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REVIEW

Ecosystem health, ecosystem services, and the well-being of humans and the rest of nature

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Abstract

An ecosystem is healthy if it is active, maintains its organization and autonomy over time, and is resilient to stress. Healthy ecosystems provide human well-being via ecosystem services, which are produced in interaction with human, social, and built capital. These services are affected by different ecosystem stewardship schemes. Therefore, society should be aiming for ecosystem health stewardship at all levels to maintain and improve ecosystem services. We review the relationship between ecosystem health and ecosystem services, based on a logic chain framework starting with (1) a development or conservation policy, (2) a management decision or origin of the driver of change, (3) the driver of change itself, (4) the change in ecosystem health, (5) the change in the provision of ecosystem services, and (6) the change in their value to humans. We review two case studies to demonstrate the application of this framework. We analyzed 6,131 records from the Ecosystem Services Valuation Database (ESVD) and found that in approximately 58% of the records data on ecosystem health were lacking. Finally, we describe how the United Nations' System of Environmental-Economic Accounting (SEEA) incorporates ecosystem health as part of efforts to account for natural capital appreciation or depreciation at the national level. We also provide recommendations for improving this system.

KEYWORDS

economic value, ecosystem health, ecosystem services, ecosystem stewardship, natural capital, natural capital health, well-being

1 | ECOSYSTEM HEALTH AND HUMAN WELL-BEING

We live in close relationship with the rest of nature in social-ecological systems (Folke et al., 2016). Humans are a part of nature, not apart from it. Human well-being depends on natural capital (i.e., the planet's stock of natural ecosystems and resources) for the provision of ecosystem services (i.e., the benefits people obtain from ecosystems), such as food, water, climate regulation, protection from natural phenomena, recreation, and inspiration, among many others (Costanza et al., 1997, 2017; Daily, 1997; Hernández-Blanco & Costanza, 2019; Millennium Ecosystem Assessment, 2005).

Nevertheless, natural capital and its services do not generate human well-being in isolation, it needs to interact with the human capital (i.e., individual human beings and their attributes, including physical and mental health, knowledge, and other capacities that enable people to be productive members of society), the social capital, (i.e., the web of interpersonal connections, social networks, cultural heritage, traditional knowledge, and trust, and the institutional arrangements, rules, norms, and values that facilitate human interactions and cooperation between people), and the built capital (i.e., the buildings, machinery, transportation infrastructure, and all other human artifacts and services) (Costanza et al., 2014). Therefore, "ecosystem services" refer to the relative contribution of natural capital to the production of various human benefits, in combination with the three other forms of capital (Costanza, 2012b, p. 103).

Furthermore, the provision of ecosystem services depends on the condition of the ecosystem, which is often referred to as ecosystem health (Costanza, 1992; Rapport, 1995; Rapport et al., 1998). Costanza (1992) states that "an ecosystem is healthy if it is stable and sustainable, that is, if it is active and maintains its organization and autonomy over time and is resilient to stress." From this definition, the author proposes vigor, organization, and resilience as the main features of ecosystem health. The vigor of a system is a measure of its activity or metabolism and can be measured through indicators such as gross primary production and net primary production. The organization of an ecosystem refers to the number and diversity of interactions among the components of the system, which can be measured through its biological diversity and by the number and strength of pathways of exchange among components of the system. Finally, resilience refers to the ecosystem's ability to maintain its structure (i.e., organization) and function (i.e., vigor) in the presence of stress (Figure 1) (Costanza & Mageau, 1999; Mageau et al., 1995).

The vigor and organization components of ecosystem health, such as primary productivity and biodiversity, provide ecological functions, which are generally referred to the habitat, biological or system properties or processes of ecosystems, and if these functions benefit people they are considered ecosystem services (Costanza et al., 1997; Daily et al., 2009; Haines-Young & Potschin, 2010; Jax, 2005). It is important to clarify that ecosystem health is independent of the presence or absence of human intervention. Nevertheless, since we want to analyze here the relationship between ecosystem health and ecosystem services, we focus in this review on the side of the concept that is related to society's dependence on the rest of nature to survive and thrive. In this sense it is perhaps more convenient to talk about "natural capital health," which has embedded the benefit people derive from healthy ecosystems. Moreover, the concept of ecosystem health implies value judgments on the desired condition of the ecosystem (Lu et al., 2015; Rapport, 1997).

We argue that ecosystem or natural capital health, should be considered an integral component of development and finally sustainable well-being. The economic system formed by the other three types of capital should agree the goal of maintaining and improving ecosystem health, a future human development symbiotic with the

