The Evolution of Economic Views on Natural Resource Scarcity[1]

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Abstract

Since the 1950s, as environmental challenges have evolved, so too have economic views on natural resource scarcity. This article discusses three distinct phases in this evolution. From the 1950s through the 1970s, the "Resource Depletion Era", the environment was viewed mainly as a source of key natural resources and a sink for waste, and thus the focus of economics was on whether there are 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 the environment and 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 and their important non-market values. From 2000 to the present, the "Ecological Scarcity Era", there has been growing concern about the state of the world's ecosystems and Earth system processes, and thus the focus has shifted back to possible "limits" to economic and population expansion, although the emphasis now is 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

This article traces the development of economic views on natural resource scarcity from the 1950s to the present. During this period, environmental and resource economics has emerged as an important and growing sub-field within economics, and as economists have addressed a wider and more complicated array of environmental problems, the discipline and its perceptions of natural resource scarcity have changed considerably. The evolution of these views can provide important insights into the contemporary history of economic thinking on the environment and identify priorities for future research and policy.

There appears to be three distinct phases in the evolution of modern economic views of natural resource scarcity. First, from the 1950s through the 1970s, the main concern of economists was whether there are physical "limits" on the availability of natural resources as economies expand and populations grow. I refer to this phase as the "Resource Depletion Era". From the 1970s to the end of the 20th century, the attention of economists shifted to the state of the environment, especially the loss of global and local environmental public goods and their important non-market values. This phase is the "Environmental Public Goods Era". Since 2000, there has been growing concern about the state of the world's ecosystems and Earth system processes, and the need to recognize "planetary boundaries" on the environmental impacts of human activities. This third phase is the "Ecological Scarcity Era".

The remainder of the article is organized as follows. The next section describes the origins -- and the broadening-- of the concept of natural capital, which is a crucial component of the views of natural resource scarcity that have evolved since the 1950s. The subsequent section briefly discusses absolute versus relative natural resource scarcity and the contribution of Barnett and Morse (1963) to differentiating these two economic perspectives. The next three sections discuss how these competing concepts of scarcity have been viewed during each of the three phases -- the 1950s to the 1970s, the 1970s to 2000, and from 2000 to the present. The article concludes with some final thoughts on how economic views of natural resource scarcity have evolved in recent decades and their implications for future research and policy.

NATURAL CAPITAL

Ever since the pioneering work of early 20th century economists, such as Gray (1914), Ise (1925), and Hotelling (1931), economics has generally viewed natural endowments as *capital assets*.[2] That is, like any other capital stock in the economy, natural resources provide a present value stream of "income" or "benefits," which makes them an important and unique form of economic wealth. However, as the type of environmental problem analyzed by economists has changed, so too has the concept of what constitutes *natural* capital. Here, I briefly trace the evolution of this concept to meet new environmental challenges, which is important for understanding how views of natural resource scarcity have also changed since the 1950s.

Early Views of Natural Capital

Up until the 1970s, the natural resource stocks considered to have value as capital assets were land, fossil fuels, minerals, and air and water sinks for wastes. 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

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[2] I am grateful to Spencer Banzhaf for pointing out that viewing natural endowments as capital could also be attributed to Ely (1893), who attempted to clarify how land and capital differ as factors of agricultural production.

value of the total rent which it will yield….” (Gray 1914, p. 468).[3] This theoretical framework for managing a natural resource stock as a form of capital was developed formally by Hotelling (1931), who showed that the rate of return from holding onto an exhaustible resource 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, it has become standard in economics to treat natural resource stocks and sinks as a form of capital.[4]

In the 1950s to 1970s, economists began applying this 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 (Clark 1976; Dasgupta and Heal 1974 and 1979; Devarajan and Fisher 1981; Scott 1955a and 1955b; 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 emissions increase over time (d’Arge and Kogiku 1973; Forster 1973; Plourde 1972).

