Journal of Environmental Management 344 (2023) 118752

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Discussion

Boundary of ecosystem services: Guiding future development and application of the ecosystem service concepts

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ARTICLE INFO

Handling editor: Jason Michael Evans

Keywords
Ecosystem service value
Renewable
Biotic
Natural capital
Human wellbeing
Conservation

ABSTRACT

Ecosystem Services (ESs) are either material or non-material benefits humans receive from ecosystems. Definitions, classifications, and typologies of ESs can vary to address different research and policy purposes. However, a boundary that distinguishes ESs from other ecosystem-related benefits (e.g., industrial products that consume raw materials, fossil fuels that used to be a part of ecosystems) is needed to avoid the risk of using ESs as an all-encompassing metaphor that captures any benefit. The boundary also maintains a common ground for communication and comparison of ESs across studies. To guide future development and application of the ES concepts, we suggest five criteria. ESs are (1) primary contributions of ecosystems, (2) flows assessed during a period or per time unit (not stock existing at a time point), (3) renewable (having the potential to be reproduced with a conceivable timeframe relevant to human use), (4) affected by biotic parts of ecosystems to occur. ESs include both biotic and some abiotic flows (e.g., water provisioning) but exclude abiotic flows (e.g., wind and solar energy) whose occurrence is unaffected by ecosystem functions, processes, or characteristics; and (5) inclusive to the benefits humans actually and potentially receive from ecosystems. These criteria link ESs with conservation of life-supporting and culturally important ecosystems, recognize use, option, and non-use values of ESs, and highlight ESs' sustainability.

1. Introduction

Ecosystem services (ESs) are commonly understood as "the benefits people obtain from ecosystems" defined by the Millennium Ecosystem Assessment (2005). This understanding leaves space for the ES concepts to evolve and adapt (Costanza, 2008). Since 1997, variations in the definitions, typologies, and classifications of ESs have occurred in literature, including several widely recognized publications listed in Appendix 1 (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005; TEEB, 2010; CICES, 2011; IPBES, 2019; United Nations SEEA-EA, 2021). The variations may help address different research and policy purposes, and future research may integrate new ES typologies (Costanza, 2008; Costanza et al., 2017). However, this does not mean the ES concepts can vary to incorporate all ecosystem-related benefits.

Instead, a boundary that distinguishes ESs from other ecosystem-related benefits is needed both for future studies and for definitional integrity of the concept in general. In the context of this paper, as indicated in Fig. 1, ESs encompass Parts E – F, whereas the other ecosystem-related benefits consist of Parts A – D. Without the boundary, it is challenging to communicate ES-related issues, compare ESs and their values across studies, and use ESs or their values as ecological or economic indicators (e.g., using ESs' values to assess regional development, environmental conditions, and governmental performance) (Fisher and Turner, 2008; Nahlik et al., 2012; Schröter et al., 2014b; Hao et al., 2022). Also, as there is growing recognition that all human wellbeing is fundamentally derived from ecosystems (World Health Organization, 2015; Costanza, 2020; United Nations SEEA-EA, 2021), integrating ecosystem-related benefits into ESs without considering the

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https://doi.org/10.1016/j.jenvman.2023.118752
Received 22 May 2023; Received in revised form 20 July 2023; Accepted 9 August 2023
Available online 11 August 2023

boundary would potentially make ESs an all-encompassing term that captures everything related to human wellbeing. This can also increase the risk of over-valuation of ESs (e.g., counting non-services as ESs) and subsequent resource misallocation from a policy perspective (e.g., overestimate of funding for conservation finance) (Hao et al., 2022).