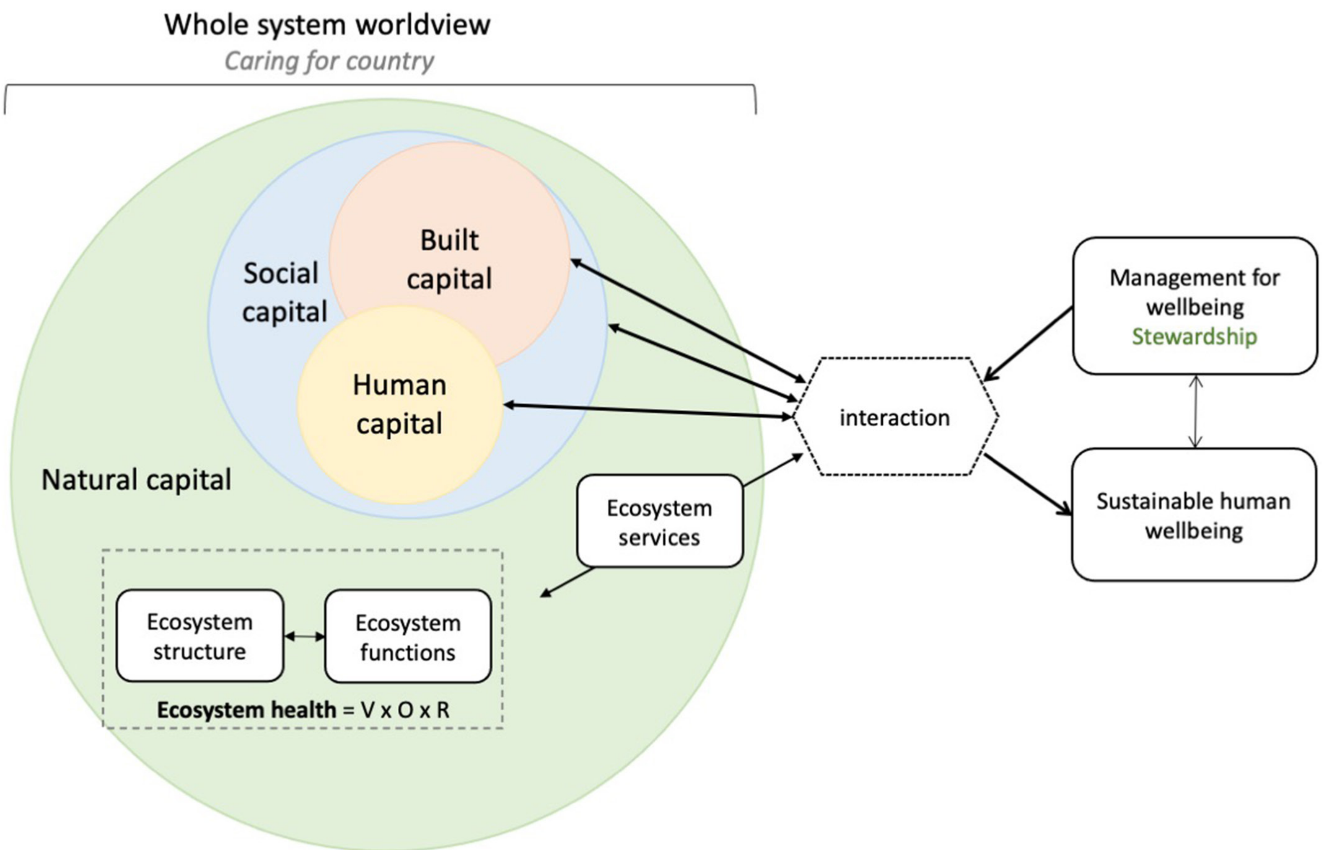

FIGURE 1 Role of healthy ecosystems in providing human well-being in combination with the other three types of capitals. This framework considers the economy as a subsystem of the broader Earth System, instead of considering nature as just another source of raw materials and sink for wastes. Ecosystem health can change positively or negatively under different ecosystem stewardship schemes. V = vigor, O = organization, R = resilience.

rest of nature. This is what some scholars call the Symbiocene, as opposed to the Anthropocene (Steffen et al., 2007; Steffen, Broadgate, et al., 2015), referring to an era where development replicates the symbiotic and mutually reinforcing life-reproducing forms and processes found in living systems (Albrecht, 2020). This approach to development integrates human with natural influences (Everard, 2016), creating a positive coevolution among capitals that secures sustainable ecosystem health.

This symbiotic development with nature will require the transformation of the predominant worldview that looks at the biosphere and its life-supporting benefits disconnected from human well-being (Folke et al., 2011). We need a whole system worldview, understanding the components of the Earth System, both human and non-human, as well as its interactions, with the common goal of stewardship of planetary ecosystem health on which people's sustainable well-being depends. In practice, this means an ecosystem-based management (EBM) focused on maintaining the ecosystem's structure and function, allowing the system to maintain redundancies and resilience in the face of changes (Ruckelshaus et al., 2008).

This kind of stewardship is also similar to the one indigenous communities apply in their land and seascapes in many parts of the world. For example, for indigenous communities in Australia, the term *Country* refers to a place that gives and receives life. These communities talk about *Country* in the same way they would talk about a person, which has defined their worldview of *Caring for Country*, meaning having knowledge of, a sense of responsibility for and an inherent right to be involved in the management of their traditional lands (Townsend et al., 2009). The relationships between people and country are inseparable; with *Country* caring for people (crudely analogous to the *Country* providing Ecosystem Services) and with people *Caring for Country*; when people care for *Country*, well-being is enhanced both directly through the act of caring and indirectly because it improves ecosystem health and thus enhances Ecosystem Services (Stoeckl et al., 2021).

2 | CHANGES IN ECOSYSTEM HEALTH

It is important to recognize that ecosystems are dynamic, and so is their health (Ehrenfeld, 1992; Rapport, 1992a, 1992b). Ecosystems are subject to periodic natural disturbances, such as droughts, floods, and fires, among others drivers of change (Rapport, 1992a, 1992b). These disturbances, if they are extreme, can significantly transform the structure and functions of an ecosystem, and therefore its health, setting the stage for recovery as part of the adaptation of the system. Although stewardship activities can enhance ecosystem services, anthropogenic disturbances often do not contribute to enhancing the resilience and adaptation capabilities of ecosystems, but instead degrades them (Rapport & Whitford, 1999).

In this context, disturbances, frequently referred as stresses, are external forces or factors, or stimuli that causes changes in the ecosystem, or causes the ecosystem to respond, or entrains ecosystemic dysfunctions that may exhibit distress symptoms (Rapport et al., 1985). These stresses often do not impact ecosystem health in isolation. Instead, they interact to produce linear and non-linear changes (Rapport, 1997).

Despite providing a myriad of valuable ecosystem services to people, ecosystems around the world have been systematically degraded due to the human-induced stresses (IPBES, 2019; Rockström et al., 2009; Steffen, Broadgate, et al., 2015; Steffen, Richardson, et al., 2015). Breaking the resilience boundary of ecosystem's health will turn the system toward another stable state, making a significant change in the metabolism and structure of the ecosystem. For example, increasing temperatures due to climate change, together with other stressors such as pollution from agrochemicals, are pushing the resilience of coral reefs in many parts of the world beyond its adaptive capacity, causing coral bleaching that can transform the once biodiverse ecosystem to another stable and less diverse state—macroalgae communities (Glynn, 1996). These changes in stable states with different ecosystem health often represent a reduction in the benefits people obtain from the previous stable states (Hernández-Blanco et al., 2020; Rapport et al., 1998).

