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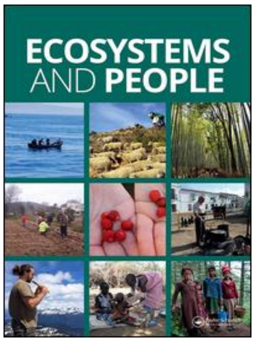

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Incorporating geodiversity in ecosystem service decisions

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ABSTRACT

Holistic conservation of ecosystem services (ES) requires a greater understanding of how the interactions of biotic and abiotic aspects of nature provide them. Currently, geodiversity, the diversity of geology, geomorphology, sediments and soils and hydrology, as well as the services that they provide in isolation of interactions with biotic nature – geosystem services (GS) – are overlooked in ES literature and frameworks. Here, we provide a series of three nested frameworks which together help to provide clarity for both the theoretical role of geodiversity in service production as well as the basis for real-world management strategies. First, we present the 'Geodiversity Flower', a framework that can be operationalised to provide clarity in terminology to decision-makers. Second, we present the 'Geo-Eco Services Framework', which establishes the difference between ES and GS. The final framework presented is the 'Geo-Eco Services Cascade Model', which builds upon the widely used ES cascade model by demonstrating how geodiversity interacts with biotic nature to simultaneously provide ES and GS. Providing a holistic model that integrates both biotic and abiotic nature alongside ES and GS allows for a greater understanding of the roles of abiotic and biotic nature to services and their associated benefits and values to people.

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1. Introduction

In the face of environmental change and the human exploitation of natural resources, there is a need to understand and manage the range of ecosystem services (ES) that benefit humankind, as well as to conserve the natural features and processes that produce them. Ecosystems are not only defined by a biological community of an area, but through the interactions of both biotic and abiotic nature. It is these interactions between the living and non-living aspects of nature that contribute to the delivery and maintenance of ES (Gray 2012; Gordon and Barron 2013). It is increasingly recognised that geodiversity actively contributes to a wide range of ES across all service categories (Prosser 2013). Geodiversity is the diversity of geological structures and processes, including rocks and minerals; geomorphology, including landforms and topography; sediments and soils, including formation processes; and hydrology, including marine, surface and subsurface waters (Gray 2013; Hjort et al. 2015). Geodiversity plays both direct and indirect roles in the delivery and maintenance of ES (Gordon and Barron 2013). The direct role of geodiversity in ES production occurs when interactions between abiotic and biotic elements of nature produce a final ES, such as the flow of rivers dispersing the seeds of hydrochorous plants (Table 1). Geodiversity also provides 'supporting or intermediate services' which indirectly regulate ES. It can be argued that these supporting services supplied by geodiversity underpin almost all ES, for example the abiotic elements of soils provide key minerals, nutrients and water required to sustain living things – which illustrates the supporting role of geodiversity in providing the physical platform for the ecological functions that produce ES (Parks and Mulligan 2010; Hjort et al. 2015; van der Meulen et al. 2016). Furthermore, geodiversity, through the creation of a diversity of resources and niches (Parks and Mulligan 2010), passively underpins many aspects of biodiversity including species richness (Hjort et al. 2012; Bailey et al. 2017), functional trait diversity (Cheesman et al. 2018) and phylogenetic diversity (Pepper et al. 2013). These facets of biodiversity in turn underpin ecosystem functioning and services (Edwards et al. 2014). However, both the active and passive roles of geodiversity are generally excluded from ES assessments (Gray 2018).

Geodiversity also contributes to a range of benefits to humans independent of interaction with biotic nature, which are often referred to as geosystem services (GS) or abiotic ecosystem services (Gray 2012; Van Ree and Van Beukering 2016). There are a wide range of GS, including the provision of rare-earth metals, regulation of thermal flows and sites of cultural significance (Van Ree and Van Beukering 2016). However, these benefits are not

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Supplemental data for this article can be accessed here.

Table 1. The active role of geodiversity in ES production.

