Sustainability and Development

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Abstract

Sustainable development requires that per capita welfare does not decline over time. The minimum condition is ensuring that any depletion of natural capital is compensated by reproducible and human capital, so that the value of the aggregate stock does not decrease. Meeting this condition is problematic if natural capital includes ecosystems, which not only provide unique goods and services but are also prone to irreversible conversion and abrupt collapse. Net domestic product accounting rules for the depreciation of the total stock of reproducible, human, and natural capital of an economy can be extended to incorporate the direct benefits provided by ecosystems. They also can integrate any capital revaluation that occurs through ecosystem restoration and conversion and the threat of irreversible collapse. These approaches confirm the economic interpretation of sustainability as nondeclining welfare. They can also be used to estimate the changes in the value of ecological capital due to economic activity.

1. INTRODUCTION

A key contribution of natural resource economics has been to establish the natural environment as a form of capital asset or natural capital (e.g., Clark 1976, Dasgupta & Heal 1979, Freeman et al. 1973, Herfindahl & Kneese 1974). This suggests that the total wealth of an economy comprises three distinct assets: (*a*) manufactured or reproducible capital (e.g., roads, buildings, machinery, factories); (*b*) human capital, which encompass the skills, education, and health embodied in the workforce; and (*c*) natural capital, including land, forests, fossil fuels, minerals, fisheries, and all other natural resources, regardless of whether they are exchanged on markets or owned. Natural capital also consists of those ecosystems that through their natural functioning and habitats provide important goods and services to the economy or ecological capital (e.g., Atkinson et al. 2012; Barbier 2008, 2011; Daily et al. 2000; Dasgupta 2008; Polasky & Segerson 2009).

Viewing these three forms of capital—reproducible, human, and natural—as the real wealth of an economy is important for determining sustainable development, which requires that the per capita welfare of an economy does not decline over time. Moreover, the minimum condition for sustainability is ensuring that any depletion in natural capital is compensated by increases in reproducible and human capital. If this condition is met, then the value of the aggregate stock, comprising human, reproducible, and the remaining natural capital, will not decrease over time.

But satisfying this sustainability condition may be problematic if natural capital also includes ecosystems, which through their natural functioning and habitats provide valuable goods and services to the economy. Such ecological capital is a unique and important component of the entire natural capital endowment that supports, protects, and is used by economic systems (Barbier 2011, Daily et al. 2000, Dasgupta 2008). Many ecosystem goods and services are essential for human welfare and may not be easily substituted by human and reproducible capital. Ecosystems are also prone to irreversible conversion and abrupt collapse. In this case, the only satisfactory compensation rule for protecting the welfare of future generations is to keep such essential ecological capital intact.

These differing economic perspectives on natural capital and sustainability are not easy to reconcile. However, by employing the inclusive wealth methodology of Dasgupta (2009) and Arrow et al. (2012), this review demonstrates how both perspectives can be used to formulate key accounting rules to adjust net domestic product (NDP) for the depreciation of the total stock of reproducible, human, and natural capital of an economy. Moreover, these rules can be extended to incorporate the direct benefits provided by the current stock of ecosystems as well as any capital revaluation that occurs if ecosystems are converted to or restored from other land uses (Barbier 2013). It is even possible to add further extensions that account for the economy-wide implications of irreversible ecological collapse, which indicates that ecosystems might be "essential" to the economy because the implications of their collapse will be reflected in changes in all aggregate wealth.

Both these approaches confirm that the economic interpretation of sustainability as nondeclining welfare is the crucial criterion defining sustainable development of an economy. This criterion is satisfied by maintaining or increasing the value of the total capital stock over time, but only if it is recognized that this stock comprises not just reproducible and human capital but also natural capital, including the unique and often irreplaceable ecosystems comprising the ecological capital of an economy. Improving our measurement of the contributions of all forms of economic wealth, including natural and ecological wealth, is the only way to improve further our understanding of sustainability and development.

2. THE CAPITAL APPROACH TO SUSTAINABILITY[1]

Economic interpretations of sustainability usually take as their starting point the consensus definition of sustainable development of the World Commission on Environment and Development (WCED): "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, p. 43). This definition is easily translated into economic terms: An increase in well-being today should not have as its consequences a reduction in well-being tomorrow.[2] Consequently, economic development today must ensure that future generations are left no worse off than present generations. Or, as some economists have succinctly put it, per capita welfare should not be declining over time (Pezzey 1989).

Figure 1 summarizes this economic approach to sustainability. As noted in the figure, the total stock of capital employed by the economic system, including natural capital, determines the full range of economic opportunities and thus well-being available to both present and future generations. Society must decide how best to use its total capital stock today to increase current economic activities and welfare and how much it needs to save or even accumulate for tomorrow, and ultimately, for the well-being of future generations.

However, it is not simply the aggregate stock of capital in the economy that may matter but also its composition, in particular whether present generations are using up one form of capital to meet the needs of today. For example, much of the interest in sustainable development has risen out of concern that current economic development may be leading to rapid accumulation of reproducible and human capital. However, this comes at the expense of excessive depletion and degradation of natural and environmental resources or natural capital. That is, by depleting the world's stock of natural wealth irreversibly, the development path chosen today will have detrimental implications for the well-being of future generations and thus is inherently unsustainable.

However, from an economic standpoint, the critical issue is not whether natural capital is being irreversibly depleted, but what the costs of these losses are and whether society today can compensate adequately future generations for these costs.[3] On this issue, economists diverge in opinion. The main disagreement is whether natural capital has a unique or essential role in sustaining human welfare and thus whether special compensation rules are required to ensure that future generations are not made worse off by natural capital depletion today. As noted in **Figure 1**, these two contrasting views are now generally referred to as weak sustainability and strong sustainability.[4]

According to the weak sustainability view, there is no inherent difference between natural and other forms of capital, and hence the same compensation rules ought to apply to both. As long as the natural capital that is being depleted is replaced with even more valuable reproducible and human capital, then the value of the aggregate stock—comprising reproducible, human, and the

[1]The approach presented here is a macrolevel aggregate perspective, whereas many applications of the notion of sustainability are microlevel approaches. Zilberman (2014) provides an overview of the latter approaches and suggests some valuable tools consistent with a microlevel perspective of sustainable development.

[2]As Bishop (1993) has pointed out, stated in this way, the objective of "sustainability" is different from that of the standard economic goal of "efficiency." That is, there are potentially an infinite number of development paths for an economy, only some of which are sustainable. Efficiency therefore does not guarantee sustainability, as some efficient paths are not sustainable. At the same time, there is no reason why an economy could not be both efficient and sustainable; see Stavins et al. (2003).

[3]For example, as stated by Pearce et al. (1989, p. 3), "Future generations should be compensated for reductions in the endowments of resources brought about by the actions of present generations."

[4]An early distinction between these weak and strong sustainability views was made by Turner (1993); see also Neumayer (2003).