To estimate changes in ecosystem health and the provision of ecosystem services, we propose a logic chain framework, composed by (1) a development or conservation policy (which could be at different geographical scales), (2) a series of management decisions (i.e., origin of the driver of change), (3) the driver of change itself, (4) the change in ecosystem health and consequently, (5) the change in the provision of ecosystem services, and (6) their value (Figure 2). For example, a country could promote an unsustainable agricultural production scheme (1), based on an excessively use of harmful agrochemicals (2), which will produce a significant level of chemical pollution (3), that changes one or more components of ecosystem health, such as biodiversity (4) that provide key ecosystem services like pollination (5), which will impact at the same time agricultural productivity (i.e., change in the ecosystem service value) (6).

This general framework of course applies for positive changes as well. For example, contrary to the above example, the promotion of a sustainable production system (1), through regenerative agriculture (2), could restore forests (3), which will increase the habitat for beneficial insects (4) that pollinates (5) a crop such as coffee, which will increase crop productivity (6) (Ricketts et al., 2004). Although we present a simplified linear chain of elements that leads to the change of ecosystem health and services, in order to protect and restore natural capital this approach should be adaptive in the sense that any undesired change resulting from the implementation of a policy should be adjusted through updates in that policy and the management decisions that originated that change. Conversely, an unsustainable development policy will probably ignore the decrease in the ecosystem health and therefore the provision of ecosystem services until these cannot be provided any more.

In terms of measuring changes in ecosystem health, following the definition provided before from Costanza (1992), ecosystem health can be expressed as an ecosystem health index, determined by multiplying the ecosystem's vigor (as a cardinal measure) by its organization (as a 0-1 index) and its resilience (as a 0-1 index). In other

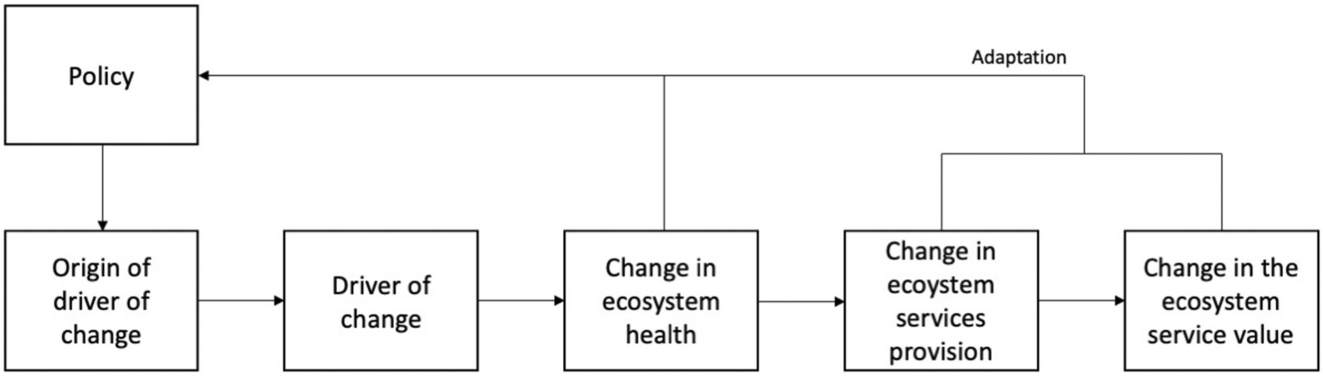

FIGURE 2 Logic chain framework to assess ecosystem health changes and the consequent changes in the provision of ecosystem services.

words, the health index estimates the ecosystem's activity weighted by indices for relative organization and resilience (Costanza, 2012a). Assessing ecosystem health using these three parameters provides a snapshot in time, and a key feature of ecosystems is that they are dynamic, and so is their health. For example, boreal forests depend on forest fires for their sustainability. If ecosystem health is assessed at the time the forest is burnt, we could wrongly state that the overall health of the system has been severely degraded. Therefore, assessments of ecosystem health should consider periods of time long enough so they can capture the different phases of ecosystems that are an intrinsic part of their long-term survival. Furthermore, due to this intrinsic dynamism of the sustainability of ecosystems, the provision of ecosystem services will also be dynamic.

Moreover, it is worth highlighting that ecosystem health is often assessed in a disaggregated way, analyzing individual ecosystems. In reality nature is a web of ecosystems which are interlinked across land and seascapes. For example, the catchment system of forests, agricultural fields, mangroves, and coral reefs in the Great Barrier Reef in Australia (Kroon et al., 2016; Packett et al., 2009; Schaffelke et al., 2005; Thorburn et al., 2013).

A final consideration regarding the measurement of ecosystem health is that its indicators are purpose dependent, namely, the interpretation given to the data is based on the purpose or issue of concern. For example, the extent of a forest can indicate progress of forest conservation or availability of forest resources (Biodiversity Indicators Partnership, 2011). Ecosystem health may be assessed for different purposes, such as monitoring status of natural resources, informing of ecosystem management, assessing environmental policy effectiveness, and tracking progress of fulfilling desired outcomes (Dybiec et al., 2020; Jing et al., 2019; Karousakis, 2018).

3 | CHANGE IN THE VALUE OF ECOSYSTEM SERVICES DUE TO CHANGES IN ECOSYSTEM HEALTH

A number of different dimensions of nature-based value can be discerned and evaluated in different ways: in monetary terms via accounting prices (market exchange value/simulated exchange values), and via economic welfare measures (total economic value (TEV), encompassing use and non-use values based on bequest and existence motivations (Pearce & Turner, 1990)); in biophysical and geochemical terms via natural science; and in often more qualitative non-monetary terms via socio-cultural and similar methods. Each of these value dimensions has validity in its own domain (Turner et al., 2003).

