Conservation Biology

Essay

Integration of ecological–biological thresholds in conservation decision making

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Abstract: *In the Anthropocene, coupled human and natural systems dominate and only a few natural systems remain relatively unaffected by human influence. On the one hand, conservation criteria based on areas of minimal human impact are not relevant to much of the biosphere. On the other hand, conservation criteria based on economic factors are problematic with respect to their ability to arrive at operational indicators of well-being that can be applied in practice over multiple generations. Coupled human and natural systems are subject to economic development which, under current management structures, tends to affect natural systems and cross planetary boundaries. Hence, designing and applying conservation criteria applicable in real-world systems where human and natural systems need to interact and sustainably coexist is essential. By recognizing the criticality of satisfying basic needs as well as the great uncertainty over the needs and preferences of future generations, we sought to incorporate conservation criteria based on minimal human impact into economic evaluation. These criteria require the conservation of environmental conditions such that the opportunity for intergenerational welfare optimization is maintained. Toward this end, we propose the integration of ecological–biological thresholds into decision making and use as an example the planetary-boundaries approach. Both conservation scientists and economists must be involved in defining operational ecological–biological thresholds that can be incorporated into economic thinking and reflect the objectives of conservation, sustainability, and intergenerational welfare optimization.*

Keywords: conservation criteria, economic valuation, planetary boundaries, safe minimum standards, sustainability, thresholds

Integración de los Umbrales Ecológicos-Biológicos a la Toma de Decisiones de Conservación

Resumen: *En el Antropoceno dominan los sistemas humanos y naturales emparejados y sólo unos cuantos sistemas naturales permanecen relativamente inafectados por la influencia humana. Por un lado, los criterios de conservación basados en las áreas de mínimo impacto humano no son relevantes para la mayoría de la biosfera. Por el otro lado, los criterios de conservación basados en los factores económicos son problemáticos con respecto a su habilidad de llegar a indicadores operativos de bienestar que pueden ser aplicados en práctica a lo largo de múltiples generaciones. Los sistemas humanos y naturales emparejados están sujetos al desarrollo económico que, bajo las estructuras de manejo actuales, tiende a afectar a los sistemas naturales y a cruzar los límites planetarios. Por esto es esencial diseñar y aplicar criterios de conservación relevantes en los sistemas del mundo real, donde los sistemas humanos y naturales necesitan interactuar y coexistir de manera sustentable. Buscamos incorporar los criterios de conservación basados en el mínimo impacto humano a la evaluación económica mediante el reconocimiento de la importancia de satisfacer las necesidades básicas así como la gran incertidumbre sobre las necesidades y preferencias de las futuras generaciones. Estos criterios requieren de la conservación de las condiciones ambientales de tal forma que se mantenga la oportunidad de optimización del bienestar inter-generacional. Para este fin, proponemos la integración de los umbrales ecológicos-biológicos a la toma de decisiones y utilizar como ejemplo la estrategia de límites planetarios. Tanto los científicos de la conservación como los economistas deben estar involucrados en la definición operativa*

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de los umbrales ecológicos-biológicos que pueden ser incorporados al pensamiento económico y que reflejen los objetivos de la conservación, la sustentabilidad y la optimización del bienestar inter-generacional.

Palabras Clave: criterios de conservación, límites planetarios, normas mínimas de seguridad, sustentabilidad, valuación económica, umbrales

Introduction

The acknowledgment that human systems, including the economic system, are embedded in biophysical systems (Fig. 1) compels social and natural scientists to move beyond the boundaries of their disciplines (Liu et al. 2007; Mavrommati et al. 2014; Díaz et al. 2015; Steffen et al. 2015). Effective integration among disciplines is essential for interpreting and addressing sustainability, and interactions among the sciences of conservation and economics are most important for 2 main reasons. First, biologists provide insights into how humans, largely though economic activities, alter biophysical systems, and identify criteria for the conservation of such systems. Second, the satisfaction of human needs and preferences, the primary subject of economics, depends, among other things, on the environment. Hence, the economist's objective of welfare optimization is not distinct from the conservation scientist's objective of conserving ecosystems.

