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From Limits to Growth to Planetary Boundaries: The Evolution of Economic Views on Natural Resource Scarcity

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Abstract

Since the 1950s, as economics has responded to new environmental challenges, views on natural resource scarcity have also evolved. Three distinct phases are discernible in this evolution. From the 1950s through the 1970s, the "Resource Depletion Era", the concern was mainly with the environment as a source of key natural resources and a sink for waste, and thus the focus was on whether there were physical "limits" on the availability of resources as economies expand and populations grow. From the 1970s to the end of the 20th century, the "Environmental Public Goods Era", attention shifted to the state of environment and processes of environmental degradation, such as climate change, deforestation, watershed degradation, desertification and acid rain, that resulted in loss of global and local environmental public goods and their important non-market values. Since 2000, the "Ecological Scarcity Era" has seen a growing concern with the state of the world's ecosystems and Earth system processes, and shifted focus back to possible "limits" to economic and population expansion, but now with the emphasis on potential "planetary boundary" constraints on human activity.

Keywords: environmental and resource economics; natural capital; natural resource scarcity; ecosystems; limits to growth; planetary boundaries.

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Introduction

The purpose of this paper is to trace the development of economic views on natural resource scarcity from the 1950s onwards. During this period, environmental and resource economics emerged as an important and growing sub-field within economics, and as economists began tackling a wider and more complicated array of environmental problems, both the discipline and perceptions of natural resource scarcity changed considerably. Consequently, these evolving views are an important insight into the contemporary history of economic thinking on the environment.

Although environmental and resource economics is a relatively new field, emerging only since the 1950s, economic thinking on natural resource scarcity can be traced back to classical political economy.[2] The two basic concepts of natural resources scarcity, *absolute or physical* limits on resource availability as opposed to *relative* or *economic* scarcity, are inherited from classical economics. Economists have adopted different views on the importance of these two scarcity concepts, depending on the type of environmental problem analyzed. For example, from the 1950s to the end of the 20th century, natural resource depletion, pollution and declining environmental public goods were characterized as problems of relative rather than absolute scarcity. The irreversible loss and degradation of ecosystems, along with their valuable "services" or benefits, were also viewed as a relative "ecological scarcity" problem. However, recent scientific evidence of the threats posed by global biodiversity loss, widespread ecosystem destruction and collapse, and irreversible climate change, has led to calls for absolute limits on

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[2] For further discussion of the early origins of natural resource economics and concepts of natural resource scarcity, including the influence of classical political economy on modern views of scarcity, see Barbier (1989); Barnett and Morse (1963); Brown et al. (2016); Crabbé (1983); Robinson (1980 and 1989); Pearce (2002); and Sandmo (2015). See also Banzhaf (2019) for a discussion of the pivotal role of environmental thinking and scientific evidence on the work of Krutilla (1967), who was instrumental to expanding the concept of natural resource scarcity to include environmental public goods.

these impacts to protect vital Earth systems and processes, implying a physical scarcity constraint.

This suggests that three distinct phases are discernible in the evolution of modern economic views of natural resource scarcity. From the 1950s through the 1970s, the concern was mainly with whether there were physical "limits" on the availability of natural resources as economies expand and populations grow. This period can be referred to as the "Resource Depletion Era". From the 1970s to the end of the 20th century, attention shifted to the state of environment, and especially the loss of global and local environmental public goods and their important non-market values. This phase is denoted as the "Environmental Public Goods Era". Since 2000, there has been growing alarm over the state of the world's ecosystems and Earth system processes, and the need to respect "planetary boundaries" on the environmental impacts from human activities. This final period is the "Ecological Scarcity Era".

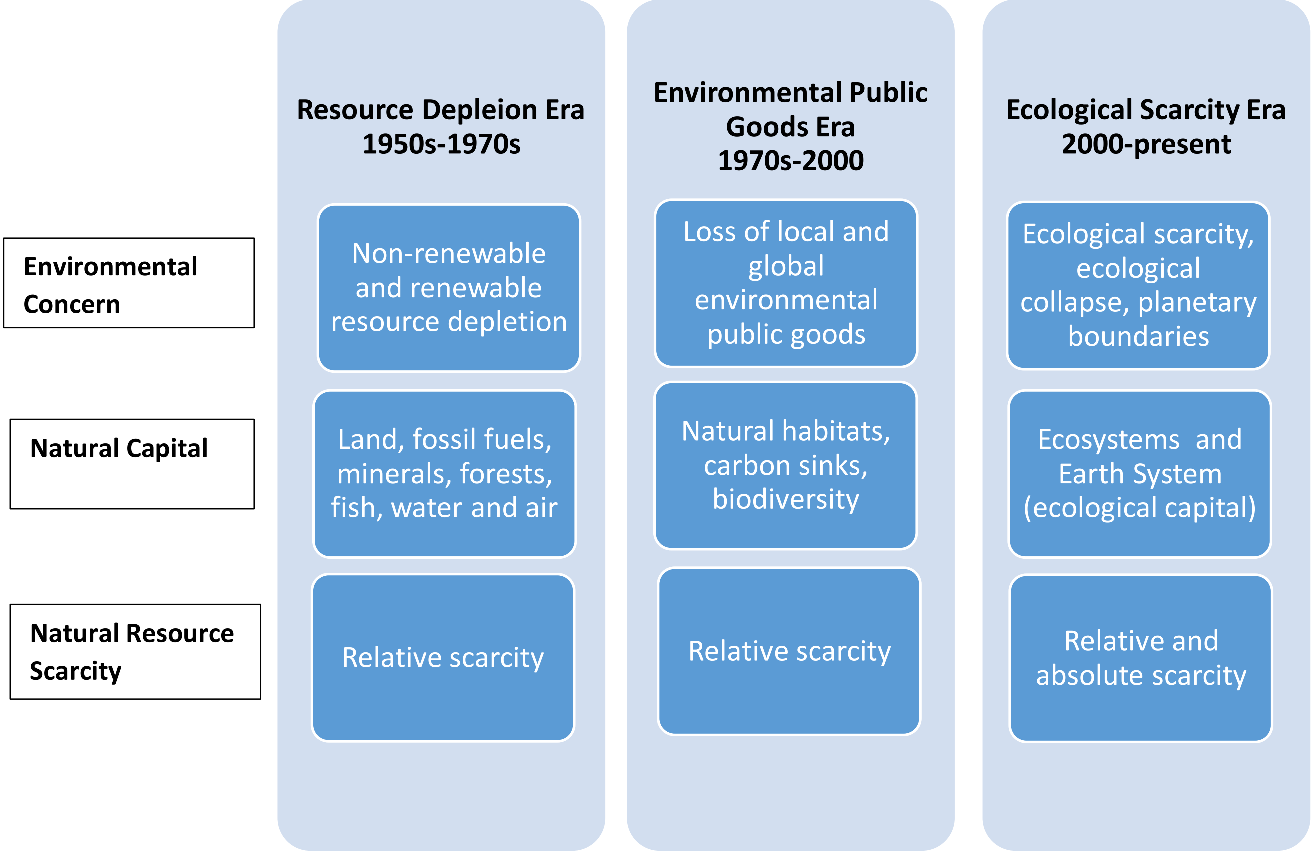
The evolution of thinking on natural resource scarcity in these phases is reflected in the three "Scarcity and Growth" volumes produced by Resources for the Future. As will be discussed below, the landmark *Scarcity and Growth* study by Barnett and Morse (1963) examined absolute and relative scarcity hypotheses for a variety of natural resources in the United States for the period 1870–1958, focusing on land, minerals, fossil fuels and forests. The second volume, *Scarcity and Growth Reconsidered* (Smith 1979), raised concerns over the increasing scarcity of non-marketed environmental public goods and common-property resources. The final volume, *Scarcity and Growth Revisited* (Simpson et al. 2005) highlights growing ecological scarcity and biodiversity loss as key scarcity problems in the "New Millennium". In the first issue of *Review of Environmental Economics and Policy*, Heal (2007) makes a similar distinction of the phases of development in environmental and resource economics thinking to handle more complex resource problems, first over the depletion of resources, then environmental public goods, and now more recently, what he calls the "new paradigm" of biodiversity and ecosystems.