Economists have undertaken so-called welfare valuations based on consumer preferences (either revealed through actions in competitive markets or expressed via in person/online surveys) (Freeman, 1993). The revealed preference approach includes for example the travel cost method to value recreation, and the expressed preference method looking to elicit "willingness-to-pay," includes technics such as contingent valuation (CV)/choice experiments (CE) techniques. There are also some hybrid methods, mixing CE/CV with deliberative processes involving stakeholders and related networks, and CE/CV together with Q methodology (Hampson et al., 2022). A growing body of literature uses the "life satisfaction" approach and has been successfully applied to value a variety of different ecosystem services (Fleming & Ambrey, 2017); information market approaches, which allow for the valuation of "bundles" of ecosystem services, also show promise (Grainger & Stoeckl, 2019). At the other end of the valuation methods spectrum come non-monetary quantitative and qualitative methods which include among others, subjective well-being measures, in-depth discussion groups, citizens juries, focus groups, semi-structured surveys, and participatory mapping GIS (Kenter, 2016).

Although the field of economic valuation of nature has been in the literature for several decades now, especially after the seminal works from Costanza et al. (1997) and Daily (1997), the Millennium Ecosystem Assessment (2005) and more recently TEEB (2010), one significant research gap that persists today is to better understand how these economic values change with changes in ecosystem health. Many CV and CE studies aim to estimate the *marginal* value of a change in ecosystem health, but these methods are *partial equilibrium* and so focus on just small (marginal) changes to a relatively small number of *attributes* assumed to be separable from other parts of the system. These methods are thus well suited to the challenge of assessing changes in values, following changes in individual aspects of ecosystem health (e.g., a change in water quality), but they have not been designed to assess larger-scale holistic changes in an entire ecosystem's health.

Of all valuation methods, perhaps benefit transfer is the method that poses the biggest challenges in accounting for ecosystem health, since it is an aggregated method that uses secondary information from a study site that will be applied to a policy site, estimating values in a standardized way without considering changes in ecosystem health in each unit of space (e.g., hectare) (Ready & Navrud, 2005). Moreover, ecosystem health in benefit transfer analysis is often ignored both in the study site as well as in the policy site.

To better understand the existence of a research gap on assessing ecosystem health in the literature of ecosystem service valuation, we analyzed the recently launched update of the Ecosystem Services Valuation Database (ESVD) (Brander et al., 2021), an open-source tool with over 6,700 value records from over 950 studies distributed across all biomes, ecosystem services, and geographic regions. The ESVD is to our knowledge the largest repository of studies on ecosystem services valuation, and therefore it is a key source of information to address this research gap. We analyzed all records specific by a type of biome (n = 6131) from the ESVD, and found that in approximately 58% of the records data on ecosystem condition (i.e., ecosystem health) was lacking (i.e., authors did not provide that information) (Table 1). Especially the estimates for Open Sea/Ocean (95%), Urban Green and Blue Infrastructure (94%), and Coral reefs (90%) do not contain information on the health of the ecosystems described in the papers. Of all the value estimates in the ESVD, 19% describe healthy ecosystems and only 6% a highly degraded ecosystem. There are several biomes containing much information on the health of ecosystems, notably Deserts and Tundra (both 100%), Grass-/Rangelands (90%), High mountain and Polar systems (73%), and Tropical forests (69%). Closely examining the seven biomes which contain more than 250 value estimates, that is, the most studied biomes in the ESVD, show that only two of the seven contain information on ecosystem health for over 50% of their value estimates, Cultivated areas (54%) and Tropical Forests (87%).

We then filtered those ecosystem services values that could be standardized in \$/ha/y (n = 4040) (Table 2) which shows the same picture: for 55% of the records no data on condition was available, 19% of the biomes were in good condition, 18% intermediate, and 8% degraded.

From Tables 1 and 2, we prove that there is a significant lack of information on ecosystem health/condition in the current literature of ecosystem service valuation. For most biomes, including some of the biomes with a high data availability, there is no information provided on ecosystem health or degradation levels.

There are several ways to bridge the knowledge gap on ecosystem health and the monetary valuation of ecosystem services. For example, including indicators of ecosystem health in primary valuation studies. These indicators can be qualitative and can vary from simply mentioning the state of ecosystems based on expert judgement and/or doing assessments using existing databases, to conducting empirical assessments of health indicators such as net primary production. Global initiatives such as the Ecosystem Services Partnership (ESP, see es-partnership.org) could play a key role in developing guidance tools and/or protocols on how to include

TABLE 1 Distribution of information of ecosystem health per biome in the ESVD

Ecosystem	Highly degraded	Intermediate	Well-functioning	No information	Total records
Coastal systems (including wetlands)	9%	10%	25%	56%	1451
Coral reefs	3%	2%	5%	90%	795
Cultivated areas	6%	25%	23%	46%	566
Desert	-	85%	15%	-	97
Grass-/Rangeland	-	56%	33%	10%	154
High mountain and Polar systems	3%	67%	3%	27%	146
Inland Un- or Sparsely Vegetated	-	8%	33%	58%	12
Inland wetlands	3%	12%	14%	71%	384
Open sea/ocean	5%	-	1%	95%	167
Other	1%	-	27%	72%	71
Rivers and lakes	1%	2%	43%	54%	416
Temperate forests	0%	10%	17%	73%	553
Tropical forests	11%	38%	20%	31%	887
Tundra	-	-	100%	-	9
Urban Green and Blue Infrastructure	2%	-	4%	94%	224
Woodland and Shrubland	25%	18%	11%	46%	199
Total	6%	17%	19%	58%	6131

Note: Numbers in red represent the cells with over 50% of all value estimates per biome.