Extending the Concept of Natural Capital

Starting in the 1960s and1970s, the concept of natural capital was gradually extended to include other environmental resources that were considered also to yield important flows of benefits (e.g., see Freeman et al. 1973; Krutilla 1967; Krutilla and Fisher 1975; Mäler 1974; Smith 1974). Key among these new assets were environmental public goods, such as undisturbed wildlands and unique natural areas, which Krutilla (1967) and others argued

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[3] See also Crabbé (1983), who discusses and illustrates Gray’s capital approach to natural resources. The intertemporal implications of treating natural resources as an asset were also noted by Ise (1925) and Ciriacy-Wantrup (1952).

[4] Gordon Munro in Brown et al. (2016) and Wilen (2000) credit Scott (1955a) with formally establishing the capital theoretic approach in natural resource economics. Scott (1955b) was the first to model fisheries as a form of “biological capital”. As Dasgupta and Heal (1974, p. 11) demonstrate formally, in models that include 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).”

generated a wide range of benefits for current and present generations that largely by-passed the market system.[5] As attention turned to global environmental issues, such as climate change, natural capital was broadened further to include other non-market environmental public goods, such as global sinks of carbon (Nordhaus 1974). Thus, in the early 1970s, Freeman et al. (1973, p. 20) proposed that we "view the environment as an asset or a kind of nonreproducible capital good that produces a stream of various services for man." This paved the way for treating all the components of the environment, such as ecosystems, as a form of capital.

Ecosystems and Ecological Capital

By the turn of the 20th century, ecosystems were also viewed as natural capital. For example, Daily et al. (2000, p. 395) suggested that "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 should be viewed as natural or *ecological capital* because 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).

However, as Dasgupta (2008, p. 3) argues, 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),

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[5] See Banzhaf (2019) and V. Kerry Smith in Brown et al. (2016) for further discussion of the environmental economics legacy of Krutilla (1967).

> (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 highlights three important characteristics of ecological capital. First, the benefits -- or the valuable goods and services -- that are generated by ecosystems are wide-ranging, but generally unmarketed. This is why they frequently “are misused or are overused”. Second, although like other assets, an ecosystem can be increased by investment (e.g., through restoration activities), ecosystems are frequently depleted or degraded, through, for example, habitat destruction, land conversion, and pollution impacts. Finally, if ecosystem depletion leads to irreversible loss of ecological landscape or, equivalently, if ecological restoration of the landscape is prohibitively expensive, then 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 (e.g., a forest degenerating into a degraded landscape or a lake deteriorating into hypoxia). Although it is possible under certain conditions for the system to recover to its original state, under other conditions the change might be permanent.

The broadening of the concept of natural capital to embrace new environmental challenges is important, because it parallels how economic views on natural resource scarcity evolved from the 1950s to the present. To understand this development, it is helpful to understand the two different ways in which scarcity is viewed by economists – absolute and relative scarcity.

ABSOLUTE AND RELATIVE NATURAL RESOURCE SCARCITY

Economic thinking about natural resource scarcity can be traced back to classical political economy.[6] The two main concepts of natural resources scarcity – *absolute* (or Malthusian) versus *relative* (or Ricardian) scarcity emerged from this early literature. Absolute scarcity implies that a resource is physically limited in the amount available, whereas relative scarcity implies that a resource is scarce relative to other inputs, and thus the cost or price of the scarce resource should rise relative to that of other inputs.

As noted by Smulders (2005), the consensus view in modern economics is that the "neoclassical trinity" of diminishing returns, substitution possibilities, and technological change in production will alleviate the economic consequences of any absolute natural resource scarcity threat. Diminishing returns makes capital accumulation and labor less productive as they are combined with fewer resource inputs. But if resources are traded in markets, their price will rise relative to capital and labor. This relative scarcity will trigger technological change and the substitution of other inputs for natural resources, thus counteracting any diminishing returns caused by scarcity.