Service listed as 'biotic' in Haines-Young and Potschin (2018)	The active role of geodiversity in service production and maintenance	Reference
Animals reared by in-situ aquaculture for material purposes (Provisioning)	Provision of non-soil nutrients – e.g. marine calcium carbonate required for coral aquaculture	Barton et al. 2015
Seed dispersal (Regulating)	Transportation of seeds by geomorphological and hydrological factors – e.g. hydrochorous plant (plants that are dispersed by water i.e. coconuts)	Araujo Calçada et al. 2015
Bioremediation by microorganisms, algae, plants, and animals (Regulating)	Temperature regulation of chemical and biological reactions – e.g. heat storage capacity of different soil types	Miri et al. 2019
Disease control (Regulating)	Geological and hydrological influences on the epidemiology of diseases e.g. transmission of disease by hydrological systems	Gordon and Barron 2013
Characteristics of living systems that enable aesthetic experiences (Cultural)	Provision of different opportunities for aesthetic experiences e.g. wildlife watching facilitated by flat land vs panoramic views facilitated by higher altitudes and rough topography	de Almeida Rodrigues et al. 2018
Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge (Cultural)	Understanding historic trends in ES e.g. information on environmental and ecological changes contained in paleo-sediments	Jeffers et al. 2015

typically classed as ES due to the absence of any interaction with biotic nature. The absence of biotic interactions should be reflected in their terminology. The term ecosystem is misleading in this context and so we prefer the term GS to abiotic ecosystem services. Though the term GS has been used to define subsurface services (services occurring below the pedosphere) (Van Ree and Van Beukering 2016), here we define it as all services associated with geodiversity independent of interactions with biotic nature (Gray 2011).

The current biocentric focus of ES literature potentially omits the value of services driven by geodiversity from any economic assessments and management strategies. This issue is exemplified by the plethora of frameworks that link biotic nature with ES (e.g. Swift et al. 2004; Tallis et al. 2008; Mace et al. 2012; Díaz et al. 2018), and the relatively few that directly acknowledge the role of geodiversity in ES delivery and maintenance (Van Ree and Van Beukering 2016; Van Ree et al. 2017; Gray 2018; Potschin-Young et al. 2018). Specifically, no framework yet exists that operationalises the linkages and interactions between geodiversity and biotic nature as well as the interactions of ES and GS within a single framework.

One framework that has included geodiversity (Van Ree and Van Beukering 2016) identified the contribution of geodiversity to the provision of GS. However, the framework represents the flow from abiotic components to GS as a separate system, which fundamentally ignores the importance of the interactions between abiotic and biotic components in underpinning ES (e.g. nutrient and habitat provision or biological weathering) as well as trade-offs between ES and GS (e.g. competition for space). The exclusion of GS from ES literature and frameworks means that decision-makers may not be fully informed of the importance of geodiversity in the delivery of these valuable services, nor the trade-offs caused by management decisions (van der Meulen et al. 2016). Here, we introduce three nested concepts which enable the un-packing of the roles of biotic and abiotic nature in service provision and together provide a conceptual framework enabling a more holistic approach to management decisions.

2. The geodiversity flower

The first obstacle to including geodiversity into an ES framework is a lack of clarity in geodiversity terminology. Geodiversity is highly multifaceted (Serrano and Ruiz-flano 2007; Parks and Mulligan 2010; Gray 2013; Ruban 2014; Bailey et al. 2017), with studies defining geodiversity using different combinations of components. This means terminology surrounding geodiversity may not be transparent to policy-makers and resource managers. We address this issue here with what we call the 'Geodiversity Flower' – a framework designed to provide a clear and flexible description of the components of geodiversity (Figure 1). We represent the structures and processes of geodiversity as petals in the Geodiversity Flower. Intersecting petals indicate the interactions and combinations of two or more geodiversity components. As previous studies have used different combinations of these components to define geodiversity, based on their specific geographic extent and aims (Serrano and Ruiz-flano 2007; Bailey et al. 2017), we do not aim to be prescriptive in our definition – our approach is flexible and allows for studies to contextually define geodiversity, whilst providing clarity. Our definitions for the main components of geodiversity are designed to be broader than other frameworks, for example Hjort et al. (2015), includes topography as a standalone component. Here, we argue that geomorphology can be a broadly applied category that encompasses physical landscape features including topography. Furthermore, to better include other sediments, including marine sediments, we have updated the labelling of soils to sediments and soils. Though the regions of the Geodiversity Flower with the most overlapping segments indicate a more holistic definition of geodiversity, the term can be applied to any of the regions – including those