TABLE 2 Standardized value estimates reporting ecosystem health the ESVD

Ecosystem	Highly degraded	Intermediate	Well-functioning	No information	Total records
Coastal systems (including wetlands)	11%	8%	23%	57%	1154
Coral reefs	4%	2%	5%	89%	296
Cultivated areas	7%	28%	17%	48%	356
Desert	-	94%	6%	-	50
Grass-/Rangeland	-	40%	50%	10%	98
High mountain and Polar systems	3%	69%	2%	26%	134
Inland Un- or Sparsely Vegetated	-	-	36%	64%	11
Inland wetlands	2%	13%	17%	68%	315
Open sea/ocean	7%		1%	93%	122
Other	4%		52%	43%	23
Rivers and lakes	1%	2%	35%	62%	222
Temperate forests	0%	10%	16%	73%	467
Tropical forests	17%	45%	26%	13%	539
Tundra	-	-	100%	-	7
Urban Green and Blue Infrastructure	-	-	-	100%	139
Woodland and Shrubland	35%	25%	8%	32%	107
Total	8%	18%	19%	55%	4040

Note: Numbers in red represent the cells with over 50% of all value estimates per biome.

ecosystem health in studies of economic valuations of ecosystem services. Finally, to obtain more insights in the ESVD data, it is recommended to be subject to spatial analyses for researching correlations between ecosystems and ecosystem health.

4 | ACCOUNTING FOR ECOSYSTEM HEALTH

Ecosystem Accounting seeks to integrate environmental and economic data to provide a comprehensive and multipurpose view of the interrelationships between the environment and the economy and the changes in stocks of environmental assets as they benefit humanity. The recently revised UN System of Environmental Economic Accounting – Ecosystem Accounting (SEEA EA) (UNCEEA, 2021) forms part of the System of Environmental Economic Accounting (SEEA) framework, providing a complementary perspective to that provided by the more established SEEA Central Framework (SEEA CF) (United Nations, 2014). In simple terms, the SEEA EA establishes standards for the measurement of ecosystem extent (referring to geographic size) and ecosystem condition (referring to the quality and health of the ecosystem asset). The SEEA EA considers that the extent and condition are, together, crucial to the ecosystem services that can be provided by the ecosystem to the economy and to society more generally, and that this flow of benefits contributes to the well-being of individuals and of society (Figure 3).

Ecosystem accounts prepared under SEEA EA are based around five interconnected stock and flow accounts (Figure 4). The first three of these are measured in physical units, representing the stock (extent and condition) of ecosystem assets at a particular point in time (the end of the accounting period), and the physical flow of ecosystem services that have been provided by that stock during the accounting period (usually 1 year). The final two accounts are measured in monetary units; the monetary ecosystem services flow account represents the monetary value of the flow of ecosystem services that has been provided in the accounting

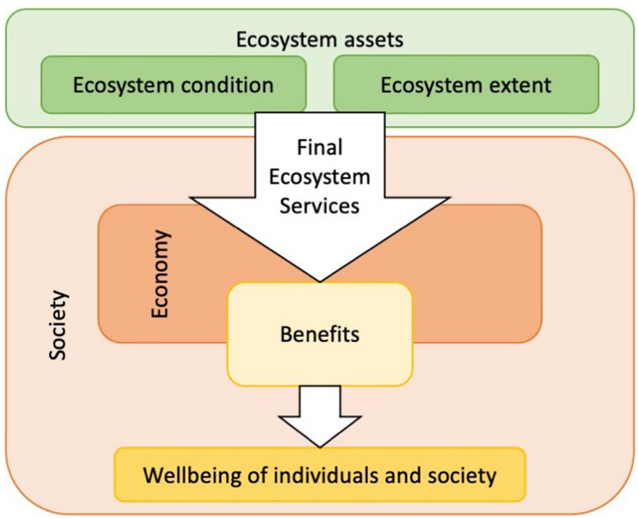

FIGURE 3 The SEEA EA general ecosystem accounting framework adapted from: SEEA Committee of Experts on Environmental-Economic Accounting (2021) System of Environmental-Economic Accounting - Ecosystem Accounting: Final Draft, Figure 2.1, page 28.

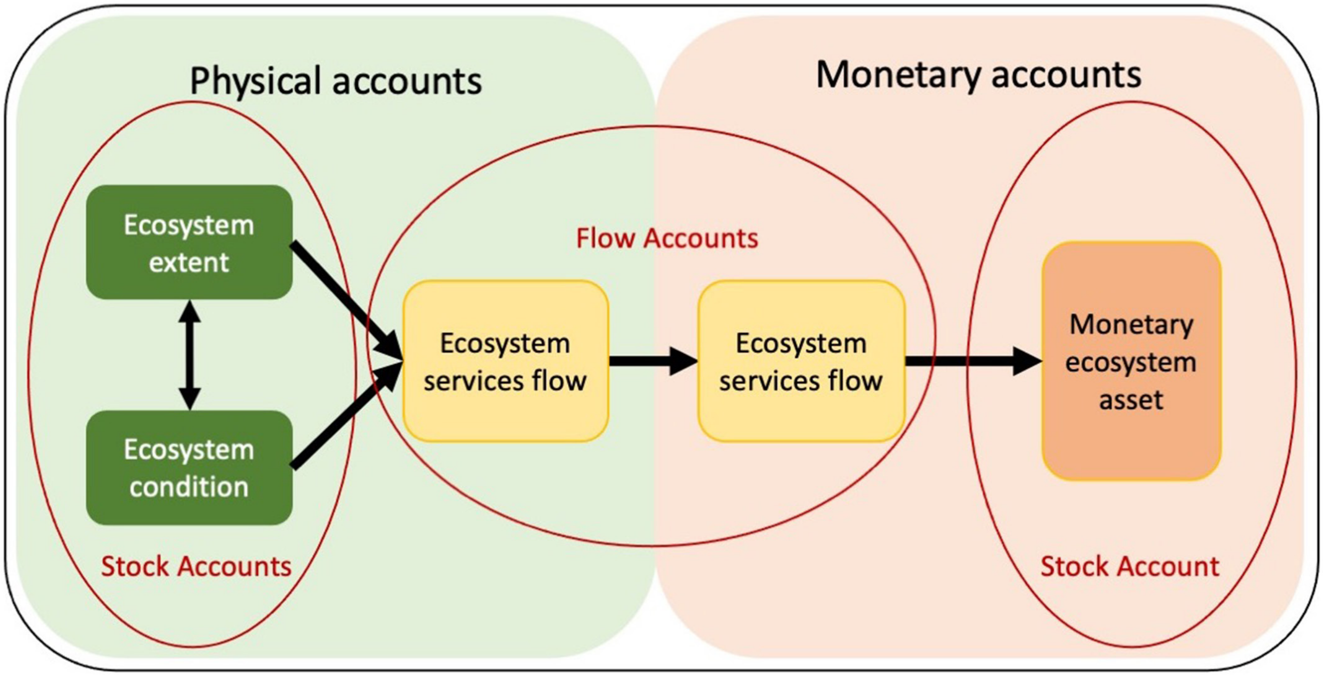

FIGURE 4 Connections between the ecosystem accounts adapted from: SEEA Committee of Experts on Environmental-Economic Accounting (2021) System of Environmental-Economic Accounting - Ecosystem Accounting: Final Draft, Figure 2.2, page 44 (UNCEEA, 2021).