However, there has not always been a consensus in economics on the relationship between diminishing returns and scarcity. For example, Barnett and Morse (1963) pointed out that the two classical political economists, Thomas Malthus and David Ricardo, put forward differing perspectives on this relationship, which in turn has shaped two competing views on how natural resource scarcity can impact economic growth:

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[6] For further discussion of the early origins of natural resource economics and concepts of natural resource scarcity, see Barbier (1989); Barnett and Morse (1963); Brown et al. (2016); Crabbé (1983); Robinson (1980 and 1989); Pearce (2002); and Sandmo (2015).

> “Modern views concerning the influence of natural resources on economic growth are variations on the scarcity doctrine 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 Barnett and Morse (1963), under the Malthusian approach, the finiteness of resources – the physically limited stock of land and other natural resources – acts as a constraint on the production of more output. Once this absolute limit is reached, more and more capital and labor must be combined with the fixed resource supply, thus causing the costs of production to rise rapidly. This suggests that in the absence of technological change, resource discoveries, or substitution of other inputs for resources in production, absolute scarcity 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 complete cessation of production.

In contrast to Malthusian, or absolute, scarcity, Ricardian scarcity includes all the characteristics of relative scarcity and diminishing returns outlined by Smulders (2005). That is, as resources are used in an order of declining quality, the cost of their use rises. For example, the less fertile the land or lower grade the resource, the greater the amount of capital and labor required to generate the same level of output. This leads to higher costs of production, which means that as soon as the initial stock of the highest quality resource has been completely utilized, there are diminishing returns, which translate into relative scarcity and thus higher prices for resources compared to other inputs. Such price signals will trigger substitution of more capital and labor for the more expensive, relatively scarce natural resource.[7]

The concepts of absolute (Malthusian) and relative (Ricardian) scarcity have not changed since the 1950s. As I will discuss in the next three sections, what *has* changed and evolved over the last several decades are economists' views of which types of scarcity pose a threat to continued economic activity. These views have, in turn, been shaped by the environmental challenges faced, the definitions of natural capital, and, ultimately, whether or not the goods and services provided by this capital are marketed. The next three sections discussed three distinct phases in this thinking: 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.

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[7] The rising relative costs may also encourage 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).

Table 1. Evolution of Economists' Views about Natural Resource Scarcity

	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 RESOURCE DEPLETION ERA: THE 1950s-1970s

From the 1950s to the 1970s, the environment was viewed mainly as a source of key natural resources and a sink for waste, and thus economists were primarily concerned with the physical availability of natural resources, and, to a lesser extent, pollution sinks, as a potential constraint on economic and population growth. This concern was fueled by studies that highlighted such potential "limits to growth" (Carson 1962; Ehrlich 1968; Meadows *et al.* 1972). In this section, I will explain how economists were able to reject this latter perspective by demonstrating how relative scarcity of natural resources as marketed energy and material inputs would mitigate any potential threat of scarcity on growth.

Rejection of Limits to Growth

Beginning with the landmark empirical study on natural resource availability by Barnett and Morse (1963), pessimistic assessments of the absolute or physical limits to growth were largely refuted by economists. Barnett and Morse (1963, p. 244) found little evidence of increasing natural resource scarcity, which they argued was because of the "continual enlargement of the scope of substitutability – the result of man's technological ingenuity and organizational wisdom." Follow-up studies confirmed these findings using a broad range of scarcity indicators, although there was some 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).

These studies generally rejected resource depletion as a potential constraint on economic activity because the empirical evidence suggested that the natural capital that supplied raw material and energy inputs to the economy displayed the characteristics of relative -- rather than absolute -- scarcity. During this era, the focus was on a select subset of natural resources – arable land, mineral ores, energy reserves, fisheries, and forests – that provide marketed energy, minerals or raw materials, and thus economists generally argued that any depletion of these resources would result in relative scarcity. That is, because these inputs are *marketed private goods* (i.e., exclusive and rival), their relative scarcity will trigger market responses and incentives that would alleviate any "limits to growth". Consequently, the prevailing view among economists during this period was that, as long as rising natural resource scarcity was 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).