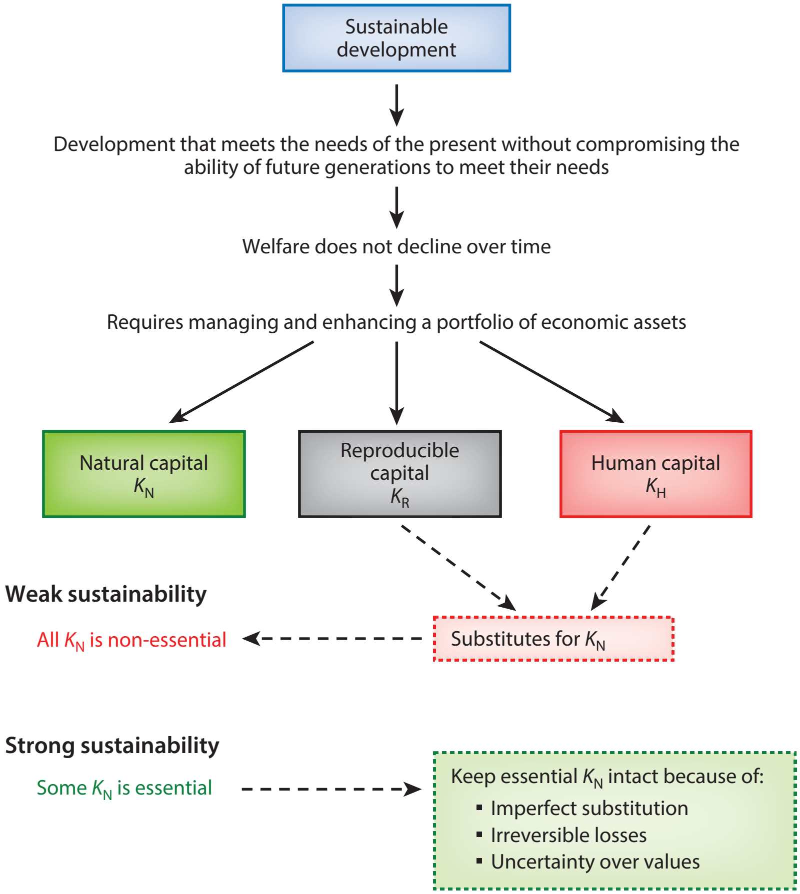

Figure 1

The capital (K) approach to sustainability. This approach assumes that ensuring that economic welfare does not decline over time requires managing a portfolio of assets: natural, reproducible, and human capital. However, there is disagreement whether "essential" natural capital, such as some unique and valuable ecosystems or natural resources, needs to be preserved to ensure sustainability.

remaining natural capital—is increasing over time.[5] Maintaining and enhancing the total stock of all capital is sufficient to attain sustainable development.

In contrast, proponents of the strong sustainability view maintain that reproducible or human capital cannot substitute for all the environmental resources composing the natural capital stock or all of the ecological services performed by nature. This viewpoint questions whether human, reproducible, and natural assets compose a single homogeneous total capital stock; instead, some forms of natural capital are essential to human welfare, particularly key ecological goods and services, unique environments, natural habitats, and even irreplaceable natural resource attributes

[5]Note, however, that rapid population growth may imply that the value of the per capita aggregate capital stock is declining even if the total value stays the same. Moreover, even if the per capita value of the asset base were maintained, it may not imply nondeclining welfare of the majority of people. These considerations also hold for the strong sustainability arguments discussed below.

such as biodiversity. Uncertainty over the economic value to human welfare of these assets, in particular the value that future generations may place on them if they become increasingly scarce, further limits our ability to determine whether we can adequately compensate future generations for irreversible losses in such essential natural capital today (Howarth & Norgaard 1995). Similar problems exist with the uncertainty over environmental impacts such as climate change, which may disproportionately impose adverse and possibly even catastrophic impacts on future generations (Heal & Millner 2014, Weitzman 2011). According to strong sustainability, the only satisfactory compensation rule for protecting the welfare of future generations is to keep essential natural capital intact, especially those environmental resources and ecological goods and services that are important for human life support and well-being.

The debate between weak and strong sustainability perspectives is not easy to reconcile. Nevertheless, it is clear that ecological capital has a special role in this debate, an issue worthy of further exploration. The global decline in ecological capital is also an important factor. Finally, the key to sustainability clearly lies in ensuring that the value of the aggregate stock (i.e., human, reproducible, and the remaining natural capital) should be at least maintained if not increasing over time. The next sections examine these issues in more detail.

3. THE SPECIAL ROLE OF ECOLOGICAL CAPITAL

For some time economists have maintained that the concept of natural capital should not be restricted just to resources, such as minerals, fossil fuels, forests, agricultural land, and fisheries, that supply the raw material and energy inputs to our economies (Freeman et al. 1973, Krutilla 1967, Krutilla & Fisher 1975, Pearce et al. 1989). Nor should we consider the capacity of the natural environment to assimilate waste and pollution the only valuable service that it performs. Instead, natural capital is much broader, encompassing the whole range of goods and services that the environment provides. Environmental amenities, such as nature-based recreation, ecotourism, fishing and hunting, wildlife viewing, and enjoyment of nature's beauty, have long been considered beneficial to humans. However, there is also an emerging consensus that ecosystems should be viewed as economic assets, as their natural functioning and habitats provide important goods and services to the economy (see, for example, Atkinson et al. 2012; Barbier 2008, 2011; Daily et al. 2000; Dasgupta 2008; Polasky & Segerson 2009). Such ecological capital is a unique and important component of the entire natural capital endowment that supports, protects, and is used by economic systems (Barbier 2011, Daily et al. 2000). This view is summarized by Dasgupta (2008, p. 3):

> 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 that are generated by ecosystems are diverse and wide-ranging. Second, if an ecosystem is left relatively undisturbed, then the goods and services that it provides are available in quantities that are not affected by the rate at which they are used. Finally, although similar to other assets in the economy, an ecosystem can be increased by investment, such as through restoration activities; ecosystems can also be depleted or degraded, e.g., through habitat destruction, land conversion, pollution impacts and so forth. Moreover, if ecosystem depletion leads to an irreversible loss of ecological landscape or, equivalently, if 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, the change might be permanent under other conditions. These three features of ecological capital are important in determining sustainability rules for development. The fact that much of this capital globally is in decline is also a key factor.

4. THE DECLINE OF ECOLOGICAL CAPITAL

An important indicator of the global decline in ecological capital was provided by the Millennium Ecosystem Assessment (MEA 2005), which found that more than 60% of the world's major ecosystem goods and services were degraded or used unsustainably.[6] Some vital benefits to humankind fall in this category, including freshwater; capture fisheries; water purification and waste treatment; wild foods; genetic resources; biochemicals; wood fuel; pollination; spiritual, religious, and aesthetic values; and regulation and control by ecosystems of regional and local climate, erosion, pests, and natural hazards. Almost all these degraded ecosystem goods and services are not marketed. Some goods, such as capture fisheries, freshwater, wild foods, and wood fuel, are commercially marketed. However, due to the poor management of the biological resources and ecosystems that are the sources of these goods, the market prices do not reflect unsustainable use, overexploitation, and excessive ecosystem damage or conversion.

