

Biogeomorphology in the Anthropocene: A hierarchical, traits-based approach

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ABSTRACT

The complex web of interactions between ecological communities and the physical landscape (biogeomorphology) is being affected by the global scale environmental changes of the Anthropocene. Climate change, habitat destruction, invasions and extinctions are having profound impacts on biogeomorphological process regimes through changes in the composition and activity of ecological communities. However, on the other hand, deliberately-targeted human interventions to biogeomorphic systems have the potential to help mitigate against, and adapt to, the Anthropocene, by managing biogeomorphic processes to enhance resilience. To evaluate these relationships, we propose a conceptual framework based on the ecological concept of functional traits. We review how the Anthropocene is causing changes in species composition, abundance and the prevalence of functional traits to produce changes to biogeomorphic processes and functions that are, as yet, only partly understood. We use examples of fluvial, dryland and coastal biogeomorphic systems to illustrate how purposeful manipulation of biogeomorphic systems (as a type of Nature-based solution) can conserve, enhance or add biogeomorphic functions that are capable of enhancing geomorphic resilience. By focussing on function, this approach offers a range of advantages/avenues for biogeomorphological research. This includes the detection and prediction of human impacts, and an improved understanding of how biogeomorphology can contribute to tackling environmental challenges in the Anthropocene.

1. Introduction

Life and landscape are intimately linked in multiple and complex ways. Many plants, animals and forms of microbial life contribute to geomorphological processes, whilst on the other hand, landforms and the dynamics of the physical landscape exert strong controls over the nature and function of ecosystems. These linkages have been well-studied by geomorphologists, ecologists and others, often under the broad heading of biogeomorphology. Much progress has been made in understanding links between some taxa and geomorphology – such as the roles played by individual ant species like *Lasius flavus*, which creates mounds in grassland areas (Bierbaß et al., 2015), non-arboreal genera of ants more widely (Viles et al., 2021), and other insects as a large and diverse group of organisms (Bétard, 2021). An extremely diverse array of taxa is significant biogeomorphic agents across a very wide spectrum of environments (as depicted in Fig. 1). Increasingly, a ‘deep time’ or evolutionary view of biogeomorphology is being developed, indicating the co-evolution of life and landscape (Corenblit et al., 2021). Several recent reviews have summarised the current state of

biogeomorphology and its future prospects (e.g., Larsen et al., 2021); however, there is still a lack of understanding of the web of biogeomorphological interactions within many ecosystems, and what the global significance of such interactions might be.

One particularly under-researched area within biogeomorphology is the role of human activity within the context of the Anthropocene. Although the Anthropocene remains an informal, rather than formally accepted, geological epoch, with considerable dispute about when it might have started and what it might mean (Zalasiewicz et al., 2021), there is general agreement that humans are now having truly global and significant impacts on the Earth system. In particular, human activities are known to be affecting global climate and biodiversity through change to land use and perturbations to biogeochemical and hydrological cycles (Malhi, 2017). These global-scale changes to the Earth system are, in turn, having impacts on geomorphology (Brown et al., 2017) and biogeomorphological systems, functions and services. While human influences on landscapes in the Anthropocene more generally have been addressed by Goudie and Viles (2016), there has been little consideration of how biogeomorphic systems are being affected by these global-

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scale human impacts (although see [Butler et al. \(2018\)](#) for a review of human impacts on zoogeomorphology over varying timescales in the Anthropocene). Nor has there been a synthesis and critical analysis of how biogeomorphic systems might contribute to the successful implementation of Nature-based Solutions (NbS) for environmental management.

In this literature review-based paper, we aim to address these knowledge gaps by assessing the state of the art and proposing a conceptual framework for biogeomorphology in the Anthropocene based on ecological functional traits. We then use this framework to explore (a) how biogeomorphic functions are being affected by the widespread impacts of environmental change in the Anthropocene, and (b) how biogeomorphic functions can be manipulated (conserved, enhanced, restored or created) to deliver ecosystem services that help mitigate against, and adapt to, the environmental consequences of the Anthropocene by creating more resilient landscapes.