This view was also supported by theoretical studies of the economics of “exhaustible resources”, which confirmed the optimal depletion rule developed by Hotelling (1931) -- that rising relative scarcity would cause any remaining natural capital to appreciate in value, and thus would be worth conserving more today for future exploitation (Dasgupta and Heal 1974; Solow 1974a; Stiglitz 1974).[8]

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

> “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.”

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[8] Neumayer (2000) and Norgaard (1990) maintain that it has been difficult to verify Hotelling’s rule that the rents of an exhaustible resource stock should rise at the rate of interest. Because resource rent is difficult to observe and measure, studies have relied on other indicators of scarcity, such as extraction costs, royalties and prices; consequently, “attempts to empirically validate Hotelling’s rule have resulted in contradictory conclusions” (Neumayer 2000, p. 314).

Dissenting Views

Some economists disagreed with the view that there is no absolute scarcity constraint on growth. Daly (1974) and Georgescu-Roegen (1971 and 1975) relied on 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 that at some point, economic growth must be constrained by this process. This means that the law of entropy 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 purely physical, arising from the constraints imposed on exponential economic and population growth by finite global sources of fossil fuels, ores and minerals, and land and pollution sinks. Indeed, Meadows et al. (1972, p. 23) 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” .

Among these dissenting economists, only Boulding (1966) took the view that the Earth itself was ultimately finite, arguing that a transition to a “spaceship economy” (i.e. one that recognizes the limits imposed by “a cyclical ecological system”) is unavoidable. More specifically, Boulding (1996 pp. 7-8) argued:

> “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 (1996) echoed 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 hand, 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).

THE ENVIRONMENTAL PUBLIC GOODS ERA: THE 1970s-2000

Beginning in the 1970s, the attention of economists shifted to viewing 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. Here, I outline the emergence of this view in economics, the unique challenges it poses for management and policy, and its connection to economic debates over sustainability.

Background

The public goods view of the environment was fostered by major international events, such as 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). However, this view began 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) called attention to the economic characteristics of environmental public goods. 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".[9] Krutilla (1967), elaborated on this point, arguing that undisturbed wildlands and unique natural areas are non-marketed public goods that generate a wide range of benefits for current and present generations. Early on, Nordhaus (1974) also identified the "global heat balance" as an environmental public good, which could be severely disrupted through the "greenhouse effect" caused by rising carbon dioxide emissions from burning fossil fuels.

Environmental Public Goods

Local and global environmental public goods have a number of unique characteristics. First, they are generally fixed in supply and their loss is irreversible. This is due to the environmental degradation that results 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 there is public policy intervention.[10] Third, the benefits they generate – a variety of amenity services, including scientific, recreational, and aesthetic values of preserved natural environments – are not exchanged via market transactions.

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[9] 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."

[10] 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."

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

However, neither environmental public goods nor their amenity services are marketed; this means that in the real world their increasing scarcity relative to marketed commodities will not lead to rising market prices or appreciating asset values, and thus there is little incentive to preserve these public goods, which contributes 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.[11] In addition, because the price of their services does not rise relative to the price of ordinary marketed commodities, there is no inducement for technological change and substitution to ameliorate the increasing relative scarcity.

Challenges for Management and Policy

These unusual characteristics of environmental public goods, their amenity and other benefits, and the threats posed by environmental degradation present unique challenges for

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[11] 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).

management and policy.[12] For one, specific policy measures are required to account for scarcity in market decisions and to raise revenues for management and investment, as well as inter-disciplinary collaboration to assess their importance to economies and society (Pearce et al. 1989). The management and policy challenges became 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). Kamien and Schwartz (1982) was one of the first studies to extend optimal growth models 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, Heal (1982) developed several analytical models to illustrate the policy challenges of managing non-marketed environmental public goods, noting that "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, in a study that included environmental public good provision along with optimal resource depletion, Krautkraemer (1985, p. 154) observed:

> "….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

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[12] To illustrate these challenges, economists extended optimal depletion models to include natural environments and their amenities (Dasgupta 1982; Krautkraemer 1985), environmental quality and sustainable development (Barbier and Markandya 1990; Becker 1982), trade and resource exploitation (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).