The main cause of environmental degradation is the prevailing pattern of economic activity driven by the ultimate goal of economic growth. Despite the various concerns that have been raised against the objective of economic growth, it remains the priority target for almost every society in a globalized economy (Baumol et al. 2007). Even the treatment of major contemporary environmental problems is sought through economic growth, as reflected in the rationale of the environmental Kuznets curves, despite evidence suggesting there is no relationship between economic growth and environmental improvement (Dasgupta et al. 2002; Harbaugh et al. 2002; Stern 2004).

The historical single-minded focus of society on the economic objective has resulted in a scale of environmental degradation in key Earth-system processes that approaches the irreversible and that will have unpredictable consequences for human well-being in the short and long run (Barnosky et al. 2012). Hence, there is no more time for misguided decisions resulting from the ineffective incorporation of conservation principles in decision making. Preventing irreversible ecosystem changes and conserving natural capital for the future should now drive policy making. For this reason, incorporating state-of-the-art knowledge of conservation science into economic evaluation is imperative for identifying sustainable pathways.

Responding to the sustainability challenge, conservation biologists have introduced numerous normative concepts, including the concept of ecological–biological thresholds (Aarts 1999; Callicott et al. 1999; Chu & Karr 2001). An ecological–biological threshold refers to "the point at which small changes in a driver may produce large responses in the ecosystems" (Groffman et al. 2006) and is an attempt to capture the complexity and nonlinearity characterizing natural systems. Unfortunately, this concept has lacked operational meaning for economic evaluation and has thus influenced decision making only marginally. The main shortcomings have been the lack of long-term data and of techniques able to forecast abrupt or irreversible ecosystem changes. Relatively few projects attempt to address these deficiencies and make the concept of ecological–biological thresholds applicable (Andersen et al. 2009; Dodds et al. 2010; Hughes et al. 2013; Banks-Leite et al. 2014).

In another vein, a group of environmental scientists has proposed 9 planetary boundaries within which humanity can safely and justly operate (Steffen & Stafford Smith 2013; Rockström et al. 2014). Translating the concept of planetary boundaries into a coherent environmental regulatory framework is still challenging, mainly due to a lack of scientific agreement about the appropriate planetary-boundary metrics. This choice implicitly affects the scale of action and degree of interaction among the multiple planetary boundaries (Mace et al. 2014). Conservation biologists and ecologists need to address these challenges and communicate their findings to economists and other social scientists, who in turn can investigate the critical issues related to the social and economic systems (e.g., governance schemes, economic instruments, social equity). Because 4 boundaries have already been crossed, resulting in increased probability of exceeding ecological–biological thresholds, a drastic policy response is needed.

In a complementary effort, economists, having gradually become aware of the environmental impacts arising from the economic process and the process's dependence on natural systems, are attempting to incorporate environmental concerns into the economic rationale. We considered 2 operational approaches, preservation of safe minimum standards (SMS) and monetary cost-benefit analysis; their relevance to sustainability science; and the difficulties of their adoption by conservation scientists. We argue that, when made operational, the concept of ecological–biological thresholds may provide a sound framework for including conservation criteria into economic evaluation and policy making while respecting the uncertainty about future conditions. In particular, we interpret the objective of sustainability as an opportunity to optimize intergenerational welfare under conditions