Throughout these three phases, the consensus view on natural resource scarcity has remained fairly consistent. Modern economics has largely rejected the notion that there are physical limits to natural resource exhaustion and environmental decline, and instead, views resource availability as a problem of relative scarcity. However, since the 1950s, as economists began tackling increasingly complex environmental problems, the economic view of natural resource scarcity has evolved. Whereas most environmental and resource concerns are still viewed as problems of relative rather than absolute scarcity, the threat posed by human disruption to the Earth's biosphere and climate suggests that absolute or physical limits to this disruption is now a serious policy concern.

The growing concern by some economists in the current Ecological Scarcity Era over "planetary boundaries" also has roots in economic debates over scarcity and sustainability in the previous two eras. In the 1950s, Ciriacy-Wantrup (1952) called attention to the economic aspects of the loss of unique natural resources and environments. By the 1960s and 1970s, various arguments were put forward to suggest that there may be "limits to growth", including from the physical availability of natural resources used as material and energy inputs by the world economy (Meadows et al. 1972), the limits that laws of thermodynamics impose on energy use by the economic process (Daly 1974 and 1977; Georgescu-Roegen 1971 and 1975), and the ultimate finite limits of Earth itself (Boulding 1966). Beginning in the late 1980s, concern about the irreversible disappearance of unique environments, ecosystems and biodiversity, with unknown consequences for future welfare, led some economists to propose "strong sustainability" views advocating preservation as a necessary "compensation rule" to ensure that future generations are not made worse off by environmental degradation today (Howarth 1991; Howarth and Norgaard 1992 and 1995; Pearce et al. 1989; Toman et al. 1995; Turner 1993). Although these dissenting views during the Resource Depletion and Environmental Public Goods Eras did not alter the economic consensus on scarcity, they did lay the foundation for to more recent concerns of the need to respect "planetary boundaries" to ensure sustainability.

Figure 1 summarizes this main theme of the paper. In the Deletion Era of the 1950s to 1970s, the focus was on the availability of natural resources, natural capital comprised a narrow range of depletable natural resources and ambient sinks, and relative scarcity was the main concern. In the Environmental Public Goods Era of the 1970s to 2000, attention shifted to processes of environmental degradation, such as climate change, deforestation, watershed degradation, desertification and acid rain, which resulted in the loss of global and local environmental public goods. Natural capital was extended to include these goods, and the growing relative scarcity of their non-market benefits was considered the predominant economic problem. From 2000 onwards, ecological scarcity and global biosphere disruption became major concerns, ecological capital was incorporated as a natural asset, and absolute scarcity has emerged to be as important as relative scarcity of environmental goods and services. This current age is the Ecological Scarcity Era.

Figure 1. Environmental Concerns, Natural Capital and Natural Resource Scarcity since the 1950s



	Resource Depleion Era 1950s-1970s	Environmental Public Goods Era 1970s-2000	Ecological Scarcity Era 2000-present
Environmental Concern	Non-renewable and renewable resource depletion	Loss of local and global environmental public goods	Ecological scarcity, ecological collapse, planetary boundaries
Natural Capital	Land, fossil fuels, minerals, forests, fish, water and air	Natural habitats, carbon sinks, biodiversity	Ecosystems and Earth System (ecological capital)
Natural Resource Scarcity	Relative scarcity	Relative scarcity	Relative and absolute scarcity

The outline of this paper is as follows. The next section describes further the origins and evolution of the concept of natural capital, which as shown in Figure 1 is a crucial component of the evolving views of natural resource scarcity since the 1950s. The subsequent section discusses briefly absolute and relative natural resource scarcity, and traces its roots in classical political economy and the seminal contribution of Barnett and Morse (1963) to the modern view of resource scarcity. The next three sections discuss in turn how these competing concepts of scarcity have been perceived over three phases, the 1950s to 1970s, the 1970s to 2000, and from 2000 onwards. The paper concludes with some final thoughts on how economic views of natural resource scarcity have evolved in recent decades, and the implications for the future.

Natural Capital

Since the pioneering work of early 20th century economists, such as Gray (1914), Ise (1925) and Hotelling (1931), economics has viewed natural endowments as *capital assets*.[3] That is, like any other capital stock in the economy, they provide a present value stream of "income" or "benefits" that make them worth holding onto. However, as the type of environmental problem analyzed has changed, so has the concept of what constitutes *natural capital.* In the 1950s to 1970s, the valuable natural resource assets of concern were land, fossil fuels, minerals, and air and water sinks for wastes. Over the 1970s to 2000, natural capital was broadened to include important environmental public goods, such as natural habitats (Fisher et al. 1972;

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[3] The idea of viewing natural endowments as special forms of capital assets is perhaps even older, especially among economists that attempted to clarify the relationship between land and capital as separate factors of production (Ely 1893). For example, Ely (1893, p. 168) made it clear that "rent is that which is paid for the use of land" and that "in economic discussion generally the term rent means only an income from land", which is separate from the "capital rent, or what we shall call gross interest", which is additional income accruing to an owner of land "who erects buildings on it". I am grateful to Spencer Banzhaf for pointing out this important contribution by Ely.

Krutilla 1967; Krutilla and Fisher 1975), and even global sinks of carbon (Nordhaus 1974). By the turn of the 20th century, ecosystems were also be viewed as natural assets, as they comprise a stock of potential ecosystem services, such as pollination, water purification, watershed protection, and support for production (Barbier 2011; Daily et al. 2000; Dasgupta 2008; MA 2005). At the global level, the ultimate natural capital may be the biosphere itself, with its essential Earth system processes of stable climate, global biodiversity and other life-support systems (Rockström et al. 2009; Steffen et al. 2015).