> supply of preserved environments will dwindle even as improved material well-being increases the demand for the amenity services provided by those environments."[13]

Consequently, Krautkraemer (1985, p 164) was able to demonstrate that "the recreational, aesthetic, and scientific amenity services provided by preserved natural environments increases the opportunity cost of extracting resources from the environment".

These management and policy challenges spurred the development of non-market valuation techniques to estimate the 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, interest increased in pursuing the coordination of international environmental policy and agreements to manage such goods (Barrett 1994a and 1994b; Carraro and Siniscalco 1993; Hoel 1997; Mäler 1989).

The Sustainability Debate

The challenges and uncertainty concerning the value of 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). Pezzey (1989, 1997) shows that satisfying this criterion for sustainable development implies that per capita welfare cannot decline over time. However, if natural capital is being irreversibly depleted, then meeting this criterion will require compensation -- that is, "future generations should be compensated for

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

reductions in the endowments of resources brought about by the actions of present generations" (Pearce et al. 1989, p. 3). The focus of debate among economists has been about the form this compensation should take. This difference in views is often referred to as *weak sustainability* versus *strong sustainability*.

Weak vs. Strong Sustainability

The main distinction between weak sustainability and strong sustainability centers on whether or not human-made capital can substitute for the valuable services provided by natural 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). Weak sustainability assumes that there is no difference between natural and other forms of capital (e.g., human or reproducible), which suggests that as long as depleted natural capital is replaced with more valuable human or reproducible capital, such as better educated and trained workers or machines, tools and factories, then the total value of wealth available to current and future generations will increase.[14] 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 maintains that some natural capital, such as unique environmental public goods and amenities, is essential, subject to irreversible loss, and has uncertain value. As a result, according to this view, the only way to protect the welfare of future generations is to

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[14] This result stems from the pioneering work of John Hartwick, who first showed that intergenerational equity can be achieved if the rents from depleting an exhaustible resource are reinvested in other forms of capital (Hartwick 1977). Building on the net national product approach of Weitzman (1976), Hartwick (1990) extended this outcome to include renewable resource depletion and pollution.

preserve these unique assets and the essential services they provide (Howarth 1991; Howarth and Norgaard 1992 and 1995).

Thus, during the Environmental Public Goods Era, economists took on the challenge of local and global environmental public goods, such as natural environments and their amenities as well as climate change and biodiversity. They still considered that the irreversible loss of these new forms of natural capital would lead to the relative scarcity of their benefits to humankind. But because neither environmental public goods nor their myriad services are marketed, their increasing scarcity does not to rising market prices or appreciating asset values that provide incentives for greater preservation. This also focused attention on the need to explicitly value the benefits provided by environmental public goods to improve their management, and on whether or not some unique natural environments need to be preserved to protect the welfare of future generations.

THE ECOLOGICAL SCARCITY ERA: 2000 TO PRESENT

The Millennium Ecosystem Assessment (MA 2005) drew attention to the rapid deterioration of global ecosystems and its detrimental impacts on ecosystem “services” – the myriad benefits that humans derive from ecosystems. This has led to an emerging view in economics that these ecosystems and their services should be treated as a form of “ecological” capital and that their increasing relative scarcity reflects their irreplaceability, the uncertainty about their values, and the possibility of abrupt collapse (Barbier 2011; Daily et al. 2000; Dasgupta 2008; Fenichel and Abbott 2014). In this section, I discuss how economists have viewed ecosystems as a special case of environmental public goods, and also how recent scientific warnings about the need for planetary boundaries on human global impacts have revived absolute scarcity concerns.

