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Discussion

Boundary of ecosystem services: Differentiating between ecosystem services and geosystem services is needed

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ABSTRACT

Geosystem services (GSs) and ecosystem services (ESs) are interconnected, both representing nature's contributions to people. Whether GSs are a subset of ESs depends on the definition of ESs. The answer would be "not necessarily" (i.e., some GSs are, while other GSs are not), if ESs are the benefits humans derive from ecological functions, processes, or characteristics. The boundary proposed by Chen et al. (2023) to differentiate ESs from other ecosystem-related benefits adopted this definition, and suggested that ESs are renewable and affected by biotic elements to occur. Gray et al. (2024) criticized this boundary for separating out bits of nature and ignoring the contributions of GSs and abiotic elements to ESs and human wellbeing. In fact, highlighting that ESs are affected by biotic elements to occur does not deny that ESs' occurrence is also affected by abiotic elements. However, ESs' dependence on abiotic elements cannot be a criterion to differentiate ESs from other benefits because abiotic elements are integral to geosystems, ecosystems, and many other natural and artificial systems, as well as to these systems' services. Conversely, while geosystems might persist without biotic elements, ecosystems cannot. Chen et al. (2023) only excluded those (not the whole) abiotic benefits, such as wind energy, that may occur independently of biotic elements, while allowing for integrating certain GSs into ESs. For example, geological structures can offer flood protection and water storage as GSs, which can also be classified as ESs when their qualities or quantities are affected by biotic elements. Differentiation between GSs and ESs should not be misinterpreted as splitting their interconnections or undervaluing or dividing nature. Instead, such differentiation and classification of nature's benefits serve to facilitate communication, management, education, research, and policy-making associated with nature's benefits, while also highlighting the richness and diversity of nature's benefits.

1. Introduction

To prevent the term "ecosystem services" (ESs) from potentially encompassing every benefit related to ecosystems, Chen et al. (2023) proposed a boundary to differentiate ESs from other ecosystem-related benefits. In summary, the benefits that can be classified as ESs need to meet multiple criteria. Two of the criteria include (1) being "renewable (having the potential to be reproduced within a conceivable timeframe relevant to human use)" and (2) being "affected by biotic parts of ecosystems to occur" (p.1). Gray et al. (2024, p. 1), however, critiqued these two criteria for not recognizing "the importance of geodiversity and geosystem services (GSs) in delivering societal benefits" and "the role of abiotic nature" in both ESs and non-ecosystem domains. GSs denote the benefits derived from geological processes or characteristics (Gray, 2012) (see examples in Table 1). We truly thank Gray et al. (2024) for raising this important topic, opening further discussion of the ES

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Table 1
A subset of examples of GSs collected from Gray et al. (2024).

Types of services	Examples
Provisioning	Stones as construction minerals; metals as industrial materials
Regulating	Flood mitigation by sand dunes; filtering water in rocks
Cultural	Spiritual connections with geologic formations; artistic inspiration from geological materials
Supporting	Rock weathering

boundary, and providing us an opportunity to further clarify our perspectives of the relationships between GSs and ESs. This indeed aligns with the purpose of Chen et al. (2023) to "stimulate further clarification and refinement of the ES concepts" (p.5).

Before addressing the specific critiques raised by Gray et al. (2024), we would like to clarify an important point. Chen et al. (2023) indicated that "the boundary that separates ESs from other ecosystem-related benefits remains unclear" (p.2). In this sentence, "separates…from…" means the boundary differentiates ESs from other benefits, instead of severing or splitting the connections between ESs and other benefits. We acknowledge that GSs and geodiversity benefit humans in various ways and are indeed essential to the production of ESs. For instance, Chen et al. (2023) recognized that "ecological processes and the production of ESs (e.g., nutrient cycling) may consume minerals (e.g., iron and potassium) in soil" (p.4). The study also noted that "the production of ESs relies partially on interactive processes between different environmental components" (p.3) and "the occurrence of ESs … needs both biotic and abiotic components of ecosystems" (p.4). Accordingly, the viewpoints in Chen et al. (2023) also align with the argument of Gray et al. (2024) that GSs and other abiotic benefits should be recognized and studied in both the ecosystem and non-ecosystem domains. In our view, the point of contention between Chen et al. (2023) and Gray et al. (2024) centers on whether GSs are a subcategory of ESs and whether GSs and ESs can be differentiated. Specifically, Chen et al. (2023) indicated that a boundary differentiating ESs from other benefits, such as GSs, is needed to prevent ESs from becoming an all-encompassing metaphor for any ecosystem-related benefit and to foster a common language for the management, comparison, and communication of ESs. Meanwhile, Gray et al. (2024) suggested that we should adopt a more holistic and integrated approach to involve all natural benefits, including ESs, GSs, and other abiotic benefits, rather than drawing a boundary of ESs.