period, while the monetary ecosystem asset represents the value of the stock of ecosystem assets at end of that period. Accordingly, changes in asset values brought about by changes in the health (condition) of the ecosystem (e.g., enhancement, degradation or conversion) are also incorporated within the monetary ecosystem asset accounts in so much as this change in health impacts the flow of benefits in the form of ecosystem services enjoyed from the ecosystem assets.

A key use of ecosystem accounting processes such as SEEA EA can be to estimate values of ecosystems at different points in time, providing information on the magnitude and direction of trends in ecosystem health. Thus, the accounts can highlight environmental degradation or resource depletion or unsustainable use patterns (Warnell et al., 2020). Such information can be useful of itself, assisting with the development of environmental policies and complementing or supplementing existing monitoring programs (Dvarskas, 2019). However, the scope for use is wider, for example, at the macro level, changes in ecosystem health estimated by the SEEA EA process could be integrated with national accounts to impact reported GDP (La Notte & Marques, 2019), or at a smaller scale, changes in ecosystem health could be reflected within the financial accounting and management processes of landowners enabling charges to be levied against those tenants and other land-users who have misused the environment and contributed to declining ecosystem health (Ogilvy et al., 2018).

However, the constraints imposed by the need to present data in monetary exchange value terms will continue to exclude some ecosystem services, and the holistic role played by biodiversity in the sustainable supply of services from the accounts. Therefore, there is a present and urgent requirement for a more comprehensive set of ecosystem/biodiversity change indicators. Rather than seeking a full integration of environmental data into the System of National Accounts (SNA) framework, we argue pragmatically, for the establishment of protocols as a set of networked complementary accounts (CAN), or similar setups, to sit alongside the economic accounts and on the same timescale (Turner et al., 2019). This path offers an immediate way forward, rather than trying to adjust the measures of production, consumption, income, and the value of assets in the SNA to fully reflect biodiversity losses or gains.

Therefore, we need to recognize that the SNA is intended to measure *income*, not *well-being*. This is an important distinction. Income is one contributor to quality of life and well-being, but not the only one (Costanza et al., 2007). Some of the contributions of natural capital are part of the income stream and SEEA is attempting to include them. But many others contribute to well-being more directly and cannot be captured via "exchange value" proxies. If our goal is measuring sustainable well-being, then we need both SEEA and additional measures of the contributions of natural capital and ecosystem services.

5 | CASE STUDIES ON ECOSYSTEM HEALTH CHANGE AND WELL-BEING

Data gaps prevent us from being able to use meta-analysis to generate empirical estimates of the impact that changes in ecosystem health have upon ecosystem service values, so we instead use the case studies below that helps to explain this.

5.1 | Case study 1. Changes in the health of tropical savannas in Australia through the revival of Indigenous fire management practices

In Australia, tropical savannas occupy 1.9 M km^2 in the north, covering a quarter of the Australian landmass. Savannas incorporate a diverse range of vegetation types including open grasslands, shrublands, savanna woodlands, and monsoon/tropical forests, and support diverse flora and fauna, with well-preserved soil and water resources (Woinarski et al., 2007; Figure. 5). Traditionally managed by Indigenous peoples over millennia through implementation of fine-scale mosaic burning, this landscape is relatively little modified by the modern practices. Consequently, Australia's savanna ecosystems support an array of services delivered to local, regional, and global populations, worth more than USD 1.6 billion year^{-1} (Russell-Smith et al., 2019; Sangha, Evans, et al., 2021).

Australian savannas represent relics of ancient ecological and social landscape interactions. These ecosystems are highly fire-prone, that require active management of fuel-loads to prevent wildfires. Wildfires in Australian savannas emit about 16Mt of greenhouse gas (GHG) emissions per year, comprising about 4% of the annual GHG emissions inventory (Sangha, Evans, et al., 2021). The eucalypts which now dominate the savannas are well adapted to fire, radiating from ~15 million years BP as the climate dried (Woinarski et al., 2007). Anthropogenic burning is likely to span >60,000 years associated with the current known prehistory of human occupation (Clarkson et al., 2017), but especially in the later Holocene period (from ~3000 years BP) with rapidly increasing population sizes (Williams et al., 2015), which together have contributed to Indigenous land (and fire) management that shape present day savannas. Traditional land management in savannas that is applied currently is the result of close human–nature interactions over thousands of years.

Ongoing Indigenous connections with the savanna landscape offer special insights for understanding the importance of managing the health of this vast, highly fire-prone region. In the past, indigenous burning practices—characterized by small-scale, cool, patchy fires over large areas—were undertaken as people traversed their estates for a variety of hunting, gathering, cultural and spiritual purposes (Garde et al., 2009; Ritchie, 2009). As a result, over time the savanna landscape has co-evolved with fire (Bird et al., 2005; Bowman, 1998). However, colonization impacted these practices severely over the last 100 years. Only since the beginning of the 21st century, has there been a revival of Indigenous fire management practices. This was partly a recognition by the Australian Government, particularly with ratification of the Kyoto Protocol in 2008, of the need to reduce GHG emissions.