Ecosystems as Environmental Public Goods

In many ways, ecosystems and their services are basically 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.[15] Moreover, as ecosystems disappear, ecological capital and their services also exhibit increasing relative scarcity that is not reflected in market outcomes.[16]

However, there are several characteristics of the ecological scarcity problem that distinguish it from the scarcity of other environmental public goods. First, as noted earlier, ecosystems are not only fixed in supply and subject to irreversible loss; they are also prone to abrupt collapse if sufficiently disturbed or degraded (Dasgupta 2008). This risk of collapse must be included in development decision making when valuing scarce ecological capital and accounting for its irreversible conversion (Barbier 2011).[17] On a global scale, the uncertainty about 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 in the future set of choices, but also by

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[15] As noted earlier, some important ecosystems, especially many forests, water systems, fisheries and rangelands, are rival but non-exclusive common pool resources (Ostrom 2010). As noted by Ostrom (2009, p. 419), although there are many examples of successful management of these complex systems, 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."

[16] This "ecological scarcity" problem was first described by Barbier (1989, pp.96-7).

[17] The importance of uncertainty about irreversible environmental losses from policy decisions was also noted in the Environmental Public Goods Era. For example, Arrow and Fisher (1974) and Henry (1974) demonstrated how such irreversibility makes wilderness preservation more valuable if it leads to better information over time about whether or not development should take place. During this era , models concerned with managing biological populations and pollution also began to incorporate the risk of collapse or catastrophe (Clark 1976), Cropper (1976) and Reed (1988).

directly 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).

Second, although the diverse benefits provided by ecosystems are generally not marketed, as is the case with other environmental public goods, many ecosystem services arise in very complex ways, through the structure and functioning of the ecosystems themselves (Barbier 2011). For example, the combination of the hydrological flows, sediment retention and unique vegetation of coastal wetlands such as mangroves and salt marsh provide a wide-range of non-marketed benefits, such as recreation, coastal protection, fishery breeding and nursery grounds, subsistence harvests and water purification. Some of these services benefit humans directly, such as harvests and recreation, whereas others indirectly benefit human well-being by supporting or protecting economic assets and production activities, such as coastal protection, water purification and nursery and breeding support for fisheries. 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).

However, because there is no market for many important ecosystem goods and services, they tend to be “undervalued” even as they increase in relative scarcity. That is, we have no information concerning 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 affecting the widespread decline in ecological capital today.

Planetary Boundaries

There is an even bigger ecological scarcity challenge. A growing scientific literature argues that there are *planetary boundaries* that must be respected in order to protect the Earth system from abrupt and irrevocable 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 “tipping points” in the Earth system (Rockström et al. 2009; Steffen et al. 2015). This literature has identified “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).

A specific set of policy tools may be required to ensure that these planetary boundaries are respected, including binding and meaningful international agreements to limit use and raising sufficient revenue to support long-term global environmental conservation and management (Sterner et al. 2019). Such policies reflect the *strong sustainability* view that some natural capital is essential (e.g., unique environments, ecosystems, biodiversity, and life-support functions), is subject to irreversible loss, and has uncertain value. 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'."

Absolute Scarcity Revisited

Specifying a planetary boundary establishes a "safe operating space", which in turn places an absolute limit on human exploitation of critical global biophysical sinks or resources (Rockström et al. 2009).[18] In effect, each safe operating space demarcates a "depletable" finite stock of environmental capital comprising such sinks or stocks (Barbier 2019). Depending on the type of planetary boundary, the finite stock of environmental capital could consist of terrestrial net primary production, available freshwater for consumption, species richness, assimilative capacity for various pollutants, forest land area, or the global carbon budget (Steffen et al. 2015).

The concept of a planetary boundary to limit human impacts that threaten the Earth system reflects 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 case, it is humankind, rather that nature, that is imposing a constraint on global

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[18] The scientific rationale for planetary boundaries is to avoid "tipping points" or "thresholds" that could lead to irrevocable changes in the Earth system and potentially catastrophic impacts on humanity. Thus, a planetary boundary limiting environmental exploitation "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). The boundary defining the safe operating space should also include a "buffer" that 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. 2015, pp. 737-738).

environmental impacts. Such a perspective challenges economists to reconsider whether absolute scarcity is a binding constraint. Moreover, here the limits are in terms of “Spaceship Earth” (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)).