For example, over 100 years ago, Lewis Cecil Gray argued that, "It is easy to determine how much the capital value of a coal mine is reduced by the process of this use. But this capital value is nothing more than the present value of the surplus income from the mine during a period of time, - that is, the present value of the total rent which it will yield…." (Gray 1914, p. 468).[4] This capital approach was developed formally by Hotelling (1931), who demonstrated that the rate of return from holding onto exhaustible resources as an asset must grow at a rate equal to the interest rate, which represents the returns on all other capital in an economy. Ever since Hotelling, treating natural resources as a form of capital has become standard in economics (Dasgupta and Heal 1974; Devarajan and Fisher 1981; Scott 1955a; Solow 1974a; Stiglitz 1974).[5]

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[4] See also Crabbé (1983), who discusses Gray's contribution to early natural resource economics and illustrates Gray's capital approach by a simple natural resource extraction model. The intertemporal implications of treating natural resources as an asset were also noted by Ise (1925), who argued that their rapid depletion in the United States was dangerously biased towards near-term use, at the expense of future generations. Ciriacy-Wantrup (1952) also echoed this theme, in particular noting how interest rate, prices, taxation, property rights, market structure and other factors could affect the time path of natural resource depletion.

[5] Gordon Munro in Brown et al. (2016) and Wilen (2000) credit Scott (1955a) for establishing the capital theoretic approach of natural resource economics, who was the first to model fisheries as a form of "biological capital" (Scott 1955b). Note that, as Dasgupta and Heal (1974, p. 11) demonstrate formally, in models invoking a social welfare objective function Hotelling's rule is generalized to "a statement concerning the equality of the rates of return on the two assets (the exhaustible resource and reproducible capital)."

Economists began applying the capital theoretic framework to a range of valuable renewable and natural resource stocks found in the environment, such as mineral ores, energy reserves, fisheries and forests, as stores of wealth (Clark 1976; Dasgupta and Heal 1979; Scott 1995b; Smith 1968; Solow 1974a; Stiglitz 1974). Pollution was also treated as a special case, where the valuable asset is the assimilative capacity of the environment to store accumulated pollution, which is depleted as more emissions occur over time (d'Arge and Kogiku 1973; Forster 1973; Plourde 1972).

By the 1970s, there was growing recognition that this concept of "natural capital" should be extended more widely to other environmental assets (e.g., see Fisher 1981; Freeman et al. 1973; Krutilla 1967; Krutilla and Fisher 1975; Mäler 1974; Smith 1974). Key among these new assets were non-market environmental public goods, such as undisturbed wildlands and unique natural areas, which Krutilla (1967) and others argued generated a wide range of benefits for current and present generations that largely by-passed the market system.[6] As a consequence, in the early 1970s, Freeman et al. (1973, p. 20) proposed that the environment should be treated as a "capital good" because of the diverse "services" that it generates:

> [We] "view the environment as an asset or a kind of nonreproducible capital good that produces a stream of various services for man. Services are tangible (such as flows of water or minerals), or functional (such as the removal, dispersion, storage, and degradation of wastes or residuals), or intangible (such as a scenic view)."

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[6] See Banzhaf (2019) and V. Kerry Smith in Brown et al. (2016) for further discussion of the legacy of Krutilla (1967) in environmental economics. Banzhaf (2019) also traces the influence of the American environmentalists Gifford Pinchot and John Muir on Krutilla's view of wildlands and unique natural areas as environmental public goods. As pointed out by Barbier (1989) and Sandmo (2015), this view can be traced back to the concern over the need for government to regulate areas of "natural beauty" as expressed by classical economists, such as John Stuart Mill. For example, Sandmo (2015, p. 48) argues that, in expressing these views, "Mill emphasized the public good nature of the natural environment and pointed out that the management of this cannot be left to market forces and individual action."

More recently, there has been rising concern over the continuing disappearance and degradation of many of the world's ecosystems and the subsequent loss in the many benefits – or "services" they provide (MA 2005). This growing literature on ecological services also implies that ecosystems are assets that produce a flow of beneficial goods and services over time. For example, Daily et al. (2000, p. 395) state, "the world's ecosystems are capital assets. If properly managed, they yield a flow of vital services, including the production of goods (such as seafood and timber), life support processes (such as pollination and water purification), and life-fulfilling conditions (such as beauty and serenity)." Consequently, ecosystems can also be viewed as natural assets – or *ecological capital* - as they comprise a stock of potential ecosystem services that support economic activity and enhance human welfare (Atkinson et al. 2012; Barbier 2011 and 2019; Fenichal and Abbott 2014; Fenichal and Hashida 2019).

Nevertheless, as Dasgupta (2008, p. 3) maintains, ecosystems are a very unique form of wealth compared to, say, human-made reproducible capital:

> "Ecosystems are capital assets. Like reproducible capital assets (roads, buildings, and machinery), ecosystems depreciate if they are misused or are overused. But they differ from reproducible capital assets in three ways: (1) depreciation of natural capital is frequently irreversible (or at best the systems take a long time to recover), (2) except in a very limited sense, it isn't possible to replace a depleted or degraded ecosystem by a new one, and (3) ecosystems can collapse abruptly, without much prior warning."

This quote stresses three important aspects of ecological capital. First, the benefits, or valuable goods and services, which are generated by ecosystems are wide-ranging, but generally unmarketed, which is why they frequently "are misused or are overused". Second, although like other assets an ecosystem can be increased by investment, such as through restoration activities, ecosystems are frequently depleted or degraded, e.g. through habitat destruction, land conversion, pollution impacts and so forth. Finally, if ecosystem depletion leads to irreversible loss of ecological landscape, or equivalently, ecological restoration of the landscape is prohibitively expensive, such irreversible conversion can increase the risk of ecological collapse. That is, large shocks or sustained disturbances to ecosystems can set in motion a series of interactions that can breach ecological thresholds that cause the systems to "flip" from one functioning state to another. Although it is possible under certain conditions for the system to recover to its original state, under other conditions the change might be permanent.

In sum, the term "natural capital" today denotes an economy's environment and natural resource endowment – including ecosystems – that yields a valuable flow of goods and services to human beings. However, up to the 1970s, only valuable renewable and natural resource stocks found in the environment, such as mineral ores, energy reserves, fisheries and forests, which provided marketed material and energy inputs were treated as capital "assets". Pollution was also treated as a special case, whereby the valuable stock depleted by accumulating emissions is the environment's assimilative capacity. Starting in the 1970s, natural habitats and environments, which yielded a wide range of non-marketed values, were included in natural capital. By the Millennium, ecological capital was also added, which were recognized as providing another set of valuable, diverse but essentially unmarketed services to humankind. As we shall see presently, this broadening of natural capital coincided with changing views of natural resource scarcity in recent decades.

Absolute and Relative Natural Resource Scarcity

As noted by Smulders (2005), in modern economics, whether an increase in physical scarcity translates into economic scarcity depends on the "neoclassical trinity" of diminishing returns, substitution and technological change in production. According to this view, whereas the diminishing returns from combining more capital and labor with the same amount of natural resource inputs leads to scarcity, technological change and substitution of other inputs for natural resources will counteract this scarcity.