One reason for the extensive habitat loss and degradation among terrestrial ecosystems globally is the ongoing conversion of forests and grasslands to agriculture, especially in tropical developing countries. Over the past 50 years, agricultural land area in the tropics has expanded, while forest area continues to decline (**Figure 2**). Agricultural land expansion is also responsible for the loss of many tropical savannahs and grasslands (Dixon et al. 2014, Suttie et al. 2005). In the major developing regions of Africa, Asia, and Latin America, demand for new land for crop production shows little sign of abating in the near future. Feeding a growing world population is expected to require an additional 3–5 million hectares (ha) of new cropland each year from now until 2030, which could contribute to additional clearing of 150–300 million ha of natural forests (Lambin & Meyfroidt 2011).

Important marine ecosystems have also experienced alarming rates of loss over recent decades. Due to coastal development, population growth, pollution, and other human activities, 50% of salt marshes, 35% of mangroves, 30% of coral reefs, and 29% of sea grasses have already been lost or degraded worldwide (Barbier et al. 2011, Doney et al. 2012). As much as 89% of oyster reefs may also have been lost globally (Beck et al. 2011). Overfishing has been a persistent and growing problem in marine environments, and loss of fisheries is also linked to declining water quality through the increasing occurrence of harmful algal blooms, offshore pollution, and oxygen depletion (hypoxia) (Halpern et al. 2008; Lotze et al. 2006; Worm et al. 2006, 2009). Finally, the disruptions in precipitation, temperature, and hydrology accompanying climate change also impact marine fisheries and the key habitats that sustain them, such as wetlands, mangroves, coral and oyster reefs, and sea grass beds (Doney et al. 2012, Sumaila et al. 2011).

[6] Although the Millennium Ecosystem Assessment reported that global climate regulation by ecosystems has been enhanced, recent scientific evidence reported by the Intergovernmental Panel on Climate Change (IPCC 2014) suggests that this may no longer be the case.

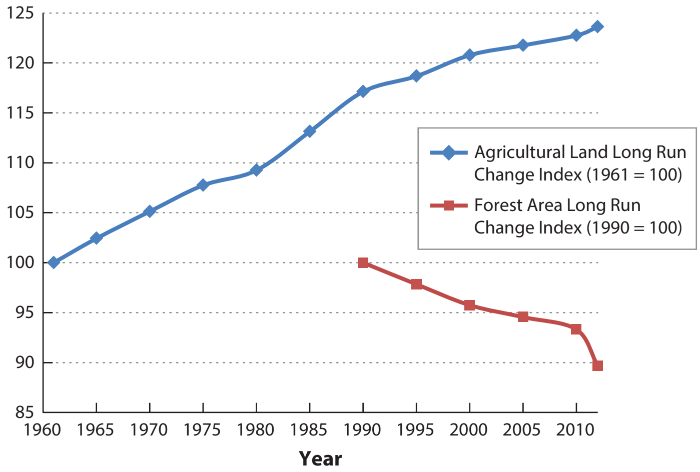

Figure 2

Long run land-use change in tropical developing countries, 1961–2012. Agricultural land refers to the share of land area that is arable, under permanent crops, and under permanent pastures. Forest area is land under natural or planted stands of trees of at least 5 m in situ, whether productive or not, and excludes tree stands in agricultural production systems, urban parks, and gardens. Tropical developing countries are low- and middle-income economies in which 2013 Gross National Income (GNI) per capita was US$12,745 or less and located in the East Asia and Pacific, Latin America and Caribbean, South Asia, and sub-Saharan Africa regions. Figure created from data obtained from the World Bank, World Development Indicators database, available from **http://databank.worldbank.org/data**.

Freshwater ecosystems are also under stress globally by a combination of interacting human-induced threats and global environmental change (Dudgeon et al. 2006, Vörösmarty et al. 2012). These systems, which comprise ponds, lakes, streams, rivers, and wetlands, are the main source of accessible water supply for humans on our planet. Other important human uses of freshwater ecosystems include inland capture fisheries, which contribute approximately 12% of all fish consumed by humans; irrigated agriculture, which supplies ~40% of the world's food crops; and hydropower, which provides nearly 20% of the world's electricity production (Johnson et al. 2001). The human-induced threats to freshwater ecosystems include modification of river systems and their associated wetlands; water withdrawals for flood control, agriculture, or water supply; pollution and eutrophication; overharvesting of inland fisheries; and the introduction of invasive alien species. The significant environmental impacts of these factors are climate change, nitrogen deposition, and shifts in precipitation and runoff patterns (Dudgeon et al. 2006, Vörösmarty et al. 2012). These threats pose a grave risk to human water security by increasing water scarcity, they endanger freshwater biodiversity, and in some cases they are detrimental to both water security and biodiversity.

The state of global biological diversity also shows considerable decline. The Living Planet Index (LPI), which measures trends in thousands of the world's vertebrate species populations, shows a decline of 52% from 1970 to 2010 (WWF 2014). In effect, over the past 40 years, the numbers of mammals, birds, reptiles, amphibians, and fish have been halved. For freshwater species, the decline has been even worse (76%). For tropical countries, the LPI shows a 56% decrease in species, with Latin America experiencing the worst decline (83%). The main causes of the losses in species globally appear to be habitat loss and degradation, hunting and fishing, and climate change.

In summary, every major indicator of the health and status of the world's most important ecosystems shows that ecological capital is in serious decline. Moreover, the problem seems to have been worsening over recent decades.

5. NATURAL CAPITAL, INCLUSIVE WEALTH, AND SUSTAINABILITY

If ecosystems are also considered capital assets, then efforts to modify national accounts to include natural and human capital should also incorporate the contributions of ecosystems. However, accounting for changes in ecological capital should involve similar rules for estimating the depreciation and appreciation of other assets in an economy. Barbier (2013) shows that by adopting and extending the inclusive wealth methodology developed by Dasgupta (2009) and Arrow et al. (2012), it is possible to include ecological capital as well. Such an accounting framework defines the aggregate wealth as the shadow value of the stocks of all an economy's assets, which should include reproducible, human, and natural capital. Adding in ecological capital is also straightforward, although two important accounting rules emerge (Barbier 2013). First, confirming a result initially identified by Mäler (1991) for environmental resources generally, accounting for ecosystems and their services leads to adjusting NDP for the direct benefits provided by the current stock of ecosystems but not for their indirect contributions in terms of protecting or supporting economic activity, property, and human livelihoods. Second, as Hartwick (1992) illustrates in the case of tropical deforestation, when one type of land use is irreversibly transformed into another, NDP must be further modified to reflect any capital revaluation that occurs.