The answer to the contested point, first, depends on the definitions of ecosystem and of ESs. Gray et al. (2024) considered an ecosystem as "a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit" (CBD, 2010). We also accept this definition of an ecosystem, as Chen et al. (2023) recognized that "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)" (p.4). The ES boundary outlined in Chen et al. (2023) is also based on the understanding that "the occurrence of ESs is affected by ecological processes, functions, or characteristics" (p. 4), which aligns with multiple seminal ES studies (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005; Costanza et al., 2017; United Nations SEEA-EA, 2021). Following this understanding, abiotic benefits, including GSs, are vital to ESs; but not necessarily a subset of ESs. Namely, some GSs can be classified as ESs (e.g., minerals used for plant growth as a supporting service), while other GSs (e.g., provisioning of diamonds) cannot.

2. Further clarification of the ES criteria proposed by Chen et al. (2023)

Chen et al. (2023) explicitly recognized that "ESs can include both biotic and some abiotic flows (e.g., water provisioning)" (p.1), rather than suggesting that any ES purely comprises biotic components or that all ESs must be predominantly biotic. We also agree with the perspective of the Common International Classification of Ecosystem Services Version 5.1 (Haines-Young and Potschin, 2018) that the boundary between biotic and abiotic services is not always clear in the sense that the production of biotic services requires abiotic factors (e.g., water, abiotic nutrients). Arguably, "there is no real-world system in which geodiversity does not in some way directly or indirectly impact on biotic services" (Fox et al., 2020, p. 154). Conversely, geosystems and their services may occur independently of biotic components (Gray et al., 2024). Since abiotic factors are fundamental to both ecosystems and geosystems—encompassing their processes, functions, and characteristics—abiotic factors alone do not differentiate between ecosystems and geosystems. Instead, the key distinction lies in their reliance on biotic factors: ecosystems must involve biotic elements, whereas geosystems may not, although biotic elements may still influence geosystems. This distinction does not attempt to cut apart the interconnections between geosystems and ecosystems; it merely suggests that, in theory, ecosystems and geosystems are not the same.

Therefore, Chen et al. (2023) suggested a criterion that "the occurrence of ESs is affected by biotic parts of ecosystems" (p.1), if ESs are regarded as the benefits whose occurrence is affected by ecological processes, functions, or characteristics. Recognizing ESs' dependence on biotic factors does not deny the role of abiotic factors in producing ESs. Based on this criterion, ESs only exclude certain (not the whole) abiotic benefits, such as solar and wind energy, whose occurrence is unaffected by biotic factors, while allowing for the potential integration of certain GSs into ESs. For example, coastal geological structures may provide flood protection as a GS (Fox et al., 2020). However, when coastal mangroves, seagrass meadows, or coral reefs decrease storm surges and tidal waves, thereby enhancing the quality or quantity of this GS (Costanza et al., 2021; United Nations SEEA-EA, 2021), we can classify this GS as an ES. This example also illustrates that the occurrence of ESs being influenced by biotic elements does not contradict the view that ESs can encompass both biotic and some abiotic benefits.

Note that, as fossil fuels originate from decomposing plants and animals under specific geological conditions and processes (National Geographic, 2023; US Department of Energy, 2023), the provisioning of fossil fuels is a GS whose occurrence is affected by biotic factors. However, this GS is not classified as an ES, because Chen et al. (2023, p. 1) also suggested that ESs are "renewable (having the potential to be reproduced within a conceivable timeframe relevant to human use)". This criterion has been explained in detail in the original paper.