The key relationship between diminishing returns and scarcity was not original to neoclassical economics but inherited from classical political economy, in particular from Thomas Malthus and David Ricardo. However, Malthus and Ricardo differed on how diminishing returns may lead to scarcity, and it is now common to associate Malthus with scarcity arising through absolute or physical limits and Ricardo with relative, or "economic", scarcity.

Barnett and Morse (1963) are credited with first drawing this distinction between "Malthusian" and "Ricardian" approaches to natural resource scarcity. In making this differentiation, the authors established the association of Malthusian scarcity with *absolute or physical* limits on resource availability and Ricardian scarcity with increasing *relative* scarcity:

> "Modern views concerning the influence of natural resources on economic growth are variations on the scarcity doctrine of developed by Thomas Malthus and David Ricardo in the first quarter of the nineteenth century and elaborated later by John Stuart Mill. There were two basic versions of this doctrine. One, the Malthusian, rested on the assumption that the stock of agricultural land was absolutely limited; once this limit had been reached, continuing population growth would require increasing intensity of cultivation and, consequently, would bring about diminishing

> returns per capita. The other, or Ricardian, version viewed diminishing returns as a current phenomenon, reflecting decline in the quality of land as successive parcels were brought within the margin of production." (Barnett and Morse 1963, p. 51).

Thus, according to this interpretation, Malthusian scarcity reflects a situation of absolute or physical scarcity. The finiteness of resources – the physically limited stock of land and other natural resources – act as a constraint on the production of more output. Only when this absolute limit is reached does this scarcity effect impact on production and lead to rising production costs and thus output prices. Once this occurs, the entire stock of natural resources is fully employed. Given the potentially abrupt and uncertain nature of reaching an absolute physical constraint, and the lack of perfect foresight of such scarcity limits, the economic system may not respond with gradually increasing prices that trigger substitution for the scarce natural resource, the use of less resource-intensive techniques, or greater resource exploration. Instead, by combining more and more capital and labor with the fixed resource supply the costs of production may rise rapidly. In the absence of technological change, resource discoveries, or substitution of other inputs for resources in production, absolute scarcity and may lead to rapidly rising costs and production restrictions. In the extreme case where the natural resource input is essential for production, the absolute limit on its availability could lead to the cessation of production.

In contrast, Ricardian scarcity exhibits all the characteristics of relative scarcity. As resources are used in successive grades of declining quality, the costs of their use rises. The less fertile the land or lower grade the resource, more capital and labor needs to be applied to generate the same level of output, which leads to higher costs of production. Consequently, as soon as the initial stock of the highest quality resource is completely utilized, diminishing returns translates into relative scarcity and thus higher prices for output that uses this resource. The economic system should therefore automatically respond to such price signals by triggering substitution for the more expense, relatively scarce natural resource with less resource-intensive techniques allowing more use of human-made capital. The rising relative costs accompanying any Ricardian scarcity effect could also foster exploration for new sources of existing stocks or "discovery or development of alternative sources, not only equal in economic quality but often superior to those replaced" (Barnett and Morse 1963, p. 244).

These two concepts of absolute (Malthusian) and relative (Ricardian) scarcity have not changed since the 1950s. However, what has changed are the views of which types of scarcity pose a threat to continued economic activity, and these views are in turn shaped by the environmental concern, what constitutes natural capital, and ultimately whether the goods and services provided by this capital is marketed or not. As we shall see next, consideration of these aspects of the environment has evolved significantly over the past several decades.

Resource Depletion Era: 1950s-1970s

From the 1950s to the 1970s, the primary concern was with the physical availability of natural resources, and to a lesser extent population sinks, as a potential constraint on economic and population growth. This concern was fueled by studies highlighting such possible "limits to growth" (Carson 1962; Ehrlich 1968; Meadows *et al.* 1972). Beginning with the landmark empirical study on natural resource availability by Barnett and Morse (1963), such pessimistic assessments of the absolute or physical limits to growth was largely refuted by economists. For example, examining per-unit labor and capital costs for extracting various raw materials and energy resources in the United States since the late 19th century, Barnett and Morse (1963, p. 244) concluded that there was little evidence of increasing natural resource scarcity, which they attributed to the "continual enlargement of the scope of substitutability – the result of man's technological ingenuity and organizational wisdom." Follow-on studies confirmed these finding using a broad range of scarcity indicators, except for evidence of short-term scarcity for fossil fuels and some minerals during the energy crises of the 1970s (Barnett 1979; Brown and Field 1978; Hall and Hall 1984; Slade 1982).[7]

Such studies rejected resource depletion as a possible constraint on economic activity as the evidence suggested that the natural capital supplying raw material and energy inputs to the economy displayed the characteristics of relative and not absolute scarcity. As these inputs are *marketed private goods* (i.e. exclusive and rival), their relative scarcity should trigger market responses and incentives that would alleviate any "limits to growth". Thus, the prevailing view among economists was that, as long as rising natural resource scarcity is reflected in rising market prices, technological change, new discoveries and substitution would mitigate any relative or absolute scarcity constraints on growth (Nordhaus and Tobin 1977; Rosenberg 1973; Solow 1974b). Such a view was supported by theoretical explorations of the economics of "exhaustible resources", which confirmed the optimal depletion rule developed by Hotelling (1931) that rising relative scarcity would also mean that any remaining natural capital should appreciate in value, and thus worth holding onto for any future exploitation (Dasgupta and Heal 1974; Solow 1974a; Stiglitz 1974).

This emerging consensus view on scarcity during the Resource Depletion Era was summarized by Nordhaus and Tobin (1977, p. 402):

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[7] However, for critical reviews of these studies, see Neumayer (2000) and Norgaard (1990). Both authors also point to a related literature that has attempted to validate empirically Hotelling's rule that the rents of an exhaustible resource stock should rise at the rate of interest. As resource rent is difficult to observe and measure, this literature has employed other indicators of scarcity, such as extraction costs, royalties and prices; nonetheless, as Neumayer (2000, p. 314) observes, "attempts to empirically validate Hotelling's rule have resulted in contradictory conclusions".

> “If the past is any guide for the future, there seems to be little reason to worry about the exhaustion of resources which the market already treats as economic goods….In a properly functioning market economy, resources will be exploited at such a pace that their rate of relative price appreciation is competitive with rates of return of other kinds of capital….Natural resources *should* grow in relative scarcity – otherwise they are an inefficient way for society to hold and transmit wealth compared to productive and physical capital. Price appreciation protects resources from premature exploitation.”

However, some economists disagreed. Daly (1974 and 1977) and Georgescu-Roegen (1971 and 1975), invoked the laws of thermodynamics to argue that the increased disorder, or entropy, of the environment is a direct consequence of the appropriation of its resources as material and energy inputs by the economic system, and at some point, economic growth must be constrained by this process. As a consequence, the entropy law imposes an absolute resource scarcity constraint that cannot be overcome with technological change, exploration, or substitution. Meadows et al. (1972) suggested that the “limits to growth” were more concrete, arising from the constraints imposed on exponential economic and population growth from finite global sources of fossil fuels, ores and minerals, land and pollution sinks. The authors concluded that, with no changes in growth trends, resource depletion, pollution, and food production would approach their absolute physical limits and result in “sudden and uncontrollable decline in both population and industrial capacity” (Meadows et al. 1972, p. 23).