Accepting 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. On the contrary, managing finite safe operating spaces requires taking into account increasing scarcity and generating the necessary values, incentives, and investments to alleviate it (Barbier 2019; Smith 2017; Sterner et al. 2019). 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.” Nevertheless, a number of challenges remain in developing economic approaches to managing safe operating spaces defined by planetary boundaries.

For one, there is not yet a scientific consensus on quantifying planetary boundaries, and thus the safe operating spaces, for some key sub-systems and processes of the global environment. 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. Others maintain that the evidence for planetary tipping points in the terrestrial biosphere, such as for freshwater, phosphorous, nitrogen and biodiversity remains unconfirmed (Brook et al. 2013).

Economists are already grappling with the implications of such uncertainties. As Weitzman (2009) first showed with the example of climate change, mitigation and precaution become much better economic options when faced with large uncertainty over potentially catastrophic consequences and neutral intergenerational time preferences. Tackling scientific uncertainty over unseen future environmental impacts, coupled with continued irreversible depletion, requires a more robust modeling approach to environmental policy decisions (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 provides a rich research agenda for economists to explore as the Era of Ecological Scarcity continues.

Finally, establishing 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.

SUMMARY AND CONCLUSIONS

This article has traced the evolution of economic thinking about natural resource scarcity since the 1950s. I have discussed three distinct phases in this thinking: 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), which are summarized in Table 1.
This evolution of economic thinking on natural resource scarcity is reflected in the three "Scarcity and Growth" volumes produced by Resources for the Future. In the landmark first volume, *Scarcity and Growth*, Barnett and Morse (1963) examined absolute and

relative scarcity hypotheses for a variety of natural resources in the United States between 1870 and 1958, focusing on land, minerals, fossil fuels, and forests. In the second volume, *Scarcity and Growth Reconsidered*, Smith (1979) raised concerns about the increasing scarcity of non-marketed environmental public goods and common-property resources. In the final volume, *Scarcity and Growth Revisited*, Simpson et al. (2005) highlighted growing ecological scarcity and biodiversity loss as key scarcity problems in the "New Millennium".[19]

The consensus economic view on natural resource scarcity has remained fairly consistent throughout all three phases. Modern economics has largely rejected the notion that there are physical limits to natural resource exhaustion and environmental decline; instead, resource availability has generally been viewed as a problem of relative scarcity. However, the perspective on natural resource scarcity adopted by economists in each era was shaped by the predominant environmental concern of the times (see Table 1). During the 1950s to the 1970s, the concern was whether the exhaustion of resources placed "limits to growth" on economic activity. From the 1970s to 2000, the state of the environment itself became an additional focus, especially the loss of global and local environmental public goods and their important non-market values. Since 2000, this perspective has 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.

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[19] In the first issue of this journal, Heal (2007) also identifies three similar phases in environmental and resource economics about natural resource problems. First there was a phase that focused on the depletion of resources; then the focus was on environmental public goods; and, more recently, the focus has been on what he calls the "new paradigm" of biodiversity and ecosystems.

As economists have tackled increasingly complex environmental problems, the concept of natural capital has also been extended to include additional “valuable” natural resource and environmental endowments (see Table 1). Initially, natural capital referred to natural resources that provided material and energy inputs or environmental sinks for waste; then it was broadened to include local and global environmental goods, and, more recently, ecosystems and Earth system processes. In addition, the technical characteristics of natural capital and its goods and services – whether they are private or public goods - matter significantly in determining how scarcity is mitigated (see Table 1).

Finally, proponents of planetary boundaries argue that humans should impose absolute limits on their global impacts, essentially creating absolute scarcity conditions. Whether humankind will be willing to accept such self-imposed limits on the scale of economic activity and its global environmental impacts in the coming decades remains to be seen. At the very least, this perspective is forcing economists to reconsider whether there should be absolute constraints binding on economic activity; 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.” Hopefully, the discussion presented here on the evolution of economic views on natural resource scarcity will help inform future research by economists into this and other important questions concerning the growing scarcity of our planet’s critical environmental assets.

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