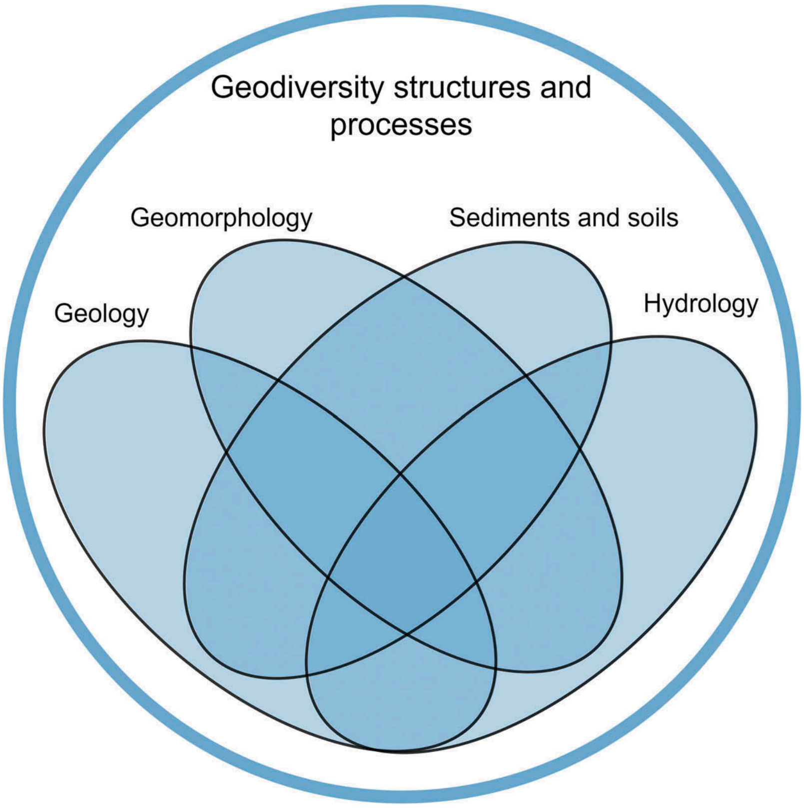

Figure 1. The Geodiversity Flower unpacks geodiversity into petals representing each of its major features, geology, geomorphology, sediments and soils and hydrology. The intersections between petals represent their combinations and interactions, whilst the term geodiversity can be applied to represent the diversity in any single petal or any variation of the intersections of petals.

representing single components. To define geodiversity clearly and consistently, the Geodiversity Flower can be operationalised by highlighting which intersections have been used to define geodiversity, thus providing better clarity to policy-makers and resource managers and allowing for better integration of the term into an ES framework.

3. The ES-GS framework

Another issue with mainstreaming geodiversity in ES assessment is that the position of geodiversity and GS within current ES science remains confused. The position of GS varies between different ES frameworks. Frameworks, for example, the Millennium Ecosystem, Assessment (Millennium Ecosystem Assessment 2005) and the Common International Classification of Ecosystem Services V5.1 (CICES) (Haines-Young and Potschin 2018) recognise services provided by hydrological features and processes, such as coastal and marine water used as an energy source, as an ES. Conversely, though the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al. 2015) acknowledges that services can be delivered without interaction with living-components of nature (i.e. aquifers and minerals), it does not include these services in its scope and only focuses on services that involve interactions with biotic components. This multifaceted approach to the inclusion of GS by frameworks presents a confusing picture to decision-makers as to whether these services are important or not. Moreover, IPBES and The Economics of Ecosystems and Biodiversity (Kumar 2010) both contain the word 'biodiversity' in their names, exemplifying the biocentric viewpoint that biodiversity is the only aspect of nature governing ES.