Indigenous fire management contributes significantly to abate GHG emissions, especially for reducing the impacts of extensive, severe late dry season (LDS) wildfires ignited both by people and lightning, while contributing to the protection and management of savanna landscapes (Edwards et al., 2015). Strategic application of small, patchy burns as firebreaks, and more generally to reduce fuel loads, in the early dry season (EDS, March–July) mitigates the risk of extensive LDS (August–December) wildfires which causes huge losses to various natural and man-made assets (worth \$95million year^{-1} for loss of ecosystem services, following Sangha, Russell-Smith, et al., 2021). In the Indigenous vernacular, prescribed burning is often described as "cleaning-up *country*," by which people mean to clear the rank (senescent) grass and protect land and water resources.

With recognition of Indigenous fire management practices in the early 2000s, and inclusion of Savanna Burning as an accountable activity for Annex 1 (Advanced Economy) countries under the Kyoto Protocol, a collaboration between scientists and Indigenous Elders was undertaken through the 2000s to develop a first-of-its-kind, market-based Savanna Burning (SB) GHG emissions accounting

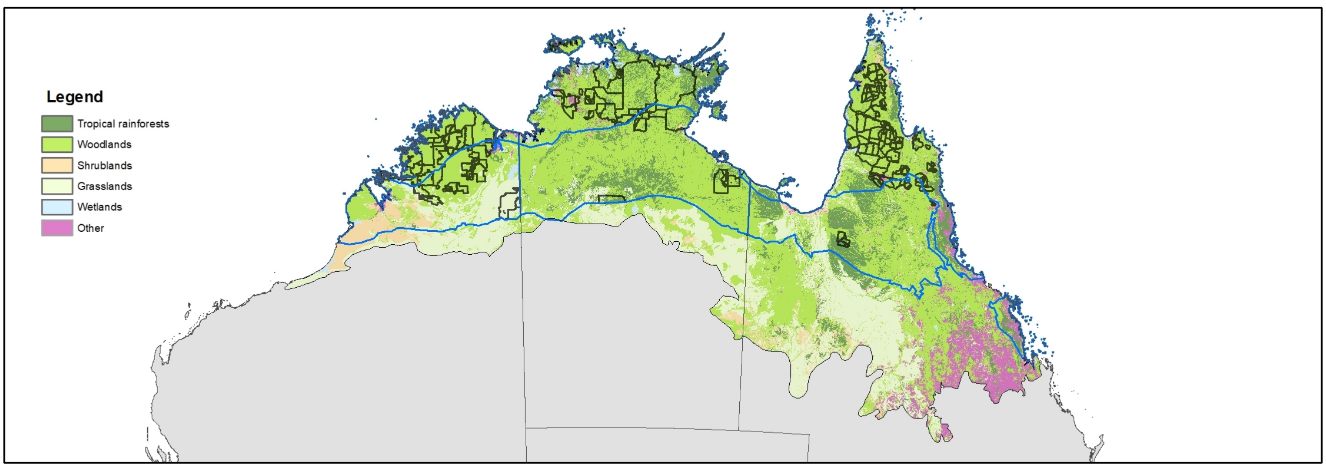

FIGURE 5 Dominant vegetation types (following the Australian National Vegetation Information System dataset) across tropical savannas in northern Australia with greenhouse gas emissions abatement "carbon"/Savanna Burning projects (outlined in black) above the 600mm rainfall isohyet (blue line) using data from the carbon project register by the Emissions Reduction Fund, Australian Government (Source: Sangha, Evans, et al., 2021).

methodology (Russell-Smith et al., 2009, 2013). The SB approach accounts for and incentivizes the undertaking of prescribed burning in the EDS period, under relatively mild fire-weather conditions, to reduce the risk of extensive LDS wildfires and resultant GHG emissions (Murphy et al., 2014). In 2011, SB was formalized under Australian Commonwealth Law through the Carbon Farming Initiative Act (2011), involving the establishment of an accredited accounting methodology for the calculation of GHG emissions reductions from registered projects (Commonwealth of Australia, 2013). In 2014, the Australian Government established the Emissions Reduction Fund (ERF) and invested AUD 2.55 billion for the next five years as a means for purchasing carbon credits (Australian Carbon Credit Unit—ACCUs) from GHG emissions abatement. This fund has recently been renewed with another AUD 2 billion investment, under the rebadged Climate Solutions Fund (Australian Government, 2020).

SBM demonstrates the application of traditional knowledge, in combination with contemporary scientific tools and techniques. It also demonstrates the value of indigenous knowledge systems. The overall benefits from SB range from USD 74.6million since the start of the methodology for marketable carbon credits alone, averaging about USD 10million per year. More importantly, the well-being benefits that flow from fire management were estimated at USD 189million year^{-1}, for >200 Indigenous communities living across the north.

Indigenous management is improving the health of savanna ecosystems in Australia, which has lead not only to significantly increase climate regulation services by mitigated more than 5million tonnes of GHG emissions to date (Sangha, Evans, et al., 2021), but has had a direct positive impact on local communities who have benefited economically for the sale of carbon credits as well as through new green jobs (Table 3).

5.2 | Case study 2. Changes in the health of the Amazon rainforest

The Amazon rainforest plays a crucial role in several ecological processes that are relevant at both local and global scales. The Amazon rainforest harbors about 15% of terrestrial biodiversity (Dirzo & Raven, 2003; Myers et al., 2000), generates rainfall levels equivalent to 2190 mm year^{-1} on average (Lovejoy & Nobre, 2018) allowing it to produce an average maximum of 240,000 m^3 s^{-1} of river discharge, which is equivalent to 15% of the worldwide total freshwater flow into oceans (Richey et al., 1986). Also, it is estimated that the region stores between 150 and 200 billion tons of carbon in total (Malhi et al., 2006; Phillips et al., 2009), and contributes to an ethnic, cultural, and linguistic diversity as a consequence of traditional indigenous groups who live there (Denevan, 1992; Moore, 2015) (Figure 6).