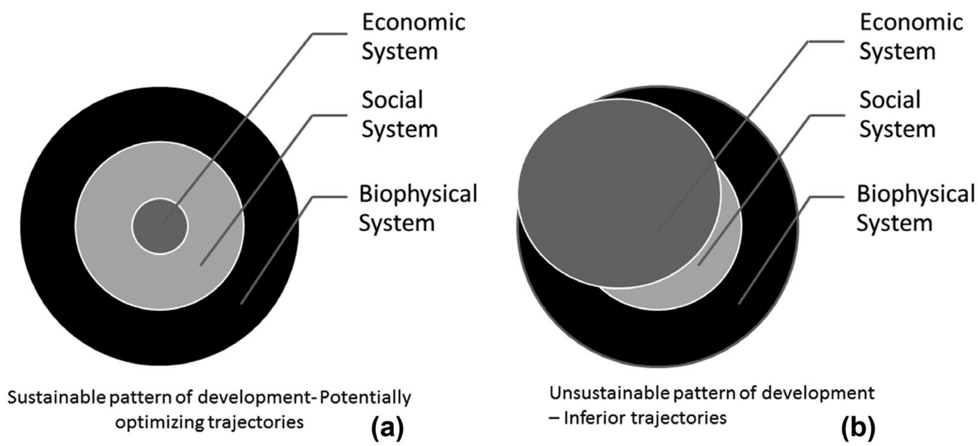

Figure 1. Relationship between biophysical, social, and economic systems: (a) a sustainable pattern of development in which the economic system respects the biophysical boundaries; that allows future generations to satisfy fundamental biological human needs and formulate preferences free from environmental constraints; and that incorporates monetary valuation of environmental impacts into decision making as long as biophysical boundaries are respected in the long run (based on Passet [1979]) and (b) an unsustainable pattern of development in which the economic system crosses biophysical boundaries; that assumes human-made capital can substitute for the loss of natural capital and thus limits the spectrum of future generations to formulate preferences free from environmental constraints; and that incorporates monetary valuation of environmental impacts into decision making even if biological-ecological thresholds are exceeded.

that explicitly preserve the rights of future generations. We argue that the potential for intergenerational welfare optimization is ensured only if the economic evaluation respects biological–ecological thresholds, and we use as an example the planetary boundary of biodiversity to present this idea. We focused on ecosystem services and goods that in the intergenerational context can be classified as nonrival, that is, their benefits can potentially be enjoyed by each succeeding generation.

Conventional Approaches for Integrating Sustainability into Economic Evaluation

The SMS approach, based on the minimax criterion of minimizing maximum possible losses, entails a clear-cut criterion for avoiding irreversible loss of natural capital: protect some minimum level or safe standard of a renewable resource in order to avoid exposing society to large future losses, irrespective of the current social cost induced by protection (Crowards 1998).

This criterion has been criticized as being restrictive because economic growth has been the ultimate driver of decision making since the 1950s. For this reason, the SMS approach has been modified in favor of economic considerations. The modified criterion proposes some minimum level or safe standard of renewable resources be preserved unless the social cost for doing so is unacceptably large (Bishop 1978). Social costs is defined as the foregone net benefits of development induced by the application of an SMS. The forgone net benefits of development, defined as the forgone benefits of development minus the expected benefits of preservation, need to be considerably greater than zero in order to violate the SMS (Ciriacy-Wantrup 1963; Crowards 1998). The incorporation of social costs into the SMS criterion complicates its essential applicability to decision making because it is difficult to estimate some categories of social costs and even if this occurs it is impossible to define when social costs are unacceptably large except through the considered judgment of decision makers subject to the applicable policies and procedures.

In recent years, the cost–benefit framework has incorporated sustainability concerns into economic evaluation by attempting to monetarily value environmental impacts. As one of the predominant subjects of environmental and ecological economics, this attempt is gaining ground in ecological and biological conservation research (Boyd & Banzhaf 2007; Salles 2011; Atkinson et al. 2012). Defining prices for ecological goods and services allows estimation of the cost of their degradation. In this way, monetary commensurability is ensured. Despite promising efforts in this direction (e.g., green accounting), serious problems preclude their applicability in the intergenerational context (Bithas 2011; Anderson et al. 2015).

The Problem with Monetary Valuation in the Intergenerational Context

Monetary valuation of the environment articulates individuals' revealed and stated preferences and adopts them as a proxy for the utility or welfare derived from the environment. Revealed-preference methods exploit real markets of normal economic goods (e.g., housing) to assign values to ecosystem services (e.g., air quality). Because the number of existing indirect markets is limited, revealed preference methods concern only a narrow spectrum of ecosystem services and goods that are probably the least important ones. This makes them of marginal practical use.

Stated preference methods attempt to elicit individuals' willingness to pay (WTP) for the preservation of ecosystem services and goods or their willingness to accept (WTA) payment for forsaking them. The rationale simulates the functioning of a hypothetical market for the ecosystem services and goods at hand. A hypothetical market is created and individuals' are asked to participate. Hypothetical markets bear all the properties of a hypothetical condition: there is no real cost of doing wrong; there is no actual requirement to act and assert what one states; and there is no real knowledge or experience concerning fundamental and intricate ecological processes and services related to environmental assets, even if individuals may perceive the most obvious characteristics of them. In economic terms, there is neither an income constraint nor real appreciation of the multidimensional properties of ecosystems; therefore, there is no real assessment of the utility arising from the available ecosystem services and goods (Limburg et al. 2002; Wegner & Pascual 2011).