Existing literature has developed many ES typologies (Appendix 1) but does not generalize the fundamental distinction between ESs and other ecosystem-related benefits. In other words, the boundary that separates ESs from other ecosystem-related benefits remains unclear. This paper suggests such a boundary (Fig. 1) by providing criteria for researchers, managers, and decision makers to consider while formulating studies, reports, and investigations. In short, ESs (regardless of being provisioning, regulating, cultural/spiritual, or supporting) are (1) primary contributions of ecosystems, (2) flows, (3) renewable, (4) affected by biotic parts of ecosystems to occur, and (5) inclusive to both realized and potential ESs. We expect application of these criteria to help prevent ESs from being an all-encompassing concept; establish a common ground for communication or comparison of ESs across studies; guide future development and application of the ES concepts; and at least provoke further research to investigate whether ESs require a boundary and, if so, to determine where that boundary should be. Subsections 2.1 to 2.5 in the subsequent Discussion section provide a detailed explanation of each of these five criteria and delve into existing debates and differing perspectives surrounding them.

2. Discussion

2.1. Do ESs comprise all benefits contributed by ecosystems?

Production of ESs and many other benefits requires interactions between natural capital (stock of ecosystems that yield flows of benefits) and human-derived capital, including human capital (human presence, health, knowledge, intelligence, and labor), manufactured capital (artificial tools and physical entities), social capital (norms, relationships, social networks, and institutions that underpin formation and operation of society), cultural capital (cultural identity and representation, beliefs), and financial capital (money that facilitates the interaction of other forms of capital) (Boumans et al., 2002; Jones et al., 2016; Costanza et al., 2017; IPBES, 2019; United Nations SEEA-EA, 2021). The concept of ESs is developed to highlight and compare benefits from natural capital with benefits from human-derived capital (Costanza and Daly, 1992; Costanza et al., 1997; Daily, 1997). Hence, ESs reflect the relative contributions of ecosystems to human wellbeing, in interaction with other forms of capital (Costanza et al., 2017). However, do ESs cover all benefits contributed by ecosystems? We suggest ESs only comprise ecosystems' primary contributions.

In this paper, we define the ecosystems' primary contributions as both (1) the benefits humans *directly* receive from ecosystems, and (2) ecosystem structures, processes, characteristics, and functions (e.g., pollination, nutrient cycling) that benefit humans *indirectly* (e.g., through maintaining and supporting the direct benefit), which are termed as indirect or intermediate ESs (Fisher and Turner, 2008; Wong et al., 2015; Costanza et al., 2017; United Nations SEEA-EA 2021). Accordingly, all ES typologies in Appendix 1 are ecosystems' primary contributions.

Other benefits excluded by the primary contributions explained above are non-primary. Using ESs to label non-primary services and goods, such as industrial products and transportation networks that integrate ecosystems' inputs (Yang et al., 2015; Tan et al., 2020), has a risk of making ESs an empty and all-encompassing concept. This is because, as mentioned earlier, arguably all benefits contain ecosystems' inputs.

2.2. Are ESs flows or stock?

Flows are something assessed over a period (e.g., a year) or per unit of time (e.g., per second), whereas stock is the quantity or amount existing and measured at a certain point in time, which can accumulate (Jones et al., 2016; Chen et al., 2022b). Both flows and stock may be either tangible or intangible. Furthermore, they may both be quantified. However, there are circumstances where quantification becomes challenging due to limited data availability, insufficient measurement techniques, or uncertainties in ecosystems (Costanza et al., 1997). See examples in Table 1. Both the flows of benefits from ecosystems and the