Among dissenting economists, only Boulding (1966) took the view that the Earth itself was ultimately finite, and thus transition to a “spaceship economy” that respects such limits is unavoidable. Thus, Boulding (1996 pp. 7-8) stated:

> "I am tempted to call the open economy the 'cowboy economy,' the cowboy being symbolic of the illimitable plains and also associated with reckless, exploitative, romantic, and violent behavior, which is characteristic of open societies. The closed economy of the future might similarly be called the 'spaceman' economy, in which the earth has become a single spaceship, without unlimited reservoirs of anything, either for extraction or for pollution, and in which, therefore, man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy."

On the one hand, Boulding was echoing the earlier absolute scarcity view of Malthus, who "found resource scarcity inherent in the finiteness of the globe" (Barnett and Morse 1963, p. 58); on the other, he was prescient in anticipating the "planetary boundaries" debate of the 21st century, which suggests that essential Earth System processes place limits on the expansion of global human activity and populations (Rockström et al. 2009; Steffen et al. 2015).

By and large, however, the notion that there may be global limits on natural resource exploitation and pollution was largely rejected by economists in the Depletion Era. Because natural capital was confined to a select subset of natural resources – arable land, mineral ores, energy reserves, fisheries and forests – that provide marketed energy, minerals or raw materials, any depletion of these resources would manifest as relative scarcity. This was not only important for holding onto remaining natural capital as stores of wealth for future use but also essential for sparking the technological change, substitution and new resource discoveries that would alleviate rising scarcity. Both outcomes were necessary and sufficient to overcome any "limits to growth" from natural resource depletion.

Environmental Public Goods Era: 1970s to 2000

However, beginning in the 1970s, attention shifted to the global and local environment as a source of beneficial public goods, and ultimately, its ability to sustain the livelihoods of both current and future generations. This concern was fostered by the 1972 UN Conference on the Human Environment (http://www.un-documents.net/aconf48-14r1.pdf) and the 1987 World Commission on Environment and Development (WCED 1987). But this interest also started to emerge among some of the early pioneers of natural resource economics, even in the 1950s (Brown et al. 2016).

For example, Ciriacy-Wantrup (1952) was likely the first to call attention to the key economic characteristics of this problem. As noted by Bishop in Brown et al. (2016, p. 31), "So far as we know, Wantrup was the first economist to concentrate on economic issues associated with the potential irreversible loss of unique resources" in the natural environment, including "groundwater reservoirs that are subject to compaction or soil inflow, and places, such as wilderness areas, where some kinds of degradation may be irreversible".[8] As noted previously, this was later elaborated on by Krutilla (1967), who was first to characterize undisturbed wildlands and unique natural areas as non-marketed public goods that generate a wide range of benefits for current and present generations. Early on, Nordhaus (1974) identified the "global heat balance" also as an environmental public good, which could be severely disrupted through the "greenhouse effect" caused by rising carbon dioxide emissions from burning fossil fuels.

However, these local and global environmental public goods have a number of unique characteristics. First, they are generally fixed in supply and subject to irreversible conversion.

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[8] Barnett and Morse (1963, p. 257) also emphasized that growing conservationist concerns over "parks, wildlife, and preservation of the natural biological environment generally reflects recognition such resources have a unique and irreplaceable contribution to make to the quality of modern life. If society deems specific characteristics of the environment worth preserving, they must be saved from irreversible destruction."

The main culprit is widespread processes of environmental degradation emanating from economic activity at all scales, such as climate change, deforestation, watershed degradation, desertification and acid rain. Second, as public goods, they are non-rival and non-exclusive, which means that they are under-supplied and un-protected unless public policy intervenes.[9] Third, the benefits they generate – a variety of amenity services including scientific, recreational and amenity values of preserved natural environments – are not exchanged via market transactions.

The result is that, as environmental degradation proceeds, more of these environmental public goods are irreversibly lost, along with their valuable but unmarketed amenity services. Over time, the services will become scarce relative to the ordinary marketed goods and services produced by an economy, and thus the price of amenities should rise relative to the price of commodities (Fisher et al. 1972; Krutilla 1967; Krutilla and Fisher 1975; Mäler 1974; Smith 1974). Such relative price increases would also mean that any remaining environmental public goods should appreciate in value, yielding rates of return comparable to other capital, and thus this unique natural capital would be worth preserving to deliver future services.

However, as both environmental public goods and their amenity services are not marketed, their increasing scarcity relative to marketed commodities does not lead to rising market prices or appreciating asset values. Because the increasing relative scarcity of such

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[9] Ostrom and Ostrom (1977) and Ostrom (1990) identify common-pool resources as an important sub-category of environmental public goods. As later defined by Ostrom (2010, pp. 644-645), a common pool-resource "shares the attribute of subtractability with private goods and difficulty of exclusion with public goods…. Forests, water systems, fisheries, and the global atmosphere are all common-pool resources of immense importance for the survival of humans on this earth." Although Ostrom (1990) and (2010) has documented many case studies of successful management of common-pool resources by the individuals and use them who use them, this success occurs under specific conditions that allow institutions to be supported by self-reinforcing agreements and maintained through strategies that align such agreements with the perceived self-interest of participants. Where these conditions are not present, common-pool resources are subject to over-exploitation, mismanagement and degradation.

natural capital is not reflected in markets, there is little incentive to preserve these public goods, thus contributing further to their over-exploitation, mismanagement and irreversible loss. In other words, market allocations preserve less than the socially optimal amount of natural environments, even as the latter are irreversibly converted and become increasingly scarce.[10] In addition, because the price of their services do not rise relative to price of ordinary marketed commodities, there is no inducement for technological change and substitution to ameliorate the increasing relative scarcity.

The challenges to optimal management and policies presented by these unique characteristics become increasingly apparent as economists began adapting models of optimal resource depletion to include non-marketed environmental public goods and common pool resources (Dasgupta 1982; Heal 1982; Kamien and Schwartz 1982; Krautkramer 1985). Morton Kamien and Nancy Schwartz were one of the first to extend models of optimal growth to include not only optimal resource depletion but also nonmarketed environmental public goods, "such as clean air and water and other amenity or environmental resources" (Kamien and Schwartz 1982, p. 47). In the same volume, Geoffrey Heal develops several analytical models to show the policy challenges of managing these resources, noting that although "the extent of this overexploitation may be reduced by institutional reform, such as redefinition of property rights or extension of the scope of markets, or by regulatory measures such as taxes, quotas, and licenses". Finally, from including environmental public good provision along with optimal resource depletion, Krautkraemer (1985, p. 154) observed:

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[10] Again, it was Krutilla (1967) who was first to emphasize this unique natural resource scarcity problem with respect to environmental public goods. As noted by Banzhaf (2019, p. 36), "this reinterpretation seems to have been in part a response to *Scarcity and Growth*" (Barnett and Morse 1963).