These limitations create a substantial number of biases that burden valuation. Beyond and above the usual technical biases, valuation suffers from one irrevocable institutional condition: the environment, in the intergenerational context, is mainly perceived as a public good. This perception endows its protection with ethical concerns. An ethically based valuation is manifest in a perceived duality between private and public values that arise when individuals value ecological goods and services, thus suggesting the coexistence of private and social preferences (Burk 1938; Tintner 1946; Ami et al. 2014). Moreover, the disputable assumptions of valuation methods (e.g., rational individuals, substitutability, sufficient information, fixed preferences, the level of discount rate) impose certain constraints on the ability of individuals to capture the fundamental dependency of the economic process on natural systems (Gowdy et al. 2010*a*). These phenomena indicate the inappropriateness of monetary values arising from hypothetical markets to capture the actual utility of ecosystem services and goods, especially in the intergenerational context.

Economic valuation methods also frequently neglect inherent characteristics of ecosystems such as nonlinearity and irreversibility and thus result in underestimates of economic values when ecosystems approach critical ecological–biological thresholds (Limburg et al. 2002; Winkler 2006*a*). As the demand for ecosystem services and goods may be inelastic, individuals can place extremely high values on these services and goods at these thresholds. This condition cannot be reflected in conventional WTP estimates defined under income constraints. Around critical thresholds WTA seems to be the appropriate measure, although it has not been applied often in empirical research (Farley 2008; Wegner & Pascual 2011). The properties of ecosystem services and goods such as nonlinearity, the public nature, and the lexicographic preferences may result in substantial differences between the WTP and WTA. This divergence has been reported repeatedly and undermines the ability of the methods to provide valid and useful results for decision making. Nevertheless, hypothetical valuation may be a useful exercise in how individuals value ecosystem services and goods and may guide environmental decisions with short-run, small-scale impacts. Yet, long-run environmental choices will likely continue to be made "without prices and without apologies" (Vatn & Bromley 1994).

The Intergenerational Impossibility

The concept of sustainable development has been defined in terms of "meet[ing] the needs of the present generation without compromising the ability of future generations to meet their own needs" (WCED 1987). Individuals evaluate the economic impacts of their actions for such a time span that covers their life expectancy and in some cases that of their descendants. Nevertheless, there is a time-span limit within which individuals perceive and hence evaluate the economic and environmental effects of their actions. Legacy effects and time lags, inherent in coupled human and natural systems, suggest that this time-span limit is too short to include effects occurring in far distant generations (Millennium Ecosystem Assessment 2005*b*; Liu et al. 2007). For example, there is a lag between habitat loss and the actual extinction of species, resulting in a time delay between management decisions and ecosystem response (Millennium Ecosystem Assessment 2005*a*). The most widely applied economic models (e.g., the Ramsey–Cass–Koopmans model of economic growth) take into account future costs and benefits to the extent that members of the present generation hold an altruistic concern for the utility or welfare experienced by their descendants. In this class of models, the net present value criterion is an operational method to incorporate the future into current decisions. However, this rationale only considers future effects indirectly based on the preferences of people living today (Howarth & Norgaard 1992). If one considers monetary valuation a prerequisite for estimating some categories of social costs (e.g., preservation benefits) in the modified SMS criterion, then determining whether social costs of conservation are unacceptably large is subject to the economic interests of the current generation. This implies that the modified SMS criterion does not treat intergenerational interests equally.

Forming a Sustainability Criterion for Optimizing Intergenerational Welfare

Our analysis is founded on the principle that sustainability can be seen as preserving the environmental conditions that permit the optimization of intergenerational welfare given fundamental uncertainties about future preferences and the workings of biophysical systems. This principle strictly requires the preservation of sufficient environmental conditions for the generations to come, whereas it does not impose unnecessary constraints on current development and thus allows trade-offs among generations. In short, the life resources that provide the basis for future generations to optimize their own welfare ought to be preserved. We assume that the welfare of future and current generations has equal importance from a moral point of view. This tenet reflects a fairness criterion for intergenerational welfare (Schroeder & Pisupati 2010). As the preferences of future generations are unknown and unknowable, our framework simply requires that sufficient environmental conditions be preserved to permit future generations to enjoy levels of welfare consistent with optimization of intergenerational welfare. In other words, society should preserve certain environmental rights on behalf of future generations (Fig. 1a).