The most important driver of environmental change in the region is deforestation and forest degradation as a consequence of diverse anthropogenic activities such as large-scale agriculture, shifting farming, cattle ranching, logging, infrastructure expansion, artisanal mining, among others, that take place in localized areas across the region (Piotrowski, 2019). These human-induced stressors over the health of the rainforest in the Amazon could endanger its ability to keep providing ecosystem services that are fundamental for society's well-being at the global scale. For instance, introducing changes in the vegetation canopy height influence temperature and humidity balances across the region, this way affecting its capability to regulate hydrological cycle. It has been found that such changes define differentiated rainfall regimes that feedback negatively to agriculture, being this issue even more critical in zones with greater production (Leite-Filho et al., 2021).

Although some studies that aim to model the connection between deforestation and moisture recycling capacity of the Amazon biome have been performed (Bagley et al., 2014; Swann et al., 2015), the relationship remains inconclusive. A few of these analyses assume that both variables are inversely correlated (Wu et al., 2017), while other authors concur in the existence of non-linear responses for the Amazon biome (Nobre & Borma, 2009). In this sense, these latter studies aim to estimate the share of lands within the region after which forested ecosystems would be unable to keep supporting the hydrological cycle that takes place in it (Lovejoy & Nobre, 2018). Using modelling methods, this "tipping point" was estimated to be reached when the share of cleared areas across the region is between 20 and 40% (Lovejoy & Nobre, 2018; Nobre & Borma, 2009). It is expected that after reaching that threshold, the region would experiment not only longer but also more extreme dry seasons and ultimately a "savannization" process, thereafter generating considerable negative impacts on the regional agriculture production (Leite-Filho et al., 2021), and also climatic conditions across the whole South American continent (Lovejoy & Nobre, 2018).

TABLE 3 Changes in the health of savanna ecosystems in northern Australia and the consequent changes in the climate regulation ecosystem service

Driver of change	Ecosystem	Change on conditions affecting ecosystem health	Ecosystem services affected by changes in ecosystem health	Economic change
Incentivized Savanna burning methodology	Tropical savannas	Less frequent and intense wildfires, hence better protection of vegetation and water resources	Climate regulation and other ES	About 30% less GHG emissions due to fine-scale fire management, generating local economies worth >USD 10 million per year and >600 ranger jobs in remote indigenous communities across northern Australia

FIGURE 6 The Amazon rainforests, extending through several countries in South America. (Source: MapBiomas, 2015).

TABLE 4 Changes in the health of tropical rainforest in the Amazon and the consequent changes in the provision of ecosystem services

Driver of change	Ecosystem	Change on conditions affecting ecosystem health	Ecosystem services affected by changes in ecosystem health	Economic change
Deforestation and forest degradation	Old-growth tropical forest	Longer drier seasons	Water regulation	Economic losses in intensive agriculture equivalent to about US$ 0.5 million ha^{-1} $year^{-1}$ in average
		Region is becoming a net carbon source	Climate regulation	Amplification of global extreme events (droughts and floods)
		Fragmented habitats favored human–wildlife species interactions	Zoonotic viruses control	COVID-like outbreaks are more likely to emerge
				COVID-19 preventive costs were estimated to be only 2% of actual costs destined to deal with it

Furthermore, the Amazon biome has a critical role in regulating future climate conditions. The magnitude of the region's carbon sink has been challenged. Recent evidence suggest that the regional carbon balance has decreased during the last three decades as a consequence of two factors: the stall of tree growth rates, and the increase in tree mortality. Nevertheless, the Amazon biome is still considered as the largest terrestrial carbon sink worldwide given its extent and organization (Phillips et al., 2017). It has been estimated that the region currently stores about 76 billion tons of carbon (Rodig et al., 2019), and that release of this carbon could bring considerable yet still non-completely predictable climate impacts (Alves de Oliveira et al., 2021; Shukla et al., 1990).

On the other hand, available evidence relates many of most recent emerging infectious diseases, including COVID-19, with increasingly frequent interactions between humans and wildlife species (Lloyd-Smith et al., 2009). In this sense, tropical deforestation increases the risk that such interactions could take place by displacing wildlife from their habitats toward human-dominated places (Barbier, 2021). Hence, forest conservation is being seen as a highly cost-effective manner to decrease risk of future worldwide pandemic outbreaks. For example, Dobson et al. (2020), estimate that actual costs that countries have incurred to deal with COVID-19 so far are up to 50 times greater than potential funds that could have been destined to prevent tropical deforestation and regulating wildlife trade.

In summary, changing the health of the Amazonian rainforest through unsustainable practices such as large-scale agriculture and logging, is the consequence of a development policy that values mainly provisioning services (e.g., timber, food) over the highly valuable services that are fundamental for human well-being at different scales, such as water and climate regulation, and the control of zoonotic viruses (Table 4). As in the Australian case study, this shows the need for an integral policy making that take in consideration the multiple values of nature and their beneficiaries.

6 | CONCLUSION

The goal of this paper was to provide an overview on the consequences that ecosystem health changes have on the provision of valuable ecosystem services, and ultimately on human well-being. To better understand this relationship, we proposed a framework that explains these interactions, considering the health of natural capital and its interaction with the human, social, and built capital to produce well-being. Although this framework is an oversimplification of the complex interaction among capitals, it can aid policy makers to design more integral conservation and restoration strategies to improve ecosystem health at different scales, and therefore conserve and/or increase the benefits society receives from the rest of nature.

Many research gaps remain in linking ecosystem health and the provision of ecosystem services. From a biophysical point of view, since ecosystems are complex adaptive systems, it is difficult to determine when the system is approaching a tipping point from the pressure from one or more stressors. Therefore, the resilience component from our definition of ecosystem health is the component that should be a priority in a research agenda on ecosystem health. From an economic perspective, as evidenced by our analysis using the ESVD, reporting the condition of the ecosystem should be a requirement of future economic valuations of ecosystem services, so the relationship between condition and value can be established.

The recognition that our physical and mental health depends on the health of the rest of nature could be the most essential principle to transform our GDP focused economy to one that embraces the Greek root of the word "economics," which is "managing our home"—in other words planetary stewardship and caring for country.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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