As well as a varying position between frameworks, GS position remains confused within frameworks. For example, CICES (Haines-Young and Potschin 2018) has started to acknowledge 'abiotic services', though only through additional material, and while still maintaining a focus on 'living processes'. Though CICES now rightly labels services associated with water as 'abiotic services', recognising they are primarily driven by hydrology and geomorphology, it elevates services such as surface water for drinking and groundwater used as an energy source alongside 'biotic services' and separates them from others driven by geodiversity. For example, the maintenance of soil quality is still classed as a 'biotic service' – ignoring the fact that soil quality and quantity are also driven by geodiversity. This is partly due to the role of geodiversity in supporting or intermediary services not being included in the scope of CICES. Moreover, the labelling of ‘abiotic services’ is confusing and does not give clarity to whether these services are being viewed as ES or GS. While CICES highlights that the boundary between abiotic and biotic services is blurred and cannot be defined practically, it goes on to then create a dichotomy between ES and GS. We suggest that this classification of what counts as a service is artificially constructed and inconsistently applied. If services driven by water, an abiotic component, are considered in tandem with ES then why are other abiotic services such as mineral fuels and ornamental materials from geological features disregarded? To provide consistency across all services, GS should be clearly distinguished from ES that are primarily driven by abiotic features and processes.

To address the confusion between GS and ES driven by geodiversity, we present the Geo-Eco Services Framework – a conceptual framework aimed at providing clarity to the differentiation of ES and GS (Figure 2). In Figure 2a the overlapping segments indicate the interactions between biotic nature and geodiversity where combinations of these interactions can give rise to ES. The non-overlapping geodiversity segment of the Geo-Eco Services Framework can be explicitly labelled as GS, representing services that can be delivered and maintained in the absence of biotic nature. Figure 2b demonstrates that ES can be primarily driven by either abiotic or biotic features and processes, with ES primarily driven by geodiversity being fundamentally different to GS as they require interactions with biotic nature to be delivered and maintained. Here, we note that there is no real distinction between ES that are primarily driven by geodiversity and those that are primarily driven by biotic nature and both should be equally viewed as ES. The value in highlighting this difference are the implications for better targeting management strategies – i.e. if an ES is mainly influenced by abiotic elements, management strategies should have a greater focus on these elements over biotic nature.

The Geo-Eco Services Framework further highlights that geodiversity (either directly or indirectly), is fundamental for ES delivery and maintenance. We include ‘biosystem services’ as a theoretical concept only – though these standalone biotic services could exist, we would argue that there is no real-world system in which geodiversity does not in some way directly or indirectly impact on biotic services. For example, ES such as medicinal materials from plants are mainly driven by biotic features and processes, however, geodiversity still plays an integral role in the delivery of such services by providing necessary supporting services such as water and nutrients. In contrast, GS such as construction materials and hydroelectric power can exist in the absence of interaction with biotic nature. However, because of the complexity in the interactions between abiotic and biotic nature in real-world systems, we acknowledge that most GS will be in some way influenced by biotic nature. Moreover, depending on the interactions that give rise to the service some services can be classified either as an ES or a GS (Figure 2c). For example, flood protection could be provided as a GS through coastal geology and geomorphology reducing wave action or flood protection could be an ES, delivered