Figure 3 outlines the basic methodology required to adjust the gross domestic product (GDP) for reproducible, human, and natural capital, including ecological capital. Once the changes in the value of these stocks are accounted for, the result is an adjusted NDP. As indicated in **Figure 3**, GDP and NDP are conventional indicators that are regularly reported in the national accounts for most economies; however, NDP accounts for the depreciation in value of only reproducible capital. Instead, as outlined in **Figure 1**, additional adjustments for changes in human, natural, and ecological capital are required to determine whether current production in the economy is reliant on depreciating or adding to overall wealth. First, any current investments in education, training, and health will likely lead to net gains in human capital. Second, NDP needs to be adjusted for the depletion of nonrenewable resources such as fossil fuels and minerals; for renewable resources such as forests and fish, NDP must include any net gains or losses in these stocks depending on whether depletion exceeds biological growth. Finally, NDP should be adjusted for the direct benefits provided by the current stock of ecosystems as well as any capital revaluation that occurs if ecosystems are converted to or restored from other land uses.[7]

The economy's real GDP, denoted as $Y(t)$, can be stated as

$$Y(t) = A\mathrm{F}[K(t), H(t), R(t), D(t), N(t)], \tag{1}$$

where F is a nondecreasing and twice-differentiable function, A represents Hicks-neutral technology (i.e., total factor productivity), and $\mathrm{F} = 0$ if any of its arguments are zero. The arguments of the production function of the economy at any time t should include a numerical index of the economy's stock of reproducible capital assets, $K(t)$, i.e., roads, railways, buildings, private dwellings, factories, machinery, equipment, and other human-manufactured fixed assets, and a numerical

[7]As Hamilton & Clemens (1999) have pointed out, if the direct benefits of any ecosystem or environmental services are negatively affected by the accumulation of pollution, then one should also consider the net changes in this harmful stock in the environment. Arrow et al. (2012) and Dasgupta (2009) apply similar reasoning to account for the climate-related damages caused by the accumulation of greenhouse gas emissions.

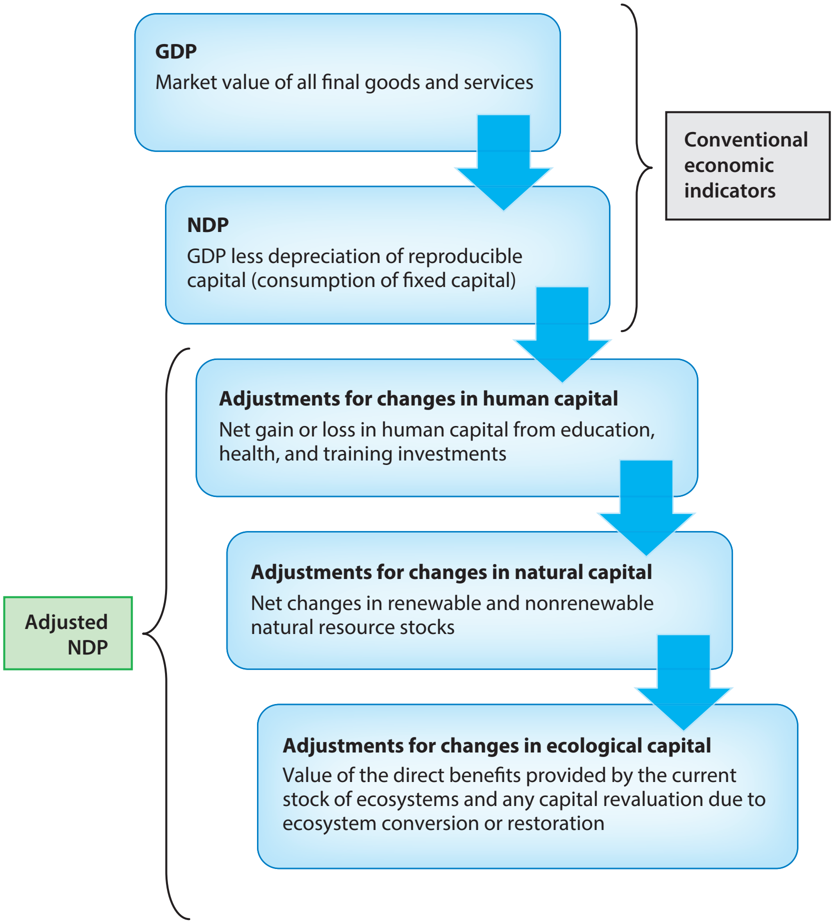

Figure 3

Adjustments to GDP for reproducible, human, natural, and ecological capital. In the national accounts of economies, gross domestic product (GDP) is routinely adjusted for depreciation in reproducible capital to obtain net domestic product (NDP). However, if NDP is to serve as a more accurate measure of sustainability, it should also be adjusted for changes in human, natural and ecological capital.

index of the total quantity of human capital, $H(t)$, i.e., the level of health, education, and skills per person. In addition, production is based on the use of any natural resource inputs by the economy, $R(t)$, and any land, $D(t)$. Finally, the production function of the economy should include ecological capital, $N(t)$, given that many ecosystem services support and protect production activities, i.e., through the provision of harvested inputs or freshwater, watershed protection, coastal habitats for offshore fisheries, flood control, storm protection, and climate management.

Following Dasgupta (2009), it is possible to define at time t a shadow price, $v^i(t)$, for each asset, i, of the economy, so that its aggregate or inclusive wealth, $W(t)$, and investment, $I(t)$, at time t are, respectively,

$$\begin{aligned} W(t) &= v^K K(t) + v^H H(t) + v^Z Z(t) + v^N N(t) + v^D D(t) \\ I(t) &= v^K \dot{K} + v^H \dot{H} + v^Z \dot{Z} + v^N \dot{N} + v^D \dot{D}, \end{aligned} \tag{2}$$

where $\dot{K} = \mathrm{d}K(t)/\mathrm{d}t$. This is the conventional notation for the time derivative of a variable that will be used throughout the paper, defining the net accumulation of reproducible capital according to $\dot{K} = Y(t) - C(t) - \omega K(t) - E(t)$. Reproducible capital depreciates at the constant rate of $\omega > 0$, the aggregate consumption of goods and services is $C(t)$, and $E(t)$ is investment in human capital (e.g., current education, health, and training expenditures). Similarly, following Hamilton & Clemens (1999), letting $h[E(t)]$ represent the rate at which education, health, and training investments are transformed into human capital, then the latter accumulates according to $\dot{H} = h[E(t)]$, $h' > 0$, $h'' \leq 0$. Finally, $Z(t)$ is an index of natural resources that are the source of raw material, land, and energy inputs to the economy, such as fossil fuels, minerals, metals, forest resources, and arable land. These stocks change according to $\dot{Z} = G[Z(t)] - R(t)$, $G'' < 0$, where the function G represents the natural growth rate for any renewable resources, which is concave with respect to its stock size.

Changes in the final two assets, $\dot{N}$ and $\dot{D}$, are important for accounting for the changes in ecological capital due to any ecosystem conversion or restoration. Let $N(t)$ be the stock of ecological capital at time t, and $N(0) = N_0$ is the initial stock. If $c(t) \geq 0$ represents any ecosystem conversion to developed land at time t, then $N(t) = N_0 - \int_0^t c(s)\mathrm{d}s$ and $\dot{N} = -c(t)$. It follows that if $D(t)$ is the area of land use in the development activity, and $D(0) = D_0$ is the initial developed land area, then $D(t) = D_0 + \int_s^t c(s)\mathrm{d}s$ and thus, the aggregate stock of developed land, $D(t)$, increases at the expense of ecological capital $N(t)$ according to

$$\dot{N} = -c(t) = \dot{D}. \tag{3}$$

In addition to supporting and protecting economic production (Equation 1), some ecosystem goods and services also contribute directly to human well-being, for example, through enhancing recreation and other direct enjoyment of the environment, augmenting our current and future natural heritage, or reducing harmful pollution and assimilating waste. These direct ecosystem benefits can be represented by the inclusion of $N(t)$ in some function for instantaneous well-being or utility $U(t)$. Utility also depends on aggregate consumption of goods and services $C(t)$, and it is assumed that the utility function is twice differentiable and concave with respect to its two arguments.