2. Functional traits and biogeomorphology

For biogeomorphology, environment-based (e.g., coasts, rivers, hillslopes, etc.) and process-based (e.g., bioerosion, bioprotection and bioconstruction) systems of classification have proved useful conceptual frameworks over the last few decades ([Corenblit et al., 2008](#); [Larsen et al., 2021](#); [Naylor et al., 2002](#)). Building on these, and mirroring developments within ecological theory, a shift in attention towards biogeomorphic *function* offers several advantages and new avenues for research and application ([Coombes, 2016](#); [Corenblit et al., 2015](#); [Viles, 2019](#)). This is particularly true in the context of the Anthropocene, both for identifying the ways in which human impacts modify biogeomorphic system functioning and for identifying those communities, species and associated functions critical to regulating ecosystem services in the face of human-driven environmental challenges. [Table 1](#) summarises the key ecological concepts used in this paper (biological traits, ecosystem processes, functions and services), their meaning, the organisational levels at which they are most relevant, and how they can be applied more specifically to biogeomorphic systems.

One important distinction made in [Table 1](#) is between biogeomorphic processes and biogeomorphic functions. Partly, this is a

Table 1 Key ecological concepts as applied to understanding biogeomorphic systems.			
Name	Meaning	Key biogeomorphic categories	Organisational level
Biological traits	Morpho-anatomical, behavioural and physiological characteristics of species	Functional effect traits Functional response Feedback traits (Corenblit et al., 2015)	Species/ community
Ecosystem processes	Translocation and transformation of energy and matter by physical, chemical or biological action	Bioturbation Bioerosion Bioweathering Bioconstruction Bioprotection Biofiltration (Mason and Sanders, 2021)	Community/ ecosystem
Ecosystem functions	Regulation of stocks of energy and matter and dynamics over time	Biogeomorphic functions include: <ul style="list-style-type: none">Fluid flow disruptionSediment dynamics effectsBiogeochemical cyclingGeodiversity effects	Ecosystem
Ecosystem services	Ecosystem processes and functions that sustain and fulfill human life	Regulating and supporting services involving biogeomorphic systems	Global

distinction according to scale and organisational level, with processes being observed and studied over smaller spatial and temporal scales and often relating to individual species or communities, and functions affecting whole biogeomorphic systems over time. While biogeomorphic processes have been well-studied and categorised following various schemes, biogeomorphic functions have received less attention and no standard terminology or approach has been proposed. Here, we simply conceive of biogeomorphic functions as involving impacts on fluid flow (be it air or water), impacts on sediment dynamics (enhancing or retarding erosion, transport and deposition), impacts on biogeochemical