Optimization trajectories cannot be uniquely defined given the uncertainty burdening the future conditions and welfare, yet a distinction could be made between 2 classes of intergenerational welfare trajectories. The preservation of certain environmental rights leads to trajectories that are superior to those trajectories in which those rights are not preserved. As a result, operationalizing sustainability requires defining environmental rights for future generations that preserve the potential for maximizing intergenerational welfare.

We incorporated 2 fundamental concepts of sustainability analysis, discounting and substitution between natural and human-made capital in our approach. Discounting is the process of estimating the present value of future welfare benefits (accounted in monetary units). There is no consensus among economists on the appropriate discount rate for intergenerational comparisons (Sumaila & Walters 2005; Nordhaus 2007; Stern 2007; Gowdy et al. 2010*a*; Petrolia & Interis 2011). Discounting encompasses economic and ethical considerations (Parks & Gowdy 2013). Discounting originates from the individual's perception of the future. Individuals are impatient; they discount the future due to the inherent uncertainty to enjoy future welfare and to the interest returns that current benefits permit. The characteristics of societies differ from those of mortal individuals, and society's consideration of the future ought to be different from that of inherently myopic individuals. Societies may be less impatient compared with individuals and treat present and future generations equally; societies should make decisions now that will not negatively affect individuals in the future (Winkler 2006*b*; Wegner & Pascual 2011). Based on this rationale, a variety of discount rates (hyperbolic, zero, or negative) have been proposed as more appropriate than any positive constant rate for addressing the intergenerational concerns of society (Gowdy et al. 2010*b*).

Discounting future benefits implies complete commensurability between costs and benefits: benefits can compensate and offset costs throughout the time considered. Discounting the future of society is inextricably linked to the extent of the substitutability of natural capital with human-made capital. Extended substitutability guarantees the potential for compensating future generations with human-made capital for the foregone benefits induced by the degraded natural capital, a condition that preserves the potential Pareto criterion in the intergenerational context. High discount rates support the potential for extensive substitutability in the future. Even if the assumption of extensive substitutability holds hypothetically, the fact that the preferences and needs of future generations are unknown and unknowable makes it essential to bequeath future generations the natural capital that allows them to shape their preferences free from environmental constraints. This uncertainty implies that potential compensation can take place as long as ecosystem services and goods do not reach ecological–biological thresholds that might reduce the freedom of future generations to form and satisfy their preferences. Future generations should enjoy an essential spectrum of opportunities at least equal to those of the current generation (Howarth 2007).

Within the context of sustainability, we sought to optimize the aggregate level of intergenerational welfare under the ethical principle that current and future generations' welfare has equal importance. Thus, for n future generations, aggregate welfare is expressed as

$$U_n = \sum_{i=1}^{n} u_i = u_1 + u_2 + \cdots + u_j \cdots + u_n, \qquad (1)$$

where U_n is the aggregate level of welfare in a finite sequence of generations; u is utility; i is generation i; j is generation j; and n is large enough to transcend the time at which ecological–biological thresholds are potentially crossed. If $n = \infty$, the problem can be reformulated to maximize $\sum_{i=1}^{\infty}(u_i - \bar{u})$. This assumes there is a maximum possible level of utility ($\bar{u}$) that can be achieved asymptotically in the long run for some feasible economic path. In this case, the summation converges to a finite value. If u_i is bounded below $\bar{u}$ in the long run, the summation would be infinitely negative. With the preferences of future generations being unknowable, one cannot estimate u_i for future generations. Under this constraint, Eq. (1) simply requires the preservation of the potential for the maximum value of U_n. This is feasible only when succeeding generations are freely able to form their preferences, including those dependent on the environment, and to pursue their fulfillment. This does not imply that all existing natural capital needs to be preserved, but at least the part that is necessary to ensure the potential for optimizing intergenerational welfare must be preserved (Fig. 1). This is then the basis for defining environmental rights for future generations. That is, a dichotomy is established separating intergenerational trajectories of welfare into 2 classes: inferior and potentially optimizing. Inferior trajectories arise when the necessary environmental conditions are violated, whereas the preservation of these conditions ensures trajectories of superior welfare that we call potentially optimizing trajectories. Uncertainty about the future makes it impossible to rank the potentially optimizing trajectories.