Define U_C as the price of consumption in utils (utility flow) and U_N as the price of ecosystem goods and services that directly influence well-being. Then, from Equations 1 and 2 the aggregate NDP of the economy at time t in utils is

$$NDP(t) = U_C C(t) + U_N N(t) + I(t). \tag{4}$$

Equation 4 depicts NDP as the sum of investment in the aggregate capital stocks of an economy plus the value of consumption and ecosystem goods and services.

As shown by Barbier (2013), the NDP Equation 4 is consistent with the basic sustainability rule for inclusive wealth derived by Arrow et al. (2012) and Dasgupta (2009). For example, letting $V(t)$ denote intergenerational well-being at time t, it follows that $V(t) = \int_t^\infty U[C(\tau), N(\tau)]\mathrm{e}^{-\delta(\tau - t)}\mathrm{d}\tau = V[K(t), H(t), Z(t), N(t), D(t)]$. Differentiating the latter expression yields $\frac{\mathrm{d}V(t)}{\mathrm{d}t} = I(t)$ and thus $\mathrm{d}V(t)/\mathrm{d}t \geq 0$ if and only if $NDP(t) \geq U_C C(t) + U_N N(t)$. As long as NDP exceeds the value of consumption and ecosystem goods and services, intergenerational welfare will not decline. As $\mathrm{d}V(t)/\mathrm{d}t \geq 0$ also implies $I(t) \geq 0$, it follows that sustainable economic development will occur at time t if the aggregate wealth of the economy, $W(t)$, does not decline.[8]

[8]However, according to Cairns (2013), as the criterion of sustainability employed by Arrow et al. (2012) and Dasgupta (2009) is nondeclining discounted-utilitarian welfare at the given reference point in time, it may not be a consistent measure of sustainability. Thus, a preferred criterion might be nondeclining max-min value.

This confirms previous economic interpretations of sustainability in which nondeclining welfare is the crucial criterion defining sustainable development of an economy.[9] Moreover, the sustainability criterion that "welfare does not decline over time" essentially "requires managing and enhancing a portfolio of economic assets, the total capital stock, such that its aggregate value does not decline over time," but only if it is recognized that "the total stock of the economy available to the economy for producing goods and services, and ultimately well-being, consists not just of human and physical capital but also of natural capital" (Pearce & Barbier 2000, pp. 20–21).

Using Equation 2 to write out $I(t)$ in full, and suppressing time arguments, Equation 4 becomes

$$\begin{aligned} NDP &= U_C C + U_N N + v^K \dot{K} + v^H \dot{H} + v^Z \dot{Z} + v^N \dot{N} + v^D \dot{D} \\ &= \tilde{Y} - v^K \omega K + [v^H h(E) - v^K E] + v^Z [G(Z) - R] + U_N N + (v^D - v^N)c, \end{aligned} \tag{5}$$

where $\tilde{Y} = v^K Y + (U_C - v^K)C = v^K(\dot{K} + \omega K + E) + U_C C$.

In Equation 5, $\tilde{Y} - v^K \omega K$ is conventionally defined as NDP, i.e., the GDP of the economy less any depreciation (in value terms) of previously accumulated reproducible capital. This is NDP as currently measured in most national accounts of economies, although of course it is usually valued at market prices rather than in utils. It is clear from Equation 5 that if NDP is to serve as a true measure of the changes in an economy's wealth, it must include any change in valuable human, natural, and ecological capital as well (see **Figure 3**). For instance, $v^H h[E(t)] - v^K(t)E(t)$ is the net gain or loss (in value terms) in human capital, and $v^Z(t)\{G[Z(t)] - R(t)\}$ represents the net changes (in value terms) in natural resource stocks.[10] In the case of nonrenewable resources such as fossil fuels and minerals, $G(Z) = 0$, and so $-v^Z R$ measures the deduction from NDP of resource depletion. For renewable resources such as forests and fisheries, NDP must include any depreciation in natural resource stocks if $G(Z) < R$. The expression $U_N N(t) + [v^D(t) - v^N(t)]c(t)$ includes both the benefits to current well-being provided by ecosystems $U_N N$ and any capital revaluation that occurs as ecosystems are converted by land-use change to development $(v^D - v^N)c$.

For example, by definition, $v^N(t) = \int_t^\infty \frac{\partial U}{\partial N}(\tau) e^{-\delta(\tau - t)} d\tau$ and $v^D(t) = \int_t^\infty \frac{\partial U}{\partial D}(\tau) e^{-\delta(\tau - t)} d\tau$. Making use of $U(C, N) = U(Y - \dot{K} - \omega K - E, N)$, it follows that

$$v^D(t) - v^N(t) = \int_t^\infty e^{-\delta(\tau - t)} U_C(\tau) A F_D(\tau) d\tau - \int_t^\infty e^{-\delta(\tau - t)} [U_N(\tau) + U_C(\tau) A F_N(\tau)] d\tau. \tag{6}$$

Thus, $v^D(t)$ is the present value of any additional production resulting from any increase in land for economic development, whereas $v^N(t)$ is the present value of any additional ecosystem benefits due to increases in ecosystem land. That is, $v^D(t)$ and $v^N(t)$ are the capitalized values, or prices, of development and ecosystem land, respectively. As ecosystems are converted by land-use change for development, $(v^D - v^N)c$ is the capital gain (depreciation) in land that occurs if $v^D > v^N$ $(v^D < v^N)$. As land is a durable and capital good, Equation 6 indicates that NDP must be adjusted for any such capital revaluation due to ecosystem conversion, as indicated in **Figure 1**.[11]

[9] For example, Pearce et al. (1989, p. 32) state: "The wellbeing of a defined population should be at least constant over time and, preferably, increasing for there to be sustainable development." This interpretation is due to Pezzey (1989), who first associated sustainable development with nondeclining welfare.

[10] It is assumed that v^Z accounts for the marginal cost of resource extraction or harvesting.

[11] Barbier (2016) shows how this approach can be modified for the alternative case of restoring ecological landscape from developed land.

6. SUSTAINABILITY AND THE RISK OF ECOLOGICAL COLLAPSE

Many ecological studies identify irreversible landscape conversion as posing a threat of ecosystem collapse (Busing & White 1993, Dobson et al. 2006, Halpern et al. 2007, Lotze et al. 2006, Peterson et al. 1998, Turner et al. 1993). That is, the ability of an ecosystem to survive may be linked to its overall landscape size or scale. For example, as Dobson et al. (2006, p. 1921) conclude, because "species drive ecosystem processes" in most ecological landscapes as habitat size declines, "we would thus expect to see an initial sequential reduction in economic goods and services as natural systems are degraded, followed by a more rapid sequential collapse of goods and services." The implication is that the probability of ecological collapse is likely to increase with a diminishing size or conversion of the ecological landscape.