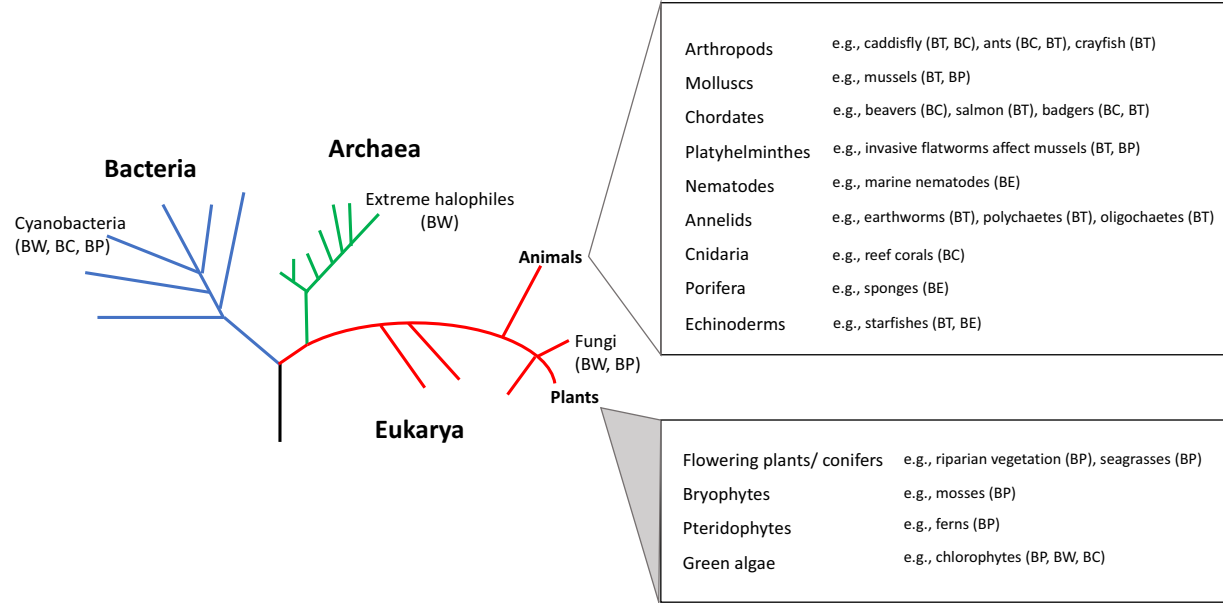


Fig. 1. Visualization of the range of life forms involved in biogeomorphology, portrayed using a phylogenetic tree based on rRNA data showing Woese's three-domain system. Named branches are those that are known to be of biogeomorphological importance, examples of activity given. BW = bioweathering, BE = bioerosion, BP = bioprotection, BC = bioconstruction, BT = bioturbation. Animal and plant panels show the major phyla/informal plant groups ranked by number of current species (top = highest rank).

cycling, and effects on geodiversity (by which we mean increasing or decreasing surface complexity).

In ecology, trait-based approaches (in contrast with species- and trophic-based approaches) have become well established (Garnier et al., 2015; Zakharova et al., 2019) with a recognition that the characteristics ('traits') of species, populations and communities underpin ecosystem processes and functions and, therefore, system dynamics and resilience (Schmitz et al., 2015). As Wilkes et al. (2020, p. 2) put it, "Trait-based ecology uses the phenotypic characteristics of organisms to study biodiversity responses to environmental change". Trait-based approaches originally developed within plant ecology, but are now commonly also applied to microbial and animal taxa (see, for example, Krause et al. (2014) on microbial functional traits, Ellis et al. (2021) on lichen traits, Retana et al. (2015) on ant traits, and Brousseau et al. (2018) on the functional traits of terrestrial arthropods). Biological traits are well-defined and measurable life-history/phenological, morphological, physiological or behavioural attributes of organisms, such as body size, reproductive rate, feeding habit, etc. (Degen et al., 2018). Although often discussed at the level of individuals, as Corenblit et al. (2015) note, the trait concept can also be applied to populations and communities. From a practical point of view, a useful distinction can be made between 'hard' (often physiological) traits that are relatively time-consuming or expensive to measure, such as photosynthetic rate, and more easily measured 'soft' (often morpho-anatomical) traits, such as leaf area and body size. Whilst hard traits are more directly linked to ecosystem processes and functions (e.g., photosynthesis and biogeochemical cycling), soft traits offer more practical surrogates for research (Belluau and Shipley, 2018).

Biological traits are considered 'functional' where they influence the local-scale transformation or translocation of energy and matter (termed ecosystem processes) and the regulation, cycling and dynamics of these stocks at larger spatiotemporal scales (termed ecosystem functions) (Degen et al., 2018; Zakharova et al., 2019). For example, as a component of primary production (an ecosystem function), rates of photosynthesis (an ecosystem process) are influenced by multiple plant functional traits including leaf size, shape, stomatal density, etc. A further distinction can be made between those functional traits that determine the impacts of species on their environment ('effect traits') and those that determine their responses to disturbance and environmental change ('response traits') (Lavorel and Garnier, 2002; Zakharova et al., 2019).