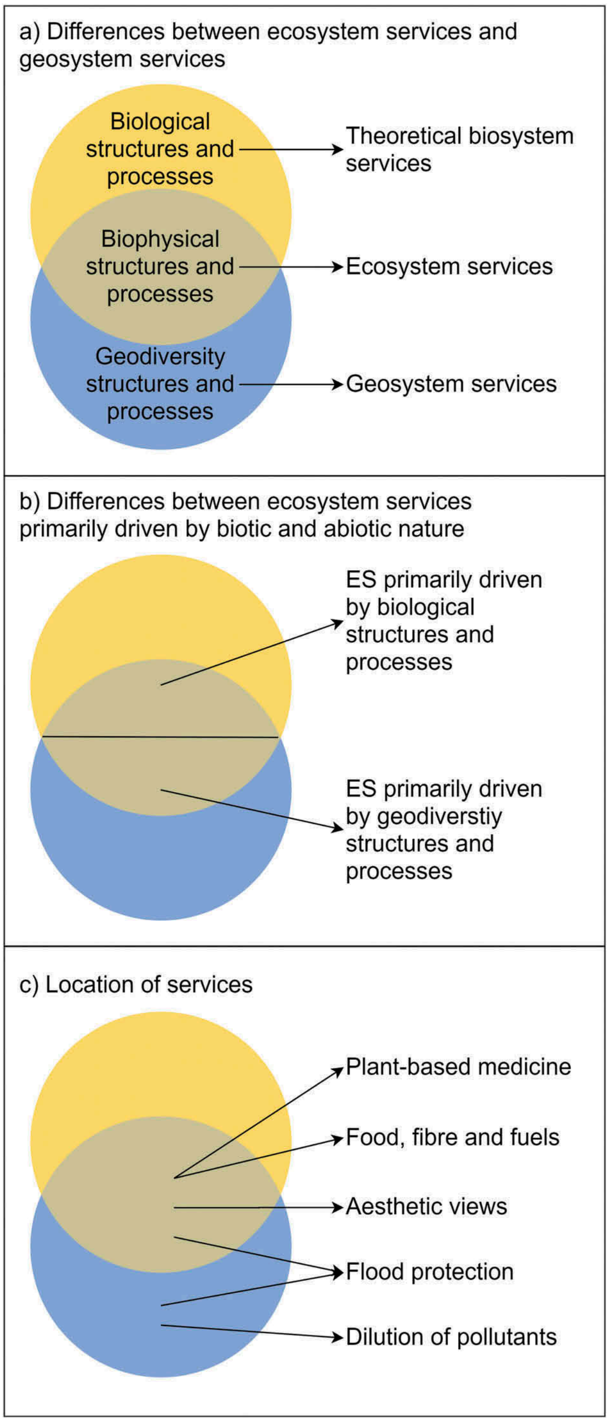

Figure 2. The Geo-Eco Services Framework, a) the different aspects of nature contributing to ES and GS, b) the difference between biotic driven ES and geodiversity driven ES, c) the hypothetical location of a range of services. While biosystem services presented in panel a are theoretically possible, the authors can think of no realised examples for panel c.

through the interactions of river geomorphology and riparian vegetation to slow the flow of a river.

4. The geo-eco services cascade model

The seminal ES 'cascade model' framework introduced by Haines-Young and Potschin (2010) demonstrates the relationship between biophysical structures and processes, ecosystem function, ecosystem service, benefit and value acting as a production chain, stepwise linking them in a cascade (De Groot et al. 2010; Potschin and Haines-Young 2011; Maes et al. 2012). The cascade model attempts to acknowledge the role of geodiversity and places biophysical structures and processes as the drivers of ES, however, the overarching theme places emphasis on the role of biotic nature. This is confounded by a lack of clarity in the terminology of biophysical structures and process which is often only associated with biodiversity (La Notte et al. 2017). By incorporating biophysical structures, the original cascade model and the updated versions that start to incorporate geodiversity and GS (Van Ree and Van Beukering 2016; Potschin-Young et al. 2018) provide a good foundation for the holistic integration of both geodiversity and GS within an ES framework.

Here, we include geodiversity in the cascade model by considering its interactions with biotic nature as the primary driver of the multiple cascades, both ES and GS (Figure 3a). Our Geo-Eco Services Cascade Model provides an organising structure helping to clarify the role of geodiversity in ES and GS production (Potschin-Young et al. 2018). By acknowledging ES and GS in tandem, our integrated services framework can also be applied to assess the trade-offs between multiple services (Lin et al. 2018). Though here the basic framework is displayed by three parallel cascades, we acknowledge that the system is neither linear nor isolated and that ecosystem functions, services and benefits from separate cascades may all interact with each other (see Figure 3b). Figure 3b does not include all possible interactions, but instead acts as an illustrative example of the potential application of the Geo-Eco Services Cascade Model rather than an exhaustive map of the pathways by which services are affected by upstream gravel extraction from a mangrove system – we unpack this further below (for further example applications see Supplementary Materials Figure S1-S3). To allow for a completely holistic approach, in Figure 3a we have again included the theoretical 'biosystem services', however in the real-world example in Figure 3b this pathway does not exist.

