultural production. Furthermore, the transition from animal to mechanical power has already been made and a transition from fossil fuels to biofuels would reduce the land available for crops for human consumption. Consequently, the bulk of increased food production will need to come from further increases in yield per hectare. Our understanding of crop production has increased dramatically over the last several decades, and new techniques from biotechnology afford some cautious optimism that the human population can continue to avoid a catastrophic food shortage.

The increased demand for other natural resource commodities will also challenge human ingenuity to continue to overcome impending resource scarcities. Fossil fuel reserves are about as abundant relative to the rate of consumption as they have been over the last century, and the technologies for discovering and recovering these resources have developed substantially over the past decades. However, the world’s petroleum supply is finite and cannot last forever—some forecasts place the peak of world oil production within the next decade or two. Coal is more abundant than petroleum, but the environmental evils of energy from coal are generally greater. There are several possible renewable substitutes, including solar thermal and voltaic, wind, geothermal, and biomass energy. Whether these energy sources will allow the same standard of living as fossil fuels depends upon technological advances yet to be made. One can be optimistic or pessimistic about future possibilities, but there doesn’t appear to be a significant shortage on the near horizon.

The same can be said of most mineral resources. The greatest dilemma is the state of ocean fisheries, particularly those species at the top of the marine food chain. Through various institutional failures, many of the oldest fisheries have been overharvested and their productivity is well past its peak. Fishing has expanded into new fisheries but, like agriculture, there is little room left for further expansion. Only better fisheries management will improve the productivity of ocean fisheries as a whole. Freshwater scarcity also threatens many regions, particularly if freshwater supplies are not managed in a more economically rational manner.

The world's economies have not been as adept at preserving natural resource amenities. By their very nature, these goods and services are subject to a variety of market and government failures. The benefits of many of these goods and services are not appropriable, so they are not fully considered when decisions for commercial exploitation of natural resource commodities are made. As a result, many of the world's ecosystems have been degraded. The inability to appropriate the benefits of natural resource amenities reduces the incentive for technological developments that could preserve or restore natural ecosystems. Further population and economic growth will increase the ecological pressures. Without significant improvements in environmental protection, the future availability of natural resource amenities is in jeopardy.

The first step is to correct the institutional failures that result in under-valuation of these goods and services. This step is necessary whether one views sustainability as an efficiency or equity issue, and it is a tremendous task in itself. We are far from an understanding of how ecosystems function, and the interdependence of their many elements makes it difficult to design simple remedies.

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