> "….the problem of providing the amenity services associated with unspoiled environments has become more pressing than the problem of conserving resource inputs for future generations. Technological progress and resource substitution might enable the economy to maintain its material standard of living. However, the supply of preserved environments will dwindle even as improved material well-being increases the demand for the amenity services provided by those environments."[11]

These unusual characteristics of environmental public goods, their amenity and other benefits, and the threats posed by environmental degradation present unique challenges for management and policy.[12] For one, they require specific policy measures to account for this scarcity in market decisions and raise revenues for management and investment, and inter-disciplinary collaboration to assess their importance to economies and society (Pearce et al. 1989). These challenges spurred the development of non-market valuation techniques to estimate the various benefits from environmental public goods and their amenity services (e.g., see Freeman et al. 2014 and Pearce 2002 for reviews). In the case of global public goods, there was increased interest in coordination of international environmental policy and agreements to manage such goods (Barrett 1994a and 1994b; Carraro and Siniscalco 1993; Hoel 1997; Mäler 1989).

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[11] In fact, as pointed out by Smith (1972 and 1974), when environmental services go unpriced, then technical change is induced to use more of them, thus further exacerbating their growing natural resource scarcity.

[12] To illustrate these challenges, during this era, economists developed different approaches to analyzing the intertemporal implications of managing the exploitation of various environmental public goods aspects of these problems, including the control of various environmental degradation processes (Dasgupta 1982), extending optimal depletion models to include natural environments and their amenities (Farzin 1996; Krautkraemer 1985), linking environmental quality decline with sustainable development (Barbier and Markandya 1990; Becker 1982), trade, resource exploitation and stock externalities (Brander and Taylor 1998; Chichilinsky 1994), and optimal policies for managing global public goods, such as climate (Toman 1998), biodiversity (Barrett 1994b) and acid rain (Mäler 1989).

The challenges and uncertainty concerning the value of unique environmental public goods also became the focus of the sustainability debate that began emerging in the late 1980s. Economists largely accepted the definition proposed by the World Commission on Environment and Development that "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, p. 43). As shown by Pezzey (1989 and 1997), this criterion has a clear economic interpretation: per capita welfare should not be declining over time. However, if natural capital depletion is being irreversibly lost, then fulfilling this criterion becomes a matter of compensation; i.e., "future generations should be compensated for reductions in the endowments of resources brought about by the actions of present generations" (Pearce et al. 1989, p. 3). The key focus of debate among economists is what form this compensation should take place. This difference in views is often referred to as *weak sustainability* versus *strong sustainability*.

The main disagreement between these two perspectives centered on whether or not the valuable services of natural capital can be substituted by human-made capital, and if not, whether special "compensation rules" are required to ensure that future generations are not made worse off by natural capital depletion today (Howarth and Norgaard 1995; Pearce et al. 1989; Solow 1993; Toman et al. 1995; Turner 1993). Following a modeling tradition of satisfying intergenerational equity through a min-max criterion first established by Solow (1974a) and then extended further by Weitzman (1976), Hartwick (1977 and 1990), Ashiem (1994) and Pezzey (1997), weak sustainability assumes that there is no difference between natural and other forms of capital (e.g., human or reproducible), and thus as long as depleted natural capital is replaced with more valuable human or reproducible capital, then the total value of wealth available to current and future generations will increase. Thus, as argued by Solow (1993, p. 184), "a correct general guide" for compensation is that "when we use up something that is irreplaceable, whether it is minerals or a fish species, or an environmental amenity, then we should be thinking about providing a substitute of equal value." In contrast, strong sustainability argues that some natural capital, such as unique environmental public goods and amenities, is essential, subject to irreversible loss, and has uncertain value. Consequently, the only way of protecting the welfare of future generations is to preserve these unique assets and the essential services they provide (Howarth 1991; Howarth and Norgaard 1992 and 1995).

Ecological Scarcity Era: 2000 to Present

The Millennium Ecosystem Assessment (MA 2005) drew attention to the rapid deterioration in global ecosystems, and the detrimental implications for ecosystem "services" – the myriad benefits that humans derive from ecosystems. This led to an emerging view in economics that these systems should be treated as a form of "ecological capital", and their increasing relative scarcity reflects the irreplaceable conversion, uncertainty over their values, and the possibility of abrupt collapse (Barbier 2011; Daily et al. 2000; Dasgupta 2008; Fenichel and Abbott 2014).

In many ways, ecosystems and their services are essentially another example of environmental public goods. After all, most ecosystems have the non-rival and non-exclusive characteristics of public goods, and most ecosystem services are not marketed.[13] Thus, as

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[13] As noted previously, some important ecosystems, especially many forests, water systems, fisheries and rangelands, are rival but non-exclusive common pool resources (Ostrom 2010). Although there are many examples

ecosystems disappear, such ecological capital and their services also exhibit increasing relative scarcity that is not reflected in market outcomes.[14]

However, there are several aspects of the ecological scarcity problem that differentiate it from the scarcity of other environmental public goods.

First, as noted previously, ecosystems are not only fixed in supply and subject to irreversible loss, but they are also prone to abrupt collapse if sufficiently disturbed or degraded (Dasgupta 2008). This risk of collapse must be taken into account in valuing scarce ecological capital and accounting for their irreversible conversion in development decision making (Barbier 2011).[15] On a global scale, the uncertainty over unforeseen future impacts coupled with irreversible and substantial environmental losses, has led to a growing literature that explores how today's actions affect future welfare, not only through a reduction of the future set of choices, but also directly by changing the risk borne by future generations (Gollier et al. 2000; Gollier and Treich 2003; Heal and Millner 2011; Iverson and Perrings 2012; Vardas and Xepapadeas 2010; Weitzman 2009, 2011 and 2013).