We agree fossil fuels, stones, geological minerals, and other GSs significantly influence the wellbeing of humans and other species and are indeed a subset of nature's services. However, acknowledging the significant role of GSs in producing ESs and other benefits for life on Earth does not mandate labeling all GSs as ESs (we are not saying "no GSs can be labelled as ESs"). This is because people can still study and raise awareness of GSs, as well as issues related to GSs, in both the ES field and other disciplines, regardless of whether GSs are considered a subclass of ESs or a distinct type of benefit. In other words, sufficient recognition of the importance of GSs is not contingent upon their classification as a subset of ESs or the disciplinary field in which they are categorized. Just as acknowledging the significance of non-human species does not necessitate classifying them as a subset of humans, Chen et al. (2023) pointed out: "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" (p.4). There is also no evidence to suggest that using alternative labels or terms for GSs and other abiotic benefits would undermine their significance.

The use of various terms or labels, in the context of this paper, is not meant to suggest that certain benefits are superior to others or to disconnect specific benefits. Rather, it aims to facilitate communication (e.g., between life and social sciences, or between science and society) and management of these benefits in certain contexts. For example, the term "ESs" may highlight the interdependence between humans and the rest of ecosystems (Costanza et al., 2017), while the term "GSs" may link human wellbeing with geodiversity (Gray, 2018). Another term, "critical zone services", focuses on the benefits (e.g., hydrologic partitioning, streamflow generation, geo-tourism) from the near-Earth surface environment that extends from the bottom of the aquifer to the top of the vegetation canopy (Field et al., 2015; Luo et al., 2019; Morante-Carballo et al., 2023). Although ESs, GSs, and critical zone services may overlap, their distinct focuses may potentially serve different purposes in research and policymaking. These examples are just a few of the many potential metaphors describing certain benefits humans receive from nature. Although we admit that such metaphors will not always guarantee transdisciplinary understanding, we do hope they foster more discussion.

3. Responses to more specific issues

Gray et al. (2024) also raised issues associated with multiple specific sentences, paragraphs, and points of view of Chen et al. (2023). Please refer to the original papers for more details. Table 2 summarizes these issues and presents our relevant responses.

4. Conclusion

Conserving and managing nature requires both a generalized approach that encompasses nature's contributions to people as a whole, as well as a specialized approach that classifies or differentiates between nature's specific contributions. These approaches need not be mutually exclusive; rather, they are complementary to each other. Classification and differentiation do not necessarily imply exclusion or disconnection but aim to facilitate effective management, research, policy-making, and inter- and transdisciplinary communication across various purposes and audiences. For instance, ESs and GSs are commonly classified into cultural, provisioning, regulating, and supporting categories. This does not imply that the different categories are always mutually exclusive or disconnected (e.g., collecting wild food may be both a provisioning and a cultural service) but can link ESs and GEs with diverse aspects of human wellbeing, potentially facilitating the formulation of different types of management strategies.

Indeed, GSs and ESs are interconnected, both representing significant contributions that nature provides to humans and even other species. However, if we consider ESs as the benefits affected by ecological functions, processes, and characteristics to occur, GSs are not necessarily a subset of ESs. The keyword is "not necessarily", implying that some GSs can be considered as ESs, while other GSs cannot. Differentiating between ESs and GSs serves the purpose of highlighting and explaining the richness and diversity inherent in nature's benefits, rather than undervaluing nature, dividing nature, or fostering a perception of what Gray et al. (2024) described as "separating out bits of nature", "excluding large sections of nature", or "detriment of a comprehensive view of its importance to society".

Whether establishing a boundary of ESs is beneficial for the conservation and sustainable management of nature's services or benefits, as questioned by Gray et al. (2024), may not warrant further discussion. This is because regardless of whether the answer is "yes" or "no", the boundary of ESs is inherent in the ES concept itself: when we introduce or define ESs or think about whether specific benefits (e.g., energy, minerals, or mental enjoyment) qualify as ESs, we already inherently engage in consideration of the ES boundary. This consideration takes place either in an explicit and more precise way, such as using the criteria proposed by Chen et al. (2023), or in an implicit, arbitrary, and more flexible way, such as classifying a certain benefit as an ES without justification or convincing reasoning. Therefore, a worthwhile further

Table 2
Responses to specific issues.