Defining Conservation Criteria

Based on our analysis, intergenerational welfare optimization requires preservation of certain environmental rights for generations to come. Operationally defining these rights implies delineating conservation criteria capable of ensuring the healthy functioning of the human race; preserving the potential for environmentally unconstrained shaping of preferences; and securing the benefits arising from the use of renewable-exhaustible resources (Bithas 2008). The main challenge is for these conservation criteria to be applicable in economic evaluation, while still obeying the fundamental principles of conservation biology and ecology.

To be applicable, these criteria should reflect social values favoring sustainability and its operational delineation through the preservation of the necessary environmental rights of future generations. Social values determine the institutional setting of economic decisions and are non-negotiable (Winkler 2006*a*). For instance, if slavery and child labor were socially accepted, labor cost could be substantially reduced. Because current social values prohibit both slavery and child labor, they set the constraints for the minimization of labor costs. Social values reflecting sustainability could be similarly operationally defined by ecological-biological objectives ensuring the environmental rights of future generations and hence the potential for intergenerational welfare optimization. Social values underlying sustainability could be further scrutinized through alternative valuation methods, such as deliberative ecological economics, that respect the uncertainty surrounding future generations' needs (Howarth & Wilson 2006; Vatn 2009). These ecological–biological objectives would need to be included in economic evaluation through interdisciplinary collaboration, and, for the time being, we refer to these as ecological–biological thresholds. Whenever ecological–biological thresholds are reached, cost–benefit and related frameworks are useless because this situation may result in loss of critical ecosystem services for human welfare and trigger the potential to lose the opportunity to optimize intergenerational welfare paths (Wegner & Pascual 2011). An economic activity can be evaluated on the basis of the relevant costs and benefits only if ecological–biological thresholds are respected and the potential for intergenerational welfare optimization is preserved.

Addressing the opportunity for intergenerational welfare optimization implies that all future generations be bequeathed certain environmental rights. Defining these rights requires conservation criteria be driven by natural sciences and complemented with socioeconomic needs (or supporting socioeconomic evaluation). We suggest that conservation scientists and ecologists propose conservation criteria that forsake methodological purism. These criteria need to reflect existing knowledge and be revised regularly to capture new scientific findings.

Using the Planetary Boundary of Biodiversity as a Conservation Criterion

Biosphere integrity contributes to human prosperity and supports the provision of a wide range of ecosystem services. The profound rate of biodiversity loss along with the vision of attaining intergenerational justice and sustainable development set the foundations of the Convention of Biological Diversity in 1993. Biosphere integrity has been proposed as one of nine planetary boundaries that, if exceeded, "compromise the biotic capacity of ecosystems to sustain their current functioning under novel environmental and biotic circumstances" (Rockström et al. 2014). A recent study characterizes the biosphere boundary as one of 2 core boundaries because crossing this boundary can by itself lead Earth's system to a new state (Steffen et al. 2015). There are various approaches with respect to the definition and measurement of the planetary boundary of biodiversity (Mace et al. 2014). We used one of the proposed approaches to develop our argument without suggesting that the specific metric and numeric boundary of biodiversity loss is the most appropriate. This is out of the scope of our analysis, and we acknowledge that the scientific community is still working on these subjects (Mace et al. 2014; De Vos et al. 2015; Laity et al. 2015).

Two components comprise biosphere integrity: genetic and functional diversity (Steffen et al. 2015). Our example, for simplicity, focuses on genetic diversity as measured by the extinction rate of well-studied organisms. There is evidence that the current rate of species extinction is 100 times greater than what it would have been without human activities (Gebaloos, 2015). The planetary boundary for the extinction rate has been identified as 1 per million species per year with a wide range of uncertainty (10 per million species per year) (Rockstrom et al. 2009; Steffen et al. 2015).

Following the rationale of our analysis and given that genetic diversity supports the provision of multiple ecosystem services essential for each aspect of human welfare, such as food production, water regulation, and habitat provision (Cardinale et al. 2012), we compared 2 alternative trajectories of intergenerational welfare related to genetic diversity. First,

$$U_n = \sum_{i=1}^{n} u_i = u_1 + u_2 + \cdots + u_j + \cdots + u_n, \quad (2)$$

for which all generations to come are assured a level of genetic diversity that does not exceed the safe operating space for humanity.