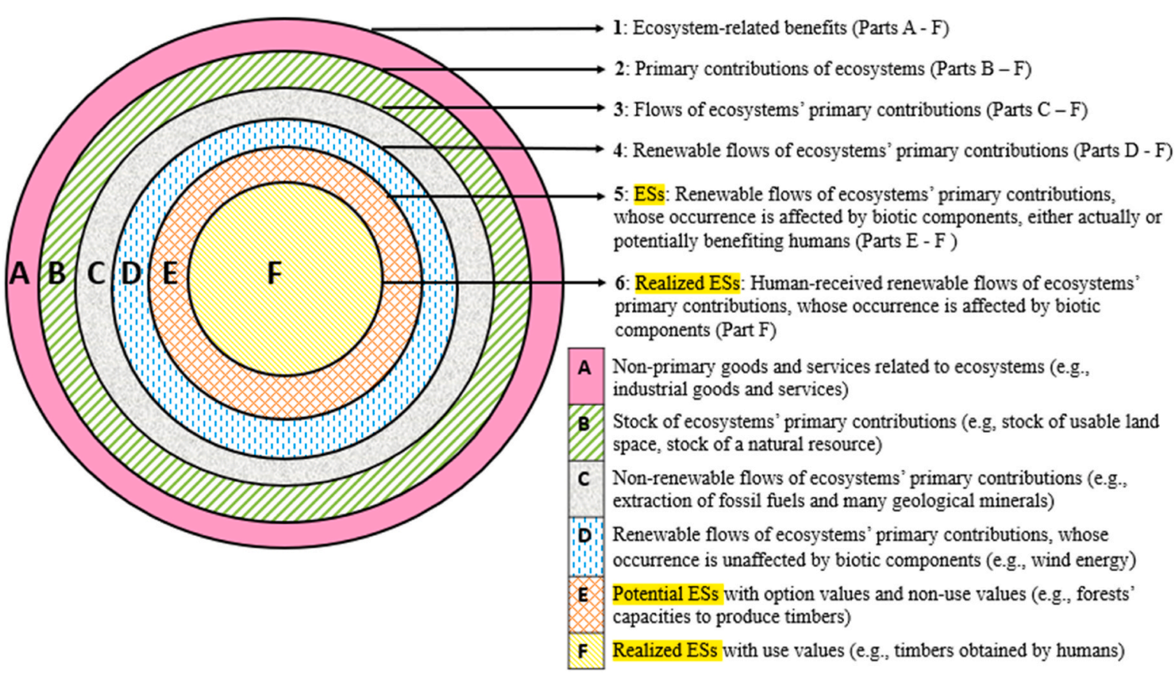

Fig. 1. Boundary between ESs and other ecosystem-related benefits. The numbers 1–6 represent six circles, where a smaller circle is a subset of the larger circle. The letters A - F represent the parts between the circles or within a circle.
Note: The terms contained in Fig. 1 will be explained in the main text when they occur.

Table 1
Examples of flows and stock.

	Flows	Stock
Tangible and quantifiable	Supply of 100 tons of water per month from a river	A total of 100 tons of water remaining in a pond at the end of a certain year
Tangible and challenging to quantify	Timber provisioning from global terrestrial ecosystems during a certain year may not be quantified when data availability is limited.	The total global living woods at a certain point in time may not be quantified when measurement techniques are insufficient.
Intangible and quantifiable	Aesthetic enjoyment and recreational experience obtained during a trip may be quantified in economic units by assessing people's willingness to pay for obtaining them (United Nations SEEA-EA, 2021).	A specific number of gigabytes in the visitors' database of a national park at the end of 2023.
Intangible and challenging to quantify	Humans' spiritual and religious experiences in nature during a certain timeframe are shaped by humans' subjective perceptions and emotions. Therefore, qualitative descriptors might be better suited than quantitative measures for assessing these benefits (IPBES, 2022).	Information stored in certain species at a certain point in time may be uncertain to quantify (Costanza et al., 1997).

stock of ecosystems are crucial factors for human well-being, ecosystem health, and sustainable development (Hernández-Blanco et al., 2022) but are described using different terms. Existing literature (TEEB, 2008; Costanza et al., 2014; Daly, 2020; United Nations SEEA-EA, 2021) commonly refers to the flows of benefits yielded from ecosystems as ESs, while the stock of ecosystems is referred to as natural capital. Accordingly, both the quantity and quality of natural capital influence the flows of ESs. Additionally, under specific circumstances, flows of a tangible good may alter the stock of that good. For example, the stock of wood can be harvested, leading to a flow of wood provisioning. This change in stock levels is interconnected with the level of flows being provided.