Our holistic framework therefore provides the conceptual foundations for hypothesis testing and quantitative assessment of the roles of abiotic and biotic components in service provision using methods such as generalized additive models (Alahuhta et al. 2018), mathematical equations (Maseyk et al. 2017), structural equation models (Deru et al. 2018) and Bayesian Belief Networks (Landuyt et al. 2013). Furthermore, as our framework allows for multiple interconnected cascades, we have also updated the previously labelled 'pressures' box (Haines-Young and Potschin 2010), to represent 'drivers of change', as a threat to one cascade may be beneficial to another. By updating the original cascade model to include drivers of change for multiple services the framework can be employed as an analytical framework aimed at guiding testable hypotheses about different management strategies (Potschin-Young et al. 2018; Spake et al. 2019).

5. Application of the framework for ES management

A concern with ES management is that some components of nature are unmanageable (Maseyk et al. 2017). Some abiotic aspects of soils, such as the physical processes governing the weathering of bedrock, are not practically manageable. However other aspects, such as soil mineral and water content, can be easily altered (Maseyk et al. 2017). Moreover, aspects of geomorphology can be manipulated for ES management, such as agricultural terracing to reduce soil erosion and water conservation (Ponette-González et al. 2015). The issue of unmanageable aspects is not unique to geodiversity and is shared by biotic elements such as trophic interactions. Therefore, like biotic nature, the trade-offs in both the manageable and unmanageable aspect of geodiversity need to be considered in ES management decisions (Maseyk et al. 2017; Spake et al. 2019).

Another challenge to managing GS and ES are the temporal differences between the replenishment of GS and ES. Generally, services that are primarily driven by abiotic nature occur over longer timescales than those that are primarily driven by biotic nature (Gray et al. 2013) (Figure 4). This is because the formation of geodiversity components vs biological components that are then drawn on to form the service may take a long time due to difference in geological and biological timescales. However, the use of ES and GS occurs at the same or similar socio-economic timescales. When services fall under both the GS and ES definition (for example, ornamental materials may be an ES, e.g. corals, or a pure GS, e.g. semi-precious stones), and the GS is non-renewable on a human time scale (centuries, decades or less) they tend be disregarded from ecological assessments (Gray et al. 2013; Brilha et al. 2018), arguably making their preservation even more important. However, the renewability of biotic features and processes providing services can be just at risk as abiotic features and processes. For instance, the renewability of