Thus, the resilience or robustness of an ecosystem—its ability to absorb large shocks or sustained disturbances and still maintain internal integrity and functioning—may be an important attribute determining the extent to which landscape conversion and ecosystem degradation affect the risk of ecological collapse (see, for example, Chavas 2015, Dasgupta & Mäler 2003, Elmqvist et al. 2003, Folke et al. 2004, Levin & Lubchenco 2008, Perrings 1998, Scheffer et al. 2001). As a consequence, one approach to accounting for the resilience property of ecosystems is to measure directly the wealth effects of resilience (Mäler 2008, Walker et al. 2010). Once these wealth effects of ecosystem resilience are estimated, then the NDP of an economy can be adjusted accordingly.

For example, Walker et al. (2010) estimate and value ecosystem resilience for the Goulburn-Broken Catchment (GBC) in Southeast Australia. The GBC is prime agricultural land, most of which is used for dairy pasture. However, the agroecosystem is threatened by increased soil salinity due to rising water tables from the removal of native vegetation. At the 2-m water table threshold, the system is in danger of flipping to a different regime dominated by degraded and salinized pasture. The authors estimate resilience as the distance from the current water table to the 2-m threshold. Under normal climate conditions, a 0.5-m change in ecosystem resilience is valued at approximately US$23 million, or approximately 7% of the total wealth of the GBC in 1991. Under drier climatic conditions, resilience is worth US$28 million or 8.4% of total wealth. As this Australian example indicates, the economic benefits of ecosystem resilience can be considerable. In such highly productive ecosystems supporting economic activity, regime shift can be catastrophic. Or to put it differently, the value of avoiding regime shift by maintaining or enhancing the resilience of ecosystems can be a sizable component of the total economic wealth generated by these systems.

Here, an alternative approach is suggested for adjusting NDP to account for the threat of ecological collapse. Instead of measuring the wealth contributions of ecosystem resilience, it should also be possible to incorporate the risk of ecosystem collapse due to conversion directly into measures of the economic benefits of ecosystems. The methodology of this approach can be easily demonstrated through modifying the above model of NDP and changes in wealth as a measure of sustainability.

Assume as before that ecosystems are represented as a stock of ecological capital, $N(t)$. Consider that this stock is vulnerable to random catastrophic collapse as ecological landscape is converted irreversibly for development. Up until the collapse (if it occurs), ecological capital can still be converted to land for development activity, $D(t)$, as governed by Equation 3, and the remaining intact ecosystems yield indirect and direct benefits. However, if ecological collapse occurs at some time t^*, a minimum level of direct ecosystem benefits are derived, which correspond to $U(N^*)$. The expected net present value of intergenerational well-being up to the time of collapse t^* is therefore

$$J = E\left\{\int_t^{t*} U[C(\tau), N(\tau)]e^{-\delta(\tau - t)}\mathrm{d}\tau + e^{-\delta t*}U(N^*)\right\}. \tag{7}$$

The likelihood of collapse can be characterized by a hazard rate function that specifies the probability that an ecological collapses occurs at time t, given that it has survived so far up to that time. Formally, the hazard rate can be defined as

$$h(t) = \lim_{\Delta t \to 0} \Pr(t \leq T < t + \Delta t / T \geq t)\Delta t = \frac{f(t)}{S(t)}, \tag{8}$$

where $f(t)$ is the corresponding density function of the probability distribution of the duration T of ecological capital $F(t) = \Pr(T < t)$. If $S(t)$ is the upper tail of this probability distribution, i.e., $S(t) = 1 - F(t) = \Pr(T \geq t)$, then $S(t)$ is the probability that ecosystems survive to time t. It follows that $h(t) = f(t)/S(t) = (\mathrm{d}F/dt)/S(t) = -(\mathrm{d}S/dt)/S(t)$, and thus

$$h(t) = -\frac{\dot{S}}{S} = -\frac{\mathrm{d}\ln S(t)}{\mathrm{d}t}, \quad -\ln S(t) = \int_0^t h(u)\mathrm{d}u, \quad S(t) = \exp\left[-\int_0^t h(u)\,\mathrm{d}u\right], \tag{9}$$

with $S(0) = 1$ and $\dot{S} = \mathrm{d}S/\mathrm{d}t < 0$. The probability that ecological capital continues to survive is decreasing over time.

As shown by Reed & Heras (1992) and in the appendix of Barbier (2013), Equation 9 can be used to introduce a new state variable $y(t) = -\ln S(t) = \int_0^t h(u)\mathrm{d}u$, and then $\dot{y} = h(t)$ and $S(t) = e^{-y(t)}$. If the probability of ecological collapse and therefore the hazard rate function depends on ecosystem conversion to developed land, $c(t)$, then the new state equation can be written as

$$\dot{y} = h(t) = \psi[c(t)], \quad \psi' > 0,\ \psi'' \geq 0,\ y(0) = 0. \tag{10}$$

It follows that Equation 10 is a new asset constraint imposed on intergenerational well-being (Equation 7), which as shown in the appendix to Barbier (2013) can be reformulated as

$$\tilde{V}(t) = \int_t^{\infty} e^{-\delta(\tau - t) - y(\tau - t)}\{U[C(\tau), N(\tau)] - \delta U(N^*)\}\mathrm{d}\tau + U(N^*). \tag{11}$$

If $v^y(t)$ is the shadow price at time t for the new asset associated with the risk of collapse $y(t)$, then the aggregate NDP of the economy at time t in utils is

$$NDP^*(t) = S(t)[U_C C(t) + U_N N(t) - \delta U_N N^*] + I^*(t), \quad I^*(t) = I(t) + v^y\dot{y}, \tag{12}$$

where $I(t)$ is defined by Equation 2. Note that aggregate NDP now has several new components due to the risk of ecological collapse. First, the change in wealth of the economy $I^*(t)$ must take into account the value of the change in the new asset that represents the likelihood of collapse, $v^y\dot{y} = v^y\psi(c)$. Second, as indicated by the terms within the square brackets of Equation 12, the value of consumption and ecosystem services to current well-being $U_C C(t) + U_N N(t)$ is now the net of the minimum direct ecosystem service benefits derived after the collapse $\delta U_N N^*$. Third, in turn, this net contribution of consumption and ecosystem services to current well-being is weighted by the probability that ecosystems survive to time t, i.e., $S(t)[U_C C(t) + U_N N(t) - \delta U_N N^*]$. Finally, the entire set of shadow prices at time t for the various assets of the economy changes, as they are defined as $v^i(t) = \partial\tilde{V}(t)/\partial i(t),\ i = K, H, Z, N, D, y$.