The studies that describe the space/stock of useable lands (Abson and Termansen, 2011; Vallés-Planells et al., 2014) and carbon stock stored in biomass or soil (Keith et al., 2019; Nel et al., 2022) as ESs reflect a lack of accurate understanding of the distinction between ESs and the stock of resources. In fact, ESs are produced, acquired, and assessed in the form of flows rather than stocks. This is because the production of provisioning, regulating, and supporting ESs relies partially on net primary production (the processes of producing organic matter) and/or interactive processes between different environmental components (Costanza et al., 2017), whereas cultural ESs are obtained through the processes of humans interacting with nature (United Nations SEEA-EA 2021; IPBES, 2022). Moreover, as mentioned previously, all ESs are produced through dynamic processes that arise from the interaction between natural and human-derived capital. The key words here are "processes", which are time frames. Existing literature, including all the widely recognized studies in Appendix 1, typically assesses ESs over a certain period of time.

Furthermore, the differences between flows and stocks are important for valuation at different scales. Valuing the stock of a resource is often more challenging than valuing the flows of benefits derived from the stock. This is because valuing the stock requires assessments of the stock's dynamics and involves summing and discounting the flows of benefits derived from the stock (Fenichel and Abbott, 2014). Moreover, valuation of the stock of a resource may be feasible on a micro scale (e.g., in an urban park) (Chen et al., 2022b) but becomes challenging and even infeasible on a national or global level. For example, if the stock of global water or oxygen disappeared, even for a week, humans could hardly survive (Farley, 2012; Chen et al., 2022b). One could also argue that, without a major component (e.g., forest) of the global ecosystems, economies cannot be maintained (Costanza et al., 1998). Hence, the total value of the global or even regional stock of a resource may be beyond estimation. However, existing studies (Costanza et al. 1997, 2014; de Groot et al., 2012; Kubiszewski et al., 2017; Jiang et al., 2021) have demonstrated the feasibility of valuing flows of a subset of benefits derived from global ecosystems over a defined period. Thus, considering ESs as flows not only differentiates ESs from natural capital, but also enables ES valuation at different scales. There is growing recognition that assessments of ESs' economic values at international, national, and sub-national scales can raise awareness of conservation, indicate environmental status, complement measurement of development quality and government performance, and assist with macro policy making (Costanza et al., 2014; Ouyang et al., 2020; United Nations SEEA-EA, 2021; Chen et al., 2022a).

2.3. Do ESs comprise both renewable and non-renewable benefits?

According to UNSD (2009), the terms "renewable" and "non-renewable" are defined as being reproducible or non-reproducible, respectively, within a timeframe that is conceivable for human use. If the terms "renewable" and "non-renewable" are defined based on the balance between the rates of consumption and replenishment, the classification of benefits as renewable or non-renewable becomes inherently relative and interchangeable. For example, certain benefits typically considered renewable, such as timber provisioning and surface freshwater provisioning, can transition into a non-renewable state when they are overused or depleted. However, to ensure a consistent classification of renewable and non-renewable benefits and to establish a clear boundary for ESs, we consider renewable or non-renewable benefits as those that have or lack the potential to be reproduced within a conceivable timeframe relevant to human use, regardless of their actual consumption rate. We emphasize again that the crucial aspect to consider here is the "potential", irrespective of the actual rate of consumption. For instance, although surface freshwater provisioning may experience over-consumption in certain real-world cases, it retains the potential for replenishment within a timeframe relevant to human use and is therefore consistently classified as "renewable" in this paper. Conversely, while fossil fuels and various minerals formed through geological processes may be reproduced at geological time scales (i.e. millions of years), such timeframe is much longer than the lifetimes of many generations of humans (National Geographic, 2022), hence this paper classifies them as "non-renewable". For clarity, the inclusion of "a conceivable timeframe relevant to human use" in the definition of renewable and non-renewable benefits is not intended to restrict any type of assessment, management, or conservation of ESs exclusively to our lifespan. Rather, it is solely meant to aid in communicating the benefits as being either renewable or non-renewable.