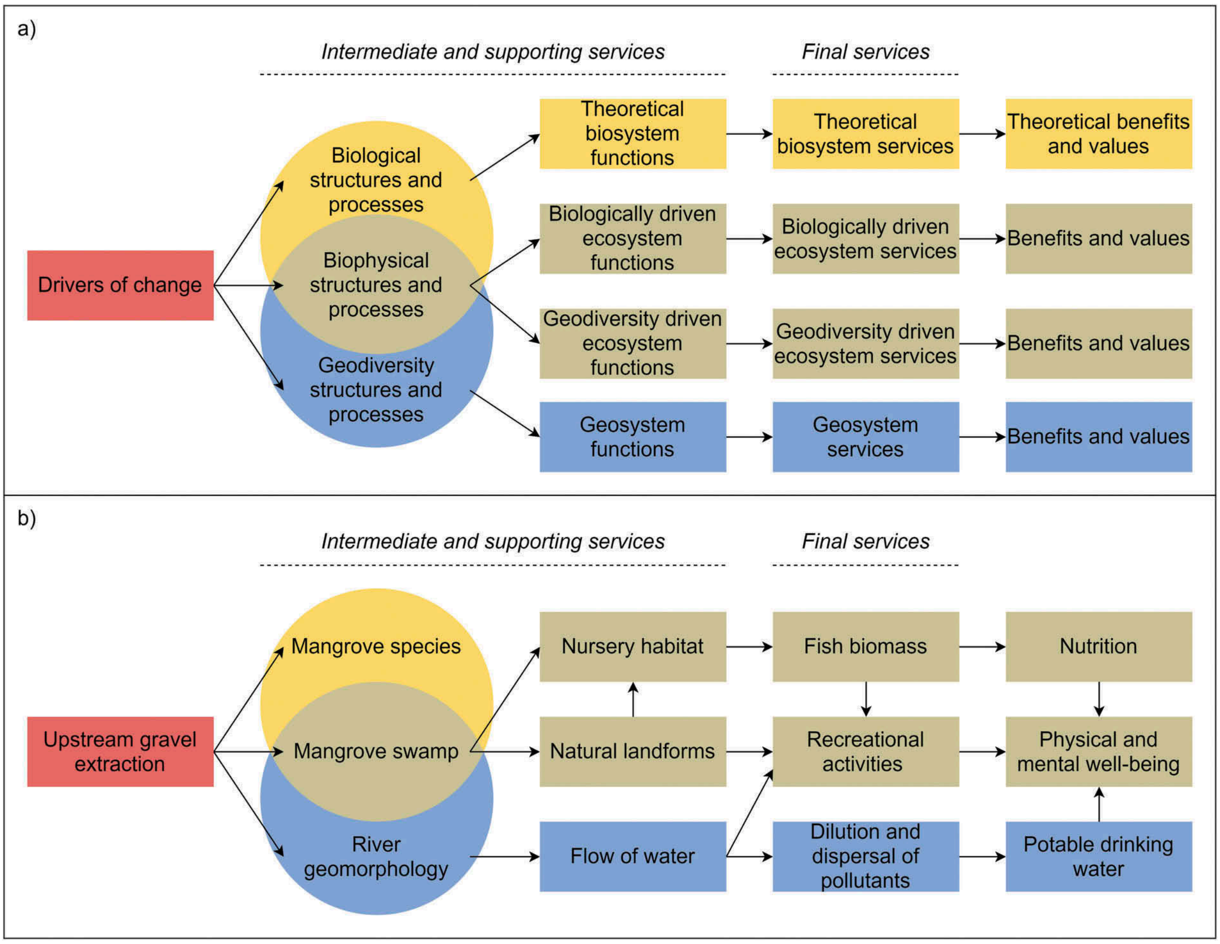

Figure 3. The Geo-Eco Services Cascade Model, after Haines-Young and Potschin (2010), a) proposed updates to the cascade model, demonstrating the flow of both ES and GS services from the interactions of abiotic and biotic nature, b) application of the framework to a real-world ecosystem – mangrove swamps. We note that the applied framework does not represent the whole system, but instead represents some of the potential interactions and services.

agricultural products could be diminished if we do not sustainably manage underlying supporting services, such as soil quality (Crenna et al. 2018). Both the economic and environmental trade-offs of prioritising short-scale services over relatively longer scale services should therefore be appropriately considered during ES decision making.

Figure 3b demonstrates how the application of the Geo-Eco Services Cascade Model for assessing a real-world ecosystem, mangrove swamps, can overcome both challenges. The mangrove swamp ecosystem is comprised of manageable and unmanageable aspects of nature as well as their associated services which occur over a range of temporal and spatial scales. In a real-world application, the cascades are not as linear as the blank framework template. The geosystem function ‘flow of water’ not only provides its own separate GS of ‘dilution and dispersal of pollutants’, by diluting the concentration of pollution, regardless of any biotic processes, but also contributes to an ES of recreational activities, i.e. boating and swimming. Furthermore, services can interact, with fish biomass (facilitated by fish population or diversity) interacting with boating (facilitated by navigable bodies of water) to present additional opportunities for recreational activities such as fishing. By including drivers of change, the framework can be utilised to assess the potential impacts of proposed anthropogenic activities on the provision of multiple services. For example, here the Geo-Eco Services Cascade Model allows for consideration of both the direct and indirect impacts of upstream gravel extraction on the entire system from biological, geodiversity and biophysical structures and processes to ES and GS and their benefits and values. With the addition of empirical data the Geo-Eco Services Cascade Model could be implemented to assess how short-term increases in sediment transportation from gravel extraction may impact mangrove species growth rates and the ES they provide (Noor et al. 2015), or how long-term decreases in sediment transportation could alter the geomorphology and natural landforms and thus long-term ES and GS delivery and maintenance.