These new components have implications for the sustainability rule. As before, as long as NDP exceeds the value of consumption and ecosystem goods and services, intergenerational welfare will not decline. But now this rule implies $NDP^*(t) \geq S(t)[U_C C(t) + U_N N(t) - \delta U_N N^*]$, and thus sustainable economic development will occur at time t if the aggregate wealth of the economy does not decline, i.e., $I^*(t) \geq 0$. However, as the risk of ecological collapse has detrimental consequences, the shadow value v^y associated with the asset representing this risk must be negative (Léonard 1981), and as indicated above, the complete set of asset prices for all the assets of the economy must also change. Thus, the sustainability rule, $I^*(t) \geq 0$, incorporates the full implications of any threat of ecological collapse on the wealth of the economy. This means that the new rule reflects strong sustainability, as it takes into account that ecosystems might be essential to the economy because the implications of their collapse will be reflected in changes in all aggregate wealth.

Further implications of the risk of ecological collapse can be explored by using Equation 3 and the relationship $v^D = v^N + v^y \psi'$ in Equation 12 to obtain

$$\begin{aligned} NDP^* = \tilde{Y} - v^K \omega K + [v^H h(E) - v^K E] + v^Z[G(Z) - R] + S(t)[U_N N - \delta U_N N^*] \\ + (v^D - v^N)\left[c - \frac{\psi(c)}{\psi'}\right], \quad \tilde{Y} = v^K Y + [S(t)U_C - v^K]C. \end{aligned} \tag{13}$$

Equation 13 indicates that we should still adjust NDP for the value of the direct benefits provided by the current stock of ecosystems $U_N N$. But now because of the risk of ecological collapse, these benefits should be weighted by the probability of ecological capital surviving, $S(t)$, while also deducting the value at time t of the minimum direct ecosystem benefits after collapse, $S(t)\delta U_N N^*$. As the latter value is deducted from current ecosystem benefits, it is also conditional on the ecosystem surviving to time t.

In addition, according to Equation 13, any capital revaluation as a result of conversion of ecosystems to other land uses $(v^D - v^N)c$ must be adjusted for the change in the risk of collapse caused by such conversion $-(v^D - v^N)\frac{\psi(c)}{\psi'}$. As the relative risk of collapse $\frac{\psi(c)}{\psi'}$ rises (falls) with increased (decreased) conversion, the sign of adjustment depends on whether the capitalized value of developed land v^D exceeds the capitalized value of remaining ecological landscape v^N. If an increase in land values occurs as a result of ecosystem conversion $v^D > v^N$, then these values must be adjusted downward because of the greater risk of collapse, as $-(v^D - v^N)\frac{\psi(c)}{\psi'} < 0$. Although land is gaining value as it is converted from an ecological landscape to development activities, the risk of collapse to the remaining ecological landscape detracts from this gain in land values. However, if the value of land depreciates as it is converted from ecosystems to development $v^D < v^N$, then land values must be corrected upward because of the increased risk, as $-(v^D - v^N)\frac{\psi(c)}{\psi'} > 0$. The net loss in land values is not as large because the remaining ecological capital may not survive.

Finally, it should be noted that although the focus here on uncertainty and sustainability is on adjusting NDP to account for the threat of ecological collapse, this approach could also be extended to other extreme environmental outcomes, such as those associated with catastrophic climate change (Weitzman 2011). However, as Heal & Millner (2014, p. 126) caution in the case of uncertainty and climate change: "Failing to account fully for scientific uncertainty results in underestimates of the thickness of the tails of the error distributions, which, in conjunction with the increased confidence intervals, greatly increases the probability of extreme outcomes." Again, this leads us back to the fundamental problem of uncertainty and sustainable development that distinguishes the weak versus strong perspectives on sustainability: When we do not have a good picture of all possible states of the world, it becomes exceedingly difficult to characterize fully the probability distributions, including those representing the risk of collapse or future catastrophes, in a model of changes in economic wealth over time.

7. ACCOUNTING FOR ECOLOGICAL CAPITAL

In addition to adjusting NDP to reflect these sustainability criteria, it may also be desirable to estimate the changes in the value of ecological capital due to land-use conversion and other economic impacts, especially if much of this capital depreciation is not normally measured as part of national income. For example, as discussed previously, over the past 50 years, ecosystems have been modified more rapidly and extensively than in any comparable period in human history. This has been largely to meet burgeoning demands for food, energy, raw materials, and other resource products and to serve as a sink to absorb waste (MEA 2005). Thus, for some important ecosystems, it may be useful to estimate the overall economic losses that might occur as a result of land-use conversion that are not estimated by conventional wealth accounting. This can be done by employing the expression $U_N N(t) + [v^D(t) - v^N(t)]c(t)$, which comprises part of Equation 5 that defines adjusted NDP. Recall that the two components of this expression are the direct benefits to current well-being provided by remaining ecosystems, $U_N N$, and any capital revaluation that occurs through conversion from land-use change for development, $(v^D - v^N)c$. Thus, the sum of these two components represents the net gain or loss in ecological capital values, and when compared to the value of ecosystem assets if no conversion occurred, one can obtain the overall loss or gain in the value of ecological capital.

Barbier (2014) illustrates this approach with the example of mangroves in Thailand from 1970 to 2009. Thailand is estimated to have lost approximately one-third of its mangroves since the 1960s, mainly to shrimp farming expansion and other coastal development (FAO 2007, Spalding et al. 2010). Yet mangroves provide four essential ecosystem benefits: collected wood and nonwood products (e.g., shellfish, plants, honey, medicines), nursery and breeding grounds for offshore fisheries, storm protection, and carbon sequestration. Estimates of these benefits can be used to determine the annual net gain or loss in mangrove value that results from conversion to other land uses (see **Figure 4**). This net mangrove value has two components. The remaining mangroves generate extra benefits each year that do not appear in the national accounts, such as net subsistence for local coastal communities and economy-wide carbon sequestration benefits. But from these values must be subtracted the net loss in land value that arises from converting mangroves each year to some other economic activity such as shrimp farming.

The economic impacts are significant and are depicted in **Figure 4** as average annual values per capita over the four subsequent decades: 1970s, 1980s, 1990s, and 2000s. For each decade, the total value of remaining mangroves represents the benefits per person provided by remaining mangroves, $U_N N$. Net change in land value from mangrove conversion estimates for each decade the capital revaluation that occurs through any conversion that has occurred due to land use change for development, $(v^D - v^N)c$. This value is negative because, on balance, mangrove deforestation due to shrimp farming has led to a net loss in values, i.e., $v^D < v^N$. The sum of these two measures is indicated by the net change in mangrove values. This is then compared to the base case of value of mangroves with no deforestation, and the net effect is indicated by the loss of value due to mangrove deforestation.