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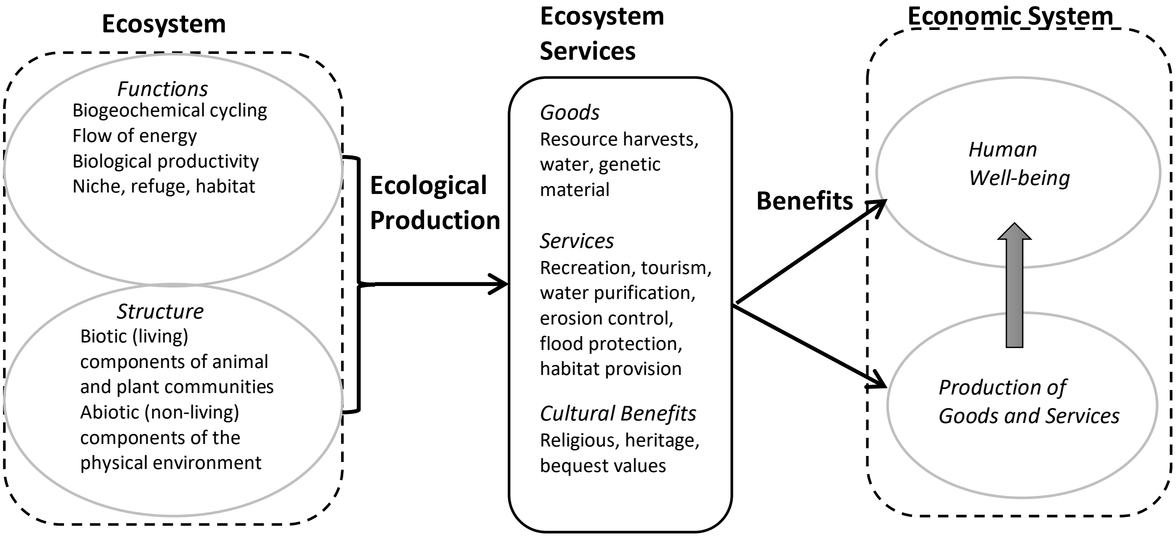
of users of these complex systems evolving successful management regimes and institutions, there are also many cases of management and failure. Problems of ecological collapse often occur "in very large, highly valuable, open-access systems when the resource harvesters are diverse, do not communicate, and fail to develop rules and norms for managing the resource" (Ostrom 2009, p. 419).

[14] This similarity was noted some time ago by Barbier (1989, pp.96-7), who described the problem of "ecological scarcity" as follows: "The fundamental scarcity problem...is that as the environment is increasingly being exploited for one set of uses (e.g., to provide sources of raw material and energy, and to assimilate additional waste), the quality of the environment may deteriorate. The consequence is an increasing *relative scarcity* of essential natural services and ecological functions.... Although the loss of these essential natural services as a result of environmental degradation is not directly reflected in market outcomes, it nevertheless has a major effect in the form of economic scarcity."

[15] The importance of uncertainty over irreversible environmental losses to policy decisions was also noted in the Environmental Public Goods Era. For example, Arrow and Fisher (1974) and Henry (1974) demonstrated how this irreversibility effect makes a policy that preserves more wilderness area more valuable if it leads to better information over time about whether or not development should take place. Similarly, development of models concerned with management of bioeconomic populations, such as fisheries, took into account that they could also collapse from over-exploitation. See Clark (1976); Cropper (1976) and Reed (1988).

Second, in common with other environmental public goods, the diverse benefits provided by ecosystems are generally non-marketed. However, many of these services arise in very complex ways, via the structure and functioning of ecosystems (see Figure 2). Some of these services benefit humans directly, whereas others indirectly benefit human well-being through supporting or protecting economic assets and production activities. Consequently, as Polasky and Segerson (2009, p. 422) maintain, "among the more practical difficulties that arise in either predicting changes in service flows or estimating the associated value of ecosystem services" include the "lack of multiproduct, ecological production functions to quantitatively map ecosystem structure and function to a flow of services that can then be valued." Thus, “the fundamental challenge of valuing ecosystem services lies in providing an explicit description and adequate assessment of the links between the structure and functions of natural systems, the benefits (i.e., goods and services) derived by humanity, and their subsequent values” (NRC 2005, p. 2).

Figure 2. The Ecological Production of Ecosystem Services for the Economic System



The structure and functioning of ecosystems lead to the ecological production of ecosystem services. Some of these services benefit humans directly, whereas others indirectly benefit human well-being through supporting or protecting economic assets and production activities.

In sum, ecosystems provide a number of valuable goods and services to humans. However, because most of these benefits are provided by ecosystems and endowed by nature, i.e. for free, they tend to be "undervalued" even as they increase in relative scarcity. That is, there is no market for many important ecosystem goods and services, and so we have no information of the "price" people are willing to pay to have more of them, nor any incentive to manage ecosystems better. Moreover, because of the complex way in which the ecological production of ecosystem services occur, and the risks incurred from the threat of ecological collapse, we often do not know the consequences for human well-being when ecosystems are lost or degraded (Vardas and Xepadeas 2010). Nor do we know the costs of replicating the ecological production of many ecosystem services, or if it is even technically feasible. Finally, "a core challenge in diagnosing" why ecosystems that are exploited by humankind "are sustainable whereas others collapse is the identification and analysis of these complex systems at different spatial and temporal scales" (Ostrom 2009, p. 420). These are all important factors behind the widespread decline in ecological capital today.

But an even bigger challenge to economic perceptions of ecological scarcity is emerging. There is now a growing scientific literature that advocates *planetary boundaries* on key anthropogenic impacts on the biosphere to protect the Earth system from abrupt and irrevocable phase changes (Rockström et al. 2009; Steffen et al. 2015). That is, scientists are increasingly emphasizing that human populations and economic activity are rapidly approaching and even exceeding the limits of key sub-systems and processes of the global environment, which could lead to abrupt phase changes, or "tipping points" in the Earth system (Dinerstein et al. 2017; Lenton et al. 2008; Rockström et al. 2009; Running 2012; Steffen et al. 2015). According to this literature, there are "nine such processes for which we believe it is necessary to define planetary boundaries: climate change; rate of biodiversity loss (terrestrial and marine); interference with the nitrogen and phosphorus cycles; stratospheric ozone depletion; ocean acidification; global freshwater use; change in land use; chemical pollution; and atmospheric aerosol loading" (Rockström et al. 2009, p. 472). Protecting these planetary boundaries may require a specific set of policy tools that ensure their absolute protection and conservation, including binding and meaningful international agreements limiting use based on sound scientific principles, and ways to raise sufficient revenue to ensure investment in their long-term conservation and management (Sterner et al. 2019). Such policies reflect the *strong sustainability* view that maintains that some natural capital is essential (e.g., unique environments, ecosystems, biodiversity and life-support functions), subject to irreversible loss, and has uncertain value. In other words, as noted by Barbier (2019, p. 20), “this strong sustainability perspective is directly related to recent scientific concerns of the need to respect ‘planetary boundaries’.”

The rationale for establishing planetary boundaries on human exploitation of key sinks and resources is to avoid “tipping points” or “thresholds” that could lead to irrevocable changes in the Earth system, with potentially catastrophic impacts for humanity. A planetary boundary therefore “aims to help guide human societies away from such a trajectory by defining a ‘safe operating space’ in which we can continue to develop and thrive” (Steffen et al. 2015, p. 737). In addition, the boundary defining the safe operating space should be set well before any “buffer” that both accounts for “uncertainty in the precise position of the threshold” and “also allows society time to react to early warning signs that it may be approaching a threshold and consequent abrupt or risky change” (Steffen et al. 2014, pp. 737-738).