Despite these relatively simple descriptions, functional traits are complex, and many questions remain about how traits vary within and between species, and across scales (Messier et al., 2010; Violle et al., 2012). Interest has also grown in how some taxa can mediate traits in others, such as the role of microbes in influencing plant functional traits (Friesen et al., 2011). Interest has also grown in phenotypic plasticity, or how environmental change can cause alterations in functional traits (Matesanz et al., 2010). How easy it is to make predictions about the ecological impacts of environmental change based on functional traits is also an open question (McGill et al., 2006). As interest in functional traits has grown, so have disagreements among ecologists about trait definitions and terminology (see Violle et al. (2007) and Dawson et al. (2021) for useful reviews). Geomorphologists wishing to engage with trait-based approaches need to be aware of these ongoing developments and debates within functional ecology.

Trait-based studies are becoming easier now that there are a wide range of openly-available trait databases, such as the coordinated TRY database, which is a distributed global plant traits database established in 2007 (Kattge et al., 2020), and more recently CESTES (Jeliazkov et al., 2020), which is a live, global database of 80 databases covering a wide range of taxonomic groups. Some global databases are also available for particularly biogeomorphologically important organisms, such as ants (the GlobalAnts database, see Parr et al., 2017). Regional databases of biogeomorphologically important organisms are also available, such as BIOTIC and ARCTIC, which cover the traits of benthic species in the UK

and Ireland and around the Arctic, respectively (Degen and Faulwetter, 2019; Hiscock and Tyler-Walters, 2006). The Polytraits database, focusing on polychaete species, even has a trait category of 'ecosystem engineering' as recorded, for example, in the entries for the burrowing worms *Nereis diversicolor* and *Polydora ciliata* (Faulwetter et al., 2014). Global databases and maps are of great use, but often only show the presence or absence of organisms at quite a coarse geographical scale and should, therefore, be used with caution when exploring the functioning of biogeomorphological systems.

Some examples of functional traits of particular relevance to biogeomorphology are explored in Table 2. For biogeomorphology, the effect traits of ecosystem engineers (Jones, 2012; Jones et al., 1994) are of great significance, having influence on both the scale of their physical impacts (e.g., body size and metabolic rate in the case of bioturbators (Cozzoli et al., 2018)), and their associated functional roles in landscape change (e.g., burrowing behaviours and sociality traits dictating bio-sediment transport rates and topographic evolution (Coombes and Viles, 2015; Gabet et al., 2003; Meysman et al., 2006)). In the context of the Anthropocene, response traits are also highly significant, broadly defining the sensitivity or 'responsiveness' of species to human-driven disturbance and change, with knock-on consequences for biodiversity, community function and the resilience of biogeomorphic systems (Corenblit et al., 2014b; Viles et al., 2008). As well as influencing engineer species' responses to climate change and resulting shifts in distribution and activity (Degen et al., 2018; Gutiérrez, 2020), response traits also dictate the likelihood of introduced species—and their geomorphological functions—becoming invasive. This includes larger, aggressive, faster-growing and more fecund invertebrates (e.g., invasive molluscs and crustaceans) outcompeting native fauna in many of the world's rivers and coastlines, coupled with altered sediment-mobilising functions (Crooks, 2002; Emery-Butcher et al., 2020; Harvey et al., 2014).

Significant progress has already been made in the application of traits and functional concepts in biogeomorphological research, especially in the contexts of organismal influences on sediment transport, deposition and stabilisation in fluvial and coastal systems (Corenblit et al., 2015; Mason and Sanders, 2021). This work can be broadly separated into (1) research on the response/sensitivity of biogeomorphic species, communities and systems to environmental change, including geomorphological regime shifts, and (2) the linkages between specific organism traits and biogeomorphic functional roles. Both of these themes have relevance for biogeomorphology in the Anthropocene. The first theme, as well as covering examples already mentioned relating to ecological responses to climate change, also includes community shifts in response to altered hydrological and sediment regimes (Balke et al., 2011) as well as the introduction, proliferation and potentially transformative effects of invasive ecosystem engineers (Fei et al., 2014). These dynamics can be closely linked, as in cases where the morphological and physiological traits of invasive species give competitive advantage over native species in altered environments, with associated shifts in biogeomorphic processes, functions and dynamics (Schwarz et al., 2016).