During the 1970s and 1980s, when mangrove deforestation was rapid, Thailand lost US$1.69 and $0.76 in mangrove net values per person per year, respectively. Thus, the effect of rapid deforestation in these two decades meant that Thailand experienced declines in value due to mangrove deforestation of US$2.30 and $1.25 per person per year. In contrast, in the 1990s and 2000s, the loss of value due to mangrove deforestation was much less, but because there were fewer mangroves left, their values were also much smaller. By 2009, approximately one-third of the 1970 mangrove area was deforested, and Thailand's population had grown rapidly. As a result, the total value from the subsistence and carbon benefits of the remaining mangroves has

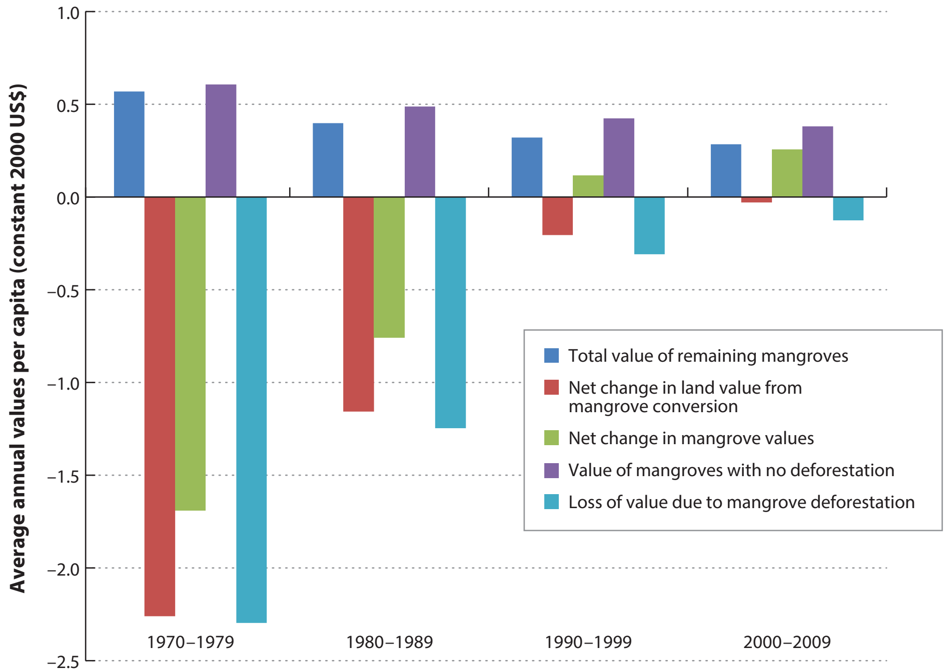

Figure 4

Accounting for mangrove capital in Thailand, 1970–2009. The total value of the remaining mangroves encompasses the net subsistence benefits to local coastal communities from mangrove nursery and breeding ground support for offshore fisheries and from wood and nonwood products collected from mangrove forests (e.g., shellfish, plants, honey, medicines) and carbon sequestration benefits. As storm protection value is based on expected damages to economic property, it is assumed that this benefit is already accounted for in the current market values of property. The net change in land value from mangrove conversion is the difference between the capitalized value of mangroves converted to shrimp farms less the capitalized value of these mangroves if they were not converted. The latter valuation includes all current and future mangrove benefits from collected wood and nonwood products, nursery and breeding grounds for offshore fisheries, storm protection, and carbon sequestration. The value of mangroves with no deforestation assumes that mangrove area remains unchanged since 1970. The total value of mangroves in 1970 was $25.2 million (constant $US 2000), and the population of Thailand was 36.9 million. The decline in per capita values over 1970–2009 is therefore due to population growth. On the basis of the annual losses from deforestation, the total per capita losses in Thailand from mangrove deforestation from 1970 to 2009 amount to $39.79 per person (constant $US 2000). Based on the 2009 population of 68.7 million, the total cumulative losses from mangrove deforestation from 1970 to 2009 are over $2.73 billion (constant $US 2000). Figure adapted from Barbier (2014).

halved, from US$0.57 to $0.28 per person per year. This means that even though mangrove loss slowed in the 1990s and 2000s, the net values of mangroves were very modest, only US$0.11 and $0.25, respectively. To put it another way, cumulative mangrove deforestation over the past four decades in Thailand has cost each Thai citizen US$40. This debit amounts to losses of more than US$2.73 billion, which has never appeared in Thailand's national accounts (Barbier 2014).

8. CONCLUSION

The sustainability criterion that welfare does not decline over time is consistent with maintaining or enhancing a portfolio of assets of an economy that comprises not just human and reproducible capital but also natural capital, including ecological assets. Moreover, NDP can measure changes in an economy's wealth, but only in addition to accounting for depreciation in reproducible capital NDP when it includes any change in valuable human, natural, and ecological capital (see **Figure 3**). Such a measure of adjusted NDP indicates whether current production in the economy is reliant on depreciating or adding to overall wealth. Consequently, as long as NDP exceeds the value of consumption and ecosystem goods and services, intergenerational welfare will not decline. Finally, if there is a risk of ecological collapse due to ecosystem conversion to developed land, then the sustainability criterion must be extended for the full implications of this threat to the aggregate wealth of the economy.

As shown with the case of mangroves in Thailand, it may also be desirable to estimate the changes in the value of ecological capital due to land use conversion and other economic impacts, especially if such changes are not included in national income. The resulting losses for Thailand from mangrove deforestation over the past four decades have been significant, totalling more than $2.73 billion or approximately $40 per person. However, the per capita value of Thailand's mangroves has been declining in recent decades, from $0.57 to $0.28 per person per year, simply because there are fewer of these ecosystems remaining due to past deforestation and rapid population growth.

Such an approach could be applied to other key ecosystems, such as tropical forests, coral reefs, freshwater wetlands, and grasslands. In addition, there are clearly intrinsic values and other important cultural benefits to preserving unique natural resources, species, and ecosystems, as well as the biological diversity contained in these systems, which have so far proven difficult to capture by current approaches to accounting for ecological capital. Other benefits of many important ecosystem services are also proving difficult to value, such as pollution control, pollination, climate regulation, and watershed protection.

The United Nations (UN) and World Bank have begun pilot studies to construct adjustments to income and wealth that include changes in ecological capital, as well as other types of natural capital besides minerals, energy, and timber harvests. The UN *Inclusive Wealth Report 2012* has developed accounts from 1990 to 2008 for 20 countries that include nontimber benefits from forests, carbon sequestration, fisheries (for four countries only), carbon damages, and agricultural land, as well as minerals, energy, and timber (UNU-IHDP 2012). The follow-up *Inclusive Wealth Report 2014* extended this analysis to 140 countries (UNU-IHDP 2014). The World Bank is expanding pilot studies on ecosystem accounting from 8 to 15 developing countries; these studies cover water, forest, and mangrove ecosystems.[12] To move beyond these pilot studies, the UN systems of national accounts must adopt a more systematic approach that all countries can follow to account for losses of natural capital and ecological capital, as we already do for depreciation of reproducible capital. The result would be better measures of sustainability and development.

Finally, the perspective on sustainability and development offered in this review is based on the concept of intergenerational equity. However, there is also a tradition in economics, beginning with the max-min framework developed by Solow (1974), to reconcile sustainability with intragenerational equity and social justice as formulated by Rawls (1971). As pointed out by Heal & Millner (2014) and Zilberman (2014), although practical application of adapting the max-min approach to derive specific sustainability rules has proven difficult, many feasible alternatives are now available. Extending the accounting approach for measuring adjusted NDP developed in this review to incorporate intragenerational equity and social justice would be one useful avenue for further research in sustainability and development.

[12]This World Bank–led global partnership initiative is called Wealth Accounting and the Valuation of Ecosystem Services (WAVES); see **http://www.wavespartnership.org**.

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