Issues raised by Gray et al. (2024)	Responses
"Rather than trying to separate out bits of nature in order to draw the boundary of ESs, it is perhaps time to avoid using 'nature' and 'biodiversity' as synonyms and think instead of a more holistic and integrated approach involving 'environmental', 'natural' or 'nature's services." (p.1)	We agree that a comprehensive approach fully involving nature's services is needed. However, further classification of nature's services with different metaphors is also necessary. This is not meant to disconnect these benefits, but to aid in communicating and managing them. If classification means exclusion or severance of connections, the classification of GSs into subclasses (e.g., provisioning, cultural) by Gray et al. (2024) would also exclude and disconnect certain sections of geodiversity and GSs.
"Chen et al.'s world is very different to that described above [which considers both biotic and abiotic components] … Chen et al. define natural capital as 'the stock of ecosystems that yield flows of benefits' … This represents a very limited view of natural capital". Gray et al. suggested that "natural capital includes all natural assets, both abiotic and biotic." (p.3)	Gray et al. (2024) misrepresented the "world" (or the natural systems) Chen et al. (2023) described. As clarified previously, Chen et al. (2023) explicitly recognized that both biotic and abiotic components are integral to ecosystems. Accordingly, considering natural capital as the stock of ecosystems in fact integrates both biotic and abiotic assets and aligns with Gray et al. (2024), rather than being "a very limited view".
"They argue that water storage and provisioning can be regarded as an ES as this refers to 'the storage and supply of potable water regulated (e.g. being intercepted and purified) by functioning ecosystems'. However, this ignores the fact that much storage of water takes place in rock aquifers and much purification of water is achieved as it moves downwards through sediments and rocks towards a water table" (p.3)	The full argument of Chen et al. (2023) was "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" (p.4). This argument already integrates the point Gray et al. (2024) thought was ignored, and better aligns with a common understanding of water-related services as used in the ES literature. A keyword here is "functioning": a functioning ecosystem must involve the life activities of organisms, not only abiotic elements and processes (Jax, 2005; Costanza, 2012). For example, rainfall, which is primarily abiotic, typically is not regarded as a water-related ES, unless it is being intercepted, filtered, or purified by both abiotic and biotic components (instead of by abiotic components alone) to become potable water. Chen et al. (2023) also indicated that "global sources of potable water are often accompanied by well-preserved biotic components (e.g., vegetation) of ecosystems" (p.4).
"Chen et al.'s statement that 'there is a growing recognition that all human wellbeing is fundamentally derived from ecosystems' is an extremely biocentric view of the world in that it largely ignores the contribution that geodiversity and GSs make to human well-being" (p.3)	This statement was actually a report of the opinions of other literature (check references in the original paper). Also, ecosystems in the context of Chen et al. (2023) comprise both biotic and abiotic components, including many geological elements. Hence, Chen et al. (2023) did not ignore the role that abiotic components can play in benefiting humans. Moreover, nowhere in the text did Chen et al. (2023) ever deny GSs' contributions to humans.
"Chen et al. provide a contradictory stance on how the absence of components of nature in ES understanding can lead to its degradation and loss. For example, they claim that 'the benefits from biotic parts of ecosystems to human wellbeing is	While Chen et al. (2023) did not explicitly address the point that neglecting the values of geodiversity could lead to geodiversity degradation and loss, they did not deny or oppose this point either. As a basic logical argument, highlighting the importance

(continued on next page)

Table 2 (*continued*)