Under the second theme, as well as a focus on the functional importance of morpho-anatomical plant traits (e.g., stem density and stiffness) and the geomorphological organization and dynamics of fluvial and coastal systems (Bouma et al., 2013; Corenblit et al., 2011), the discussion has broadened to consider the role of life-history traits in controlling biogeomorphic outcomes and system resilience (e.g., Butler et al., 2018). This includes the effects of colonisation timing and growth strategies on vegetation establishment in coastal, fluvial and sedimentary slope systems (Balke et al., 2011, 2014; Eichel et al., 2016; Friess et al., 2012; Jerin and Phillips, 2020; Schwarz et al., 2018). Life-history traits have also been used by Mason and Sanders (2021) to explain the various zoogeomorphic roles of a range of river invertebrates.

Across these two themes, important linkages exist between species response and effect traits in the context of biogeomorphology. In the

Table 2

Examples of potentially biogeomorphologically relevant functional traits in microbes, lichens, plants and animals (compiled using information from [Ellis et al., 2021](#); [Fountain-Jones et al., 2015](#); [Krause et al., 2014](#); [McGill et al., 2006](#); [Violle et al., 2007](#); [Westoby and Wright, 2006](#)).

Trait category	Microbes	Lichens	Plants	Animals
Morphological	Cell size Extent/thickness (of biofilms and microbial soil crusts)	Thallus size/mass Growth form (foliose, fruticose, crustose) Thallus colour/ albedo Thallus water-holding capacity Photobiont type	Leaf area/aerial biomass Growth habit (herbs, climbers, trees, etc.) Stem diameter/ stiffness/ density Root architecture Reproductive strategy (seed dispersal/propagation) Nutrient uptake strategy/rate	Body mass/size Fossorial adaptations (forelimb size, claws, etc.) Body shape Fecundity
Physiological	Motility (e.g., chemotaxis) Enzyme activity	N-fixation rate Nutrient uptake strategy/rate	Metabolic rate Seedbank longevity	Environmental tolerances (temperature/moisture, pH) Metabolic rate
Phenological	Organic acid production/exudates Bio-mineralisation Seasonal abundance/composition (e.g., blooms) Seasonal decomposition rate	Tissue water stress (seasonal)	Reproduction (e.g., flowering/seed maturation/germination) Life-history (perennial, biennial, annual/senescence)	Life-cycle traits (e.g., breeding season/ growth period/life-span) Over-wintering strategy
Behavioural/ ecological	Life strategy (e.g., single-celled/ biofilm-forming) Lithobiontic niche	Community growth traits (e.g., lichen mat diversity/thickness)		Sociality/colony size Habitat preference/spatial aggregation Foraging habit/diet

case of riparian vegetation, for example, the close links between plant responses to abiotic stressors and the morphological effect traits that influence their water and sediment interception functions have been demonstrated ([Diehl et al., 2017](#)). Furthermore, the trait-specific processes and functions of engineer species, which can be modulated by variations and shifts in geomorphic and other environmental regimes including discharge rates and sea level, may be scale-dependent ([Koch et al., 2009](#); [Schwarz et al., 2015](#)). Extending these ideas, in the context of plants in coastal and fluvial systems, [Corenblit et al. \(2015\)](#) use the term ‘feedback traits’ to describe those biological traits influencing the responses of engineer plant species and communities to their own physical modifications, having evolutionary connotations via niche construction and coevolution over long timescales. [Phillips \(2016a, 2016b\)](#) also recognises that biogeomorphic processes and functions are ‘contingent’, whereby a species’ engineering traits in one environment (or set of environmental conditions) may not elicit the same functions in another. Similar ideas have recently been applied to the controls of sediment type and environmental context on the biogeomorphic functions of in-stream invertebrates ([Mason and Sanders, 2021](#)).