ES literature (Tables in Appendix 1, except Table S4 that integrates geological minerals) has tended to focus on renewable benefits, but some studies (Campbell and Brown, 2012; Kroll et al., 2012) integrated non-renewable benefits into ESs without explaining the reasoning. Consequently, divergent perspectives exist regarding the integration of both renewable and non-renewable benefits within ESs. However, we suggest ESs only comprise renewable benefits if application of the ES concepts intends to meet the following objectives (Daily, 1997; Costanza et al., 2014; CBD, 2020b; United Nations SEEA-EA, 2021; IPBES, 2022):

1. Raise awareness of nature's contributions to socio-economic development,
2. Highlight the interdependence between humans and the rest of nature,
3. Promote biodiversity conservation,
4. Motivate conservation of life-supporting functioning ecosystems and their cultural values,

5. Ultimately contribute to sustainable human wellbeing.

Integrating non-renewable benefits into ESs may align with the Objectives 1 and 2. Conversely, such integration may not satisfy the Objectives 3 or 4, because global-scale extraction and consumption of non-renewable resources (e.g., fossil fuels, gold ore, iron ore) has been a major driver of ecosystem degradation, biodiversity loss, damages to World Heritage Sites, and climate change (IUCN, 2011; Lele et al., 2013; IPBES, 2019; IPCC, 2021). As listed, the Objectives 1–4 all serve as instrumental steps towards achieving the ultimate Objective 5, which is sustainable human wellbeing. However, the pursuit of sustainable human wellbeing may conflict with the use of non-renewable benefits, as global consensuses have acknowledged that safeguarding a sustainable future for both people and the planet requires humans to phase down consumption of non-renewable energy (e.g., fossil fuels) and enhance conservation of biodiversity and ecosystems (CBD, 2020a; UNFCCC, 2021; CBD, 2022). Even if the use of non-renewable resources does not impact ecosystems negatively, it cannot sustain due to the limited stock and non-renewability of these resources.

2.4. Can ESs include abiotic flows of benefits?

Biotic flows are derived from living matter or organisms, whereas abiotic flows are derived from non-living matter or components of ecosystems. See examples in Table 2. United Nations SEEA-EA (2021) found that ES literature has tended to focus on biotic flows of benefits, probably because the essence of ES concepts is that the benefits from biotic parts of ecosystems to human wellbeing is often ignored and undervalued, which results in ecosystem degradation and biodiversity loss (Lele et al., 2013). Hao et al. (2022) and Zhang et al. (2022) indicated ESs have to be biotic. However, some studies (CICES, 2011; Van der Meulen et al., 2016; Kubalíková, 2020; Urban et al., 2022) regard abiotic flows as ESs, because (1) ecosystems involve both biotic and abiotic processes (e.g., photosynthesis, water evaporation) and structures (e.g., species composition, physical shapes of lands), as well as interaction between biotic and abiotic components (e.g., vegetation interacts with soil), (2) the fact that water provisioning, a widely adopted ES, may be abiotic already justifies that ESs can include abiotic flows, (3) abiotic components of ecosystems can potentially offer important habitats, which are widely recognized as an ES (4) nature's contributions to humans, including cultural values from abiotic environment (e.g., aesthetic appreciation of a rock), should be recognized and integrated into decision making more comprehensively.