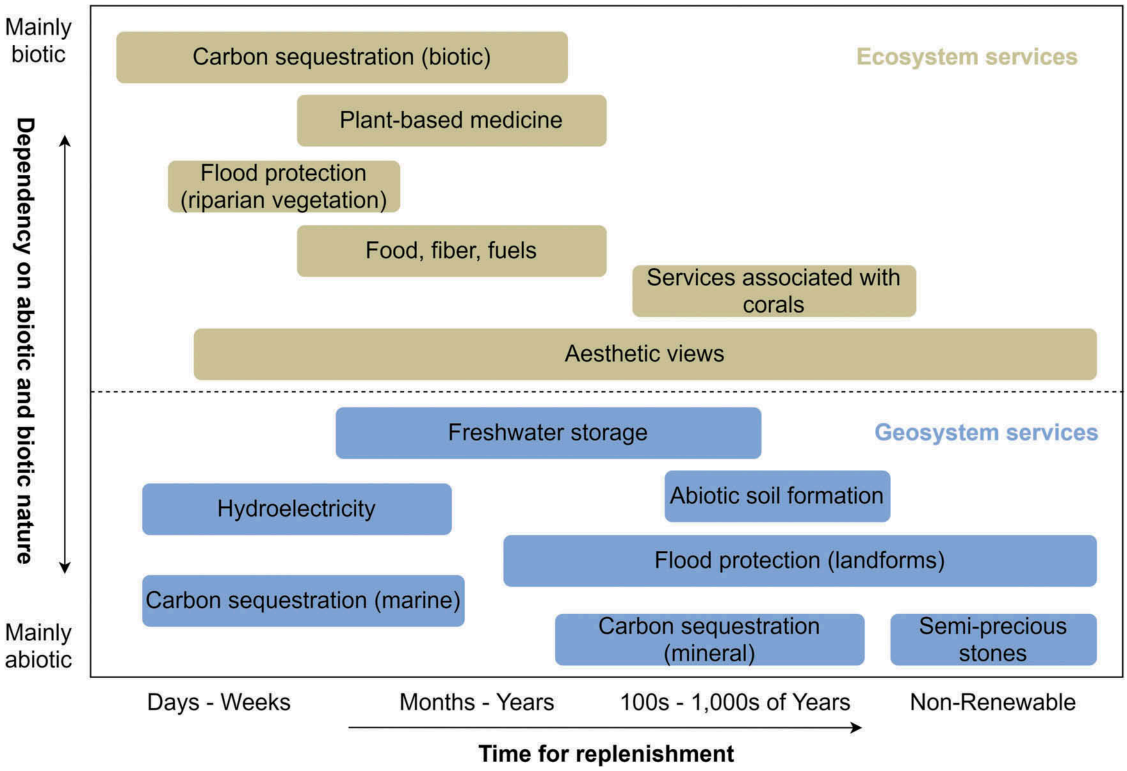

Figure 4. Time taken for the replenishment of a range of ES and GS and their dependencies on abiotic nature. Here, services are placed on a general timescale, but these timescales may vary.

6. Moving forward: applying the framework

As geodiversity and GS are omitted from most ES literature and frameworks, ES policy and decisions often place focus on the management of living systems. This current fragmentation of management and policy impedes efforts to halt and reverse declines in ES. Without consideration of GS, there is the risk that ES management will generate conflicts between ES and GS, such as destruction of natural landforms by human constructed flood defences. Therefore, ES management decisions need to incorporate the role of geodiversity in the delivery and management of both ES and GS. By providing consistency and clarity to geodiversity terminology through the Geodiversity Flower, geodiversity can be better integrated into ES science, policy and management in a more transparent manner.

By taking account of abiotic and biotic nature, as interacting components, our work builds upon the successful cascade framework and provides a novel update that acts as an organising framework, providing clarity regarding the conceptual role of geodiversity in ES production. Through the provision of an organising structure, our updated cascade model also provides the foundations for empirical studies evaluating the relationship of abiotic and biotic nature to ecosystem function, service, benefit and value. By updating threats to include all drivers of change, both positive and negative, as well as providing scope for multiple cascades for different ES and GS, our Geo-Eco Services Cascade Model allows for a greater understanding of trade-offs. Utilising our framework allows for stakeholders to empirically test the impact of proposed service use and management strategies on multiple services. We recommend that future studies build upon this framework using empirical methods to advance our knowledge of the functional links between abiotic and biotic nature, and socio-economic and socio-cultural systems.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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