Second,

$$W_n = \sum_{i=1}^{n} w_i = w_1 + w_2 + \cdots + w_j + \cdots + w_n, \quad (3)$$

for which the healthy functioning of the human race is seriously disrupted after a finite number of generations (e.g., generation j) because genetic diversity crosses the critical threshold. In addition, crossing this threshold results in diminishing opportunities for future generations to enjoy a spectrum of preferences dependent on biological resources. As a result, $w_j + w_{j+1} + \ldots$ may tend to 0 for a number of generations after generation j.

Evidently, $U_n > W_n$ as n becomes large, so the former trajectory of intergenerational welfare is, according to the welfare-optimization criterion, superior to the latter. The U_n sequence of successive generations' welfare has the potential to optimize compared with W_n. This ranking can be indisputably defined without the need for estimating future welfare or dealing with the uncertainty burdening future generations' utility. This implies it would be better for scenario-building work with respect to sustainable coexistence of human and natural systems to focus on identifying alternative pathways that permit the potential for optimization of life opportunities rather than to assume future generations' utility.

Applying the concept of the biodiversity boundary at an operational level is a complex task due to boundary interactions and scale (Steffen et al. 2015). The degree of interaction between the biodiversity planetary boundary and other boundaries is subject to the chosen metric of biodiversity (Mace et al. 2014). For example, Mace et al. (2014) discuss 3 approaches to define biodiversity loss boundaries—the genetic library of life, functional type diversity, and biome condition and extent—and argue that biome integrity has more remarkable interactions with other planetary boundaries. The issue of scale is also critical because metrics of the biodiversity boundary need to be implementable at local and regional scales, where most decisions and policies take place.

In line with the 2030 agenda of Sustainable Development Goals, it has been proposed that coupling social equity objectives within the planetary boundaries framework can lead humanity to a "safe and just operating space" (Dearing et al. 2014). It is possible to integrate social equity objectives into management through consideration of spatial distribution (Steffen & Stafford Smith 2013). For example, the globalized economy may be responsible for paying for the ecosystem services derived from biodiversity given that there is evidence that crossing the planetary boundary of biodiversity at the regional scale has global implications (Barnosky et al. 2012). This may enable developing countries to benefit from economic activities dependent on biodiversity, such as tourism (Steffen & Stafford Smith 2013).

Discussion

The degradation of Earth's ecological state over the last 30 years reflects science's inability to understand ecosystems and the inappropriateness of current management frameworks to achieve sustainability. The objective of sustainability constitutes a social value which should be adequately reflected in the institutional settings framing economic decisions. The monetary valuation of ecosystem services and goods seems inadequate to encompass the objectives of sustainability because it is based on the preferences of the current generation's individuals whereas those of future generations are ignored or, at best, assumed. Prices are right when social values are right, and the social value of sustainability evades the myopic consideration of individuals. An effective operational criterion should direct individual considerations toward the objective of sustainability. The original safe-minimum-standards approach can be a useful starting point toward sustainability once it incorporates "state-of-the-art" knowledge of natural sciences. The concepts of planetary boundaries and ecological–biological thresholds encompass important conservation properties in operational terms.

We argue for greater interaction among scientists studying sustainability by shedding light on the shortcomings of current evaluation frameworks toward sustainability. Conservation criteria should be applied in decision making. The concepts of ecological–biological thresholds and planetary boundaries offer an operational, transparent, and testable management tool for communicating ecological–biological necessities to decision makers and to a democratic society. Ecological–biological thresholds and planetary boundaries are not seen as monolithic static conservation concepts but rather as subject to continuous scrutiny and redefinition by the relevant disciplines. Simultaneously, ecological–biological thresholds and planetary boundaries can be meaningfully incorporated in the methodological framework of economics as an ethical constraint to utilitarian objectives. The collaboration between conservation scientists and economists is essential to designing policy frameworks within which humanity can operate safely and justly at inter- and intragenerational levels. Conservation and other natural scientists should focus on identifying the most appropriate measures to quantify the boundaries at different spatial scales, whereas economists and other social scientists should then design the pathways that optimize welfare within these boundaries.

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