We agree ESs include both biotic and some abiotic flows (e.g., water provisioning). However, abiotic flows whose occurrence is unaffected by biotic parts of ecosystems are not ESs for the following reasons. (1) The occurrence of ESs not only needs both biotic and abiotic components of ecosystems but is also affected by ecological processes, functions, or characteristics (Costanza et al., 2017). Therefore, for example, while ecological processes and the production of ESs (e.g., nutrient cycling) may consume minerals (e.g., iron and potassium) in soil, we do not consider provisioning of geological minerals (e.g., natural diamond, gold, copper) as an ES. This is because the formation of geological minerals occurs through geological, physical, or chemical processes (National Geographic, 2023a), rather than being affected by ecological processes, functions, or characteristics. However, we consider provisioning of biominerals, which are the minerals produced by living organisms (e.g., calcium carbonate produced by corals and shells) (Hardy and Scheibel, 2010), as an ES. Additionally, it is true that solar energy plays an integral role in ecological processes and the production of ESs, and biotic processes and components of ecosystems can also affect the amount of solar energy absorbed in a particular location by altering the albedo (the relative amount of light that a surface reflects compared to the total incoming sunlight) (NASA, 2023). However, we do not regard provisioning of solar energy as an ES, because its occurrence results from nuclear fusion in the sun (National Geographic, 2023b) without being affected by ecological processes, functions, or characteristics. (2) It is true that water may be stored and supplied through abiotic processes. However, water storage and provisioning in the ES context refers to the storage and supply of potable water regulated (e.g., being intercepted and purified) by functioning ecosystems (IPBES, 2019; United Nations SEEA-EA, 2021; Zhang et al., 2022) and hence is affected by biotic components of ecosystems to occur. Global sources of potable water are often accompanied by well-preserved biotic components (e.g., vegetation) of ecosystems (Dudley and Stolton, 2008; Harrison et al., 2016). (3) While abiotic components of ecosystems, such as sand dunes and rocks, may potentially provide a habitat service (which is an ES), it is important to recognize that a habitat service inherently involves biotic inputs. This is because a habitat is the "locality in which a plant or animal naturally grows or lives … or a physical portion of the environment that is inhabited by an organism or population of organisms. A habitat is characterized by a relative uniformity of the physical environment and fairly close interaction of all the biological species involved" (United Nations InforMEA, 2023). In other words, abiotic components alone cannot constitute a habitat without the presence of biotic components. (4) While humans need more comprehensive recognition of nature's benefits, including those unaffected by biotic parts of ecosystems to occur, enhancing this recognition does not necessarily require considering all abiotic benefits as ESs. Instead, alternative labels exist, including abiotic "contributions from the environment" (United Nations SEEA-EA, 2021) and "geosystem services" derived from geological processes and characteristics (Gray, 2012).

Table 2
Examples of abiotic/biotic and renewable/non-renewable flows of nature's primary contributions.

	Renewable	Non-renewable
Biotic flows	Many ESs (e.g., water purification, cultural benefits of forests, provisioning of biominerals produced by living organisms)	Not applicable
Abiotic flows whose occurrence is affected by biotic parts of ecosystems	Some ESs (e.g., water provisioning and storage)	Annual extraction of fossil fuels (e.g., coal, oil) that used to be biotic parts of ecosystems.
Abiotic flows whose occurrence is unaffected by biotic parts of ecosystems	Wind energy, solar energy, tidal energy, hydropower	Annual extraction of gold, silver, iron ore, and many other geological minerals produced through geological processes.

2.5. Can ESs include both the benefits humans actually and potentially receive?

Realized ESs are the ESs humans have actually received, whereas potential ESs are the services an ecosystem can potentially produce but not necessarily received by humans (see references in Table 3). Thus, realized and potential ESs produced by an area may not be the same and have been labelled differently in some studies (Table 3). However, Yu et al. (2021) and Wang et al. (2022) found that many ES studies focused

Table 3
Examples of terms.

Literature	Terms expressing potential ESs ecosystems can produce	Terms expressing ESs people actually receive
(IPBES, 2019)	Potential nature's contributions	Realized nature's contributions
(Jones et al., 2016; Wang et al., 2022)	Potential ESs	Realized ESs
(Villamagna et al., 2013; Schröter et al., 2014a)	Capacities to provide ESs	Flows of ESs

on potential ESs without considering if the ESs are actually received by humans. Whether ESs should only comprise realized ESs has not reached a consensus, but we suggest ESs comprise both potential and realized ESs.

While the distinction between realized and potential ESs exists in theory, the feasibility of separating them in practical assessments is questionable. If we restrict ESs to what humans actually receive, who should we consider? If we only consider humans in ESs-providing areas, many scarcely populated protected areas with crucial ecosystems, biodiversity, and cultural values would have little amount of ES value. This is not tenable if ESs are used to reflect the ecological importance, ecosystem health, and conservation status of an area (Hernández-Blanco et al., 2022). In fact, ES-providing areas and ES-benefiting areas (where people need and receive ESs) may have spatial mismatch (Syrbe and Walz, 2012), and ES receivers can be outside of ES-providing areas.