Specifying a planetary boundary to demarcate a “safe operating space” places an absolute limit on human exploitation of critical global biophysical sinks or resources (Rockström et al. 2009). In effect, each safe operating space is a special form of “depletable” environmental capital (Barbier 2019). Depending on the type of planetary boundary, measurement of the finite stock could be in terms of terrestrial net primary production, available freshwater for consumption, species richness, assimilative capacity for various pollutants, forest land area, or the global carbon budget (Dinerstein et al. 2017; Gerton et al. 2013; Mace et al. 2014; Running 2012; Steffen et al. 2015). However, demarcating safe operating spaces to limit human exploitation of critical global sinks and resources raises important issues of *intragenerational equity*. If current access to these sinks and resources is unequally distributed and dominated by wealthy nations, regions and individuals, then some form of compensatory policy may be necessary either to improve access by the poor or to ensure that they are adequately reimbursed for any additional burdens imposed by reduced access.

The concept of a planetary boundary that limits impacts from human activities that threaten critical Earth system resources and sinks revives the absolute scarcity view of Malthus, who “found resource scarcity inherent in the finiteness of the globe” (Barnett and Morse 1963, p. 58). However, in this instance it is humankind that is required to place an absolute limit on its global environmental impacts, rather that nature imposing this constraint. This perspective challenges economics to reconsider whether absolute scarcity is a binding constraint. However, this time the limits are in terms of the “Spaceship Earths” as defined by Boulding (1966) rather than the “Limits to Growth” from running out of strategically important energy and raw material stocks as predicted by Meadows et al. (1972).

It is also clear that, demarcating planetary boundaries to protect vital global sinks and resources is the first step in a policy approach that must adjust to managing finite safe operating spaces, and to do so in an efficient, sustainable and equitable manner (Barbier 2019; Smith 2017; Sterner et al. 2019). Recognizing absolute limits to global human impacts does not mean that managing the relative scarcity of natural capital, including environmental public goods and ecosystems is no longer relevant. To the contrary, the second essential step in a policy approach that manages finite safe operating spaces is to adopt policies that take into account increasing scarcity and generate the necessary values, incentives and income for investments to alleviate it. As argued by Sterner et al. (2019, p. 19), "Keeping within planetary boundaries requires that we make better and more cost-effective use of the finite resources and sinks available to us." This can be accomplished by viewing the safe operating defined by scientists for any critical global biophysical sink or resource as a special form of "depletable" environmental capital that must be optimally managed (Barbier 2019). These two steps are inter-related. By identifying a quantifiable safe operating space for exploiting a global resource or sink, scientists have effectively specified an asset that can be safely depleted without causing possibilities of threshold effects or tipping points, thus leaving much of the remaining asset preserved well before any unpredictable threshold effects occur (see Figure 3).

However, such an approach assumes that there is scientific consensus on a quantifiable planetary boundary. But a different approach is required in the case of human impacts on important global sinks and resources for which planetary boundaries, and thus safe operating spaces, are not yet quantified by scientists. For example, Steffen et al. (2015) suggest that this is the case for the introduction of novel entities, functional biodiversity loss and atmospheric aerosol loading. As Weitzman (2009) first showed with the example of "fat-tail uncertainty" over catastrophic climate change, mitigation and precaution become much better economic options when faced with large uncertainties over potentially large-scale consequences for humankind and neutral intergenerational time preferences are adopted. Tackling such scientific uncertainties over unseen future environmental impacts coupled with continued irreversible depletion requires a more robust modeling approach to policy decisions concerning global environmental problems (Gollier et al. 2000; Gollier and Treich 2003; Heal and Millner 2011; Iverson and Perrings

2012; Vardas and Xepapadeas 2010: Weitzman 2009, 2011 and 2013). Clearly, this is a rich research agenda for economists to explore as the Era of Ecological Scarcity ensues.

Conclusion

This paper has traced the evolution of economic thinking on natural resource scarcity since the 1950s. Three distinct trends in this thinking can be discerned: the Era of Depletion (1950s to 1970s), the Era of Environmental Public Goods (1970s to 2000) and the Era of Ecological Scarcity (2000 to present). Table 1 summarizes the evolution in views on natural resources and the environment in each of these eras.

Table 1. Evolution in Views of Natural Resource Scarcity since the 1950s

	Resource Depletion Era 1950s-1970s	**Environmental Public Goods Era 1970s-2000**	**Ecological Scarcity Era 2000-present**
Concern	Non-renewable and renewable resource depletion	Loss of local and global environmental public goods	Ecological scarcity, ecological collapse, planetary boundaries
Natural capital	Land, fossil fuels, minerals, forests, fish, water and air	Natural habitats, carbon sinks, biodiversity	Ecosystems and Earth System (ecological capital)
Scarcity	Relative	Relative	Relative and absolute
Goods	Energy and material inputs	Amenity, recreation, clean environments	Ecosystem services, biosphere resilience
Characteristics	Rival and exclusive, marketed	Non-rival and non-exclusive, non-marketed	Non-rival and non-exclusive, non-marketed
Mitigation	Substitution, technological change	Valuing and pricing externalities, public policy	Reducing scale of human activity and its impacts

The perspective on natural resource scarcity adopted by economists in each of these eras was shaped by the predominant environmental concern of the times. During the 1950s to 1970s, the concern was whether the exhaustion of resources placed “limits to growth” on economic activity. From the 1970s to 2000, an additional focus was the state of environment itself, and especially the loss of global and local environmental public goods and their important non-market values. Since 2000, this perspective was widened further to encompass the state of the world's ecosystems and Earth system processes, and the need to respect "planetary boundaries" on the environmental impacts from human activities.

As economists has tackled more complex environmental problems, the concept of natural capital was also broadened to include additional "valuable" natural resource and environmental endowments. Initially, it was natural resources that provided material and energy inputs or environmental sinks for waste, then local and global environmental goods, and more recently, ecosystems and Earth system processes.

Since the 1950s, most environmental and resource concerns have been viewed as problems of relative rather than absolute scarcity. However, the technical characteristics of natural capital and its goods and services matter significantly in determining how scarcity is mitigated. Natural resources, such as arable land, mineral ores, energy reserves, fisheries and forests, provide marketed energy, minerals or raw materials. Any scarcity of these resources would trigger rising costs and prices in the economy, thus inducing the technological change, substitution and new resource discoveries that would alleviate rising scarcity. Environmental public goods and ecosystems are fixed and supply, and thus their irreversible loss should also lead to relative scarcity of their valuable services compared to ordinary commodities. However, these assets and their services are non-rival and non-exclusive, and are generally not marketed, under-valued and under-supplied. Public policy interventions are necessary to assess and price their values and to protect these public goods.

Finally, proponents for planetary boundaries are advocating that humans impose absolute limits on their global impacts, essentially creating absolute scarcity conditions. Whether in the coming decades humankind is willing to accept such self-imposed limits on the scale of economic activity and its global environmental impacts remains to be seen. At the very least, this debate is forcing us to reconsider whether absolute scarcity is a binding constraint – albeit as defined by Boulding (1966) rather than Meadows et al. (1972). As Sterner et al. (2019, p. 14) note, "Today, more than ever, 'Spaceship Earth' is an apt metaphor as we chart the boundaries for a safe planet."

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