Issues raised by Gray et al. (2024)	Responses
often ignored and undervalued, which results in ecosystem degradation and biodiversity loss', yet when discussing geodiversity they state that 'recognition does not necessarily require considering all abiotic benefits as ESs'. So, they acknowledge that excluding biodiversity elements from ESs can contribute to biodiversity loss yet overlook how this exact same scenario could lead to geodiversity degradation and loss" (p.3)	of biodiversity or biotic elements does not deny the importance of geodiversity or abiotic elements. Hence, there was no contradictory stance on how the lack of explicit discussion about a certain component of nature in ES literature could lead to the degradation or loss of the component. Furthermore, Section 2 has explained why recognizing the importance of abiotic benefits does not necessitate labeling all of them as ESs. There is also no evidence to suggest that using alternative labels or metaphors for abiotic benefits would undermine their conservation efforts.
"Much research in nature conservation is recognizing that one way of conserving biodiversity is to conserve geodiversity" (p.4)	We agree that geodiversity conservation may benefit biodiversity conservation. While Chen et al. (2023) did not elaborate this point, they never denied or opposed it. Moreover, geodiversity conservation is necessary, but not sufficient, for biodiversity conservation, which also requires ES approaches that link human wellbeing with functioning ecosystems.
"Chen et al. argue that '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 … In other words, abiotic components alone cannot constitute a habitat without the presence of biotic components'. While this is certainly true, it misses the point that the abiotic world comprises a wide diversity of physical habitats with which biotic nature is inherently connected" (p.4).	The point Gray et al. (2024) thought was missing in fact was already integrated by Chen et al. (2023), who explicitly recognized that abiotic components of ecosystems, such as sand dunes and rocks, may potentially provide a habitat service. Please note the keyword "potentially" here. The viewpoint of Gray et al. (2024), as shown in the left column, merely rephrases the argument of Chen et al. (2023).
"Chen et al. state that '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 … '. In fact, the search for diamonds and gold have influenced human history and settlement as part of important economic cycles in the past." (p.4)	Diamonds and gold are indeed important to human history. However, following this logic of Gray et al. (2024), if we consider something as an ES merely because of their influences on human history, should we classify airplanes and computers as ESs? We doubt this. Also, sufficient recognition of the importance of GSs is not contingent upon their classification as a subset of ESs or a distinct type of benefit.
"Like iron and potassium, copper is an essential nutrient and, therefore, vital to the health of humans, animals, and plants … These elements are transferred into soils during the physical, chemical, and biological weathering of rocks and sediments, are absorbed by plants and then animals by ecological processes and thereafter become human foodstuffs." (p.4)	We agree. Provisioning of the minerals in foodstuffs falls into the ES boundary of Chen et al. (2023), as these minerals are affected, altered, or stored by plants, animals, or ecological processes. Chen et al. (2023) only excluded certain (not the whole) minerals that "occur through geological, physical, or chemical processes, rather than being affected by ecological processes, functions, or characteristics" (p. 4). Also, Chen et al. (2023) explicitly regarded provisioning of biominerals as an ES.
"Chen et al. argue that only renewables should be included as ESs, but it can be argued that it is the non-renewables that should have priority for conservation and sustainable use for the simple reason that many abiotic resources are finite, and will eventually become exhausted and not available to future generations." (p.5)	Chen et al. (2023) recognized that non-renewable resources can contribute to human wellbeing and socio-economic development. We also agree with conservation and sustainable management of non-renewable resources. However, as explained earlier, the importance and effectiveness of their conservation does not depend on whether they are considered ESs.

discussion might be whether we prefer a vaguer and less strict ES boundary (e.g., to expand the scope of usage of the ES concept) as opposed to a more measurable and precise one. If it is the latter one, we propose that the boundary suggested by Chen et al. (2023) is one approach—not the only one—to enhancing the clarity, coherence, and consistency of the ES concept, including its definition and application.

CRediT authorship contribution statement

Haojie Chen: Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Project administration. **Matthew R. Sloggy:** Writing – review & editing, Funding acquisition. **Francisco Escobedo:** Writing – review & editing. **Teemu Koskimäki:** Writing – review & editing. **Tianchu Lu:** Writing – review & editing. **Ziqi Meng:** Writing – review & editing. **A. Rifaee Rasheed:** Writing – review & editing. **José J. Sánchez:** Writing – review & editing. **Xin Tan:** Writing – review & editing. **Weishan Yang:** Writing – review & editing. **Fang Yu:** Writing – review & editing. For emphasis, Haojie Chen proposed the main points of this paper, conductd the original drafting, and made the most significant intellectual contributions.

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.

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