Existing studies have developed methods to identify ES-benefiting areas of their target ESs (Serna-Chavez et al., 2014; Cai et al., 2020; Gao et al., 2020; Tusznio et al., 2020; Cid et al., 2022). Also, there are discussions and guidance on who should be counted in the processes of decision making and/or policy analysis, such as economic cost-benefit analysis (Boardman et al., 2022), environmental management (Colvin et al., 2016), and payment for ESs projects (Long et al., 2015). However, identified ESs-benefiting areas and ES beneficiaries, especially those assessed at local or regional scales, only "partially" reflect the places that, and the people who, receive ESs, because:

(1) ESs may be multi-directional flows that can reach more places and people than researchers can assess. For example, in an increasingly globalized economy, provisioning ESs from a local ecosystem may be delivered globally (Tan et al., 2020). Carbon sequestration, even if being assessed at a local level, is related to global climate change (Serna-Chavez et al., 2014; Chen, 2021).
(2) The ESs people perceive may be less than the ESs people receive (Costanza, 2008). Unlike many provisioning ESs that require active human intervention (e.g., collection of raw materials) to receive them, regulating ESs tend to be received passively (Jones et al., 2016) and are especially likely to be unnoticed until their degradation or loss has caused negative impacts on human wellbeing (Sutherland et al., 2018).

Furthermore, although humans may only be willing to consider use values (of utilizing something) of realized ESs (Hao et al., 2022), ESs are not solely restricted to use values. Instead, stronger recognition of non-use values (attributed to existence of something, bequest, or altruistic purposes) and option values (of maintaining something for future use and potential benefits) of ESs is needed to (1) shape a more comprehensive view of the contributions nature make to human well-being, (2) promote conservation of ecosystems and biodiversity for future use, (3) diversify views on human-nature relationships and interdependence, (4) recognize nature's cultural/spiritual importance that may not be appropriately described as use values, and (5) measure ecosystem conditions and capacities for underpinning sustainable development (IPBES, 2019; CBD, 2020a; Schröter et al., 2021; United Nations SEEA-EA, 2021; Chen et al., 2022a; IPBES, 2022). Therefore, ESs include potential ESs.

3. Conclusion

ESs are (1) primary contributions of ecosystems, (2) flows (not stock), as ESs are produced, acquired, and assessed over a defined period or time unit, instead of at a specific point in time (3) renewable, as extraction and utilization of non-renewable flows may conflict with biodiversity conservation and sustainable development, and (4) affected by biotic parts of ecosystems to occur. ESs can include biotic and some abiotic flows but exclude abiotic flows that are unaffected by ecosystem functions, processes, and characteristics to occur. (5) ESs include both realized and potential ESs, because use, option, and non-use values are all integral to ESs. Also, although realized and potential ESs differ in theory, quantifying the proportion of potential ESs that are realized or actually received by humans in practice may prove to be unrealistic.

Humans have not fully understood the socio-economic, cultural, and ecological complexity of human-nature relationships. Therefore, the ES boundary we suggested may evolve with the development of ES knowledge. We recognize and respect that researchers may hold diverse perspectives on ESs, and thus, we do not consider the proposed ES boundary as a universally applicable guideline. However, we anticipate that this boundary will stimulate further clarification and refinement of the ES concepts. We also expect this boundary to promote communication and comparison of ESs across studies; link ESs with conservation of biodiversity and life-supporting ecosystems; recognize use, option, and non-use values of ESs; and highlight the sustainability of ecosystems' contributions to human wellbeing.

Statement of authors' contributions

Haojie Chen proposed the research, drafted, and revised the paper. Matthew R. Sloggy, Ahmad Dhiaulhaq, Francisco Escobedo, A. Rifaee Rasheed, Jose J. Sanchez, Weishan Yang, and Fang Yu provided valuable editing, refinement, and assistance with revisions. Ziqi Meng prepared Appendix 1. All authors reviewed and approved the manuscript for submission.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Acknowledgement

This research was supported in part by an appointment to the U.S. Forest Service Research Participation Program administered by the U.S. Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energyand the U.S. Department of Agriculture. All opinions expressed in this paper are the authors' and do not necessarily reflect the policies and views of any agency. We thank the journal editor and anonymous reviewers for their comments.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2023.118752.

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