The ecosystem services that biogeomorphic systems provide are also increasingly recognised, particularly as interest has grown in NbS to environmental change ([Naylor et al., 2016](#)). The concept of ecosystem services has been extended, refined and debated since being introduced more than 20 years ago ([Costanza et al., 2017](#)), and has helped articulate the ways in which the natural environment contributes provisioning, regulating, cultural and supporting services to humanity. Biogeomorphic systems contribute, in particular, to regulating and supporting services, through moderating or preventing disturbance/hazards, regulating water flows, reducing erosion, helping soil formation and maintaining soil fertility, regulating climate (through carbon sequestration), and enhancing biodiversity and functional diversity. Such important roles have, for example, recently been reviewed for rivers ([Brown et al., 2018](#)), watersheds ([Osterkamp et al., 2012](#)) and seagrass meadows ([Vacchi et al., 2017](#)). The IUCN defines NbS as actions to protect, sustainably manage and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. Such NbS actions enhance the ecosystem services provided by natural systems. Crucially, both geomorphological and ecological insights are needed for successful NbS implementation. For example, in the context of mangroves, [Balke and Friess \(2016\)](#) show how geomorphological knowledge enhances the conservation, management, restoration and, in some cases, creation of biogeomorphic ecosystem services (also see

[Gijssman et al., 2021](#)). Similarly, in Europe, the importance of research on the influence of plant morphological traits on the wave-attenuating functions of saltmarsh communities has been acknowledged ([Spencer et al., 2015](#); [Wolters et al., 2008](#)). These and many other studies illustrate that biogeomorphic systems can be employed as NbS to tackle Anthropocene challenges when an understanding of biological traits is central to management decisions ([Wolters et al., 2008](#)).

The concept of NbS should not be applied uncritically by biogeomorphology, as many questions remain about how feasible and effective such strategies can be in addressing the extensive and pervasive modifications of biogeomorphological systems in many environments. Much has been written recently about the general challenges and limitations of NbS thinking and implementation, which geomorphologists need to take on board. For example, the concept of NbS has been variably interpreted and operationalised, and there is always a danger of it becoming an empty buzzword ([Hanson et al., 2020](#)). The notion of any environmental management strategy being a ‘solution’ has also been criticised, with the term of “nature-based interventions” proposed as an alternative framing ([Chausson et al., 2020](#)). In terms of implementation, criticisms have been made of the possibility that NbS can produce maladaptation, that scaling up of NbS can shift the ecological damage elsewhere (“leakiness”), that non-analogue conditions might lead to failure of NbS, and that financial and governance issues preclude NbS from being effectively adopted ([Seddon et al., 2020](#); [Seddon, 2022](#)). Finally, many authors have pointed out the difficulties of evaluating or predicting the success of NbS, with a lack of data from many parts of the world (e.g., [Chausson et al., 2020](#)).

This growing body of research demonstrates that (1) the application of a traits-based approach offers significant potential for the advancement and application of biogeomorphology; (2) currently, most work in this area has focussed on plants in fluvial and coastal sedimentary systems, whilst applications in other contexts remain underexplored; and (3) a deeper understanding and application of functional traits and concepts from functional ecology is both necessary and advantageous when managing biogeomorphic systems and the services they provide in the face of environmental change.

3. A hierarchical trait-based framework for biogeomorphology in the Anthropocene

As alluded to in [Section 2](#), biogeomorphology exists within a scalar hierarchy of linkages from species traits to ecosystem processes and functions, which culminates in ecosystem services. Building on these

concepts, Fig. 2 illustrates a trait-based conceptual model that considers linkages between human impacts and biogeomorphology, and forms the basis for the rest of this paper. Within this framework, we conceptualise biogeomorphic systems (shown in the grey box in the centre of Fig. 2) as comprising (1) the geomorphological process regimes and emerging landform assemblages that accompany them, and (2) ecological communities, characterised by their component species and associated traits. These two elements are tightly intertwined by a series of interactions, largely conditioned by response and effect traits. Our approach amplifies and goes beyond that of Corenblit et al. (2015) who focus on what they define as ‘biogeomorphic ecosystems’, prone to disturbance, such as salt marshes, mangroves, coastal dunes and fluvial floodplains.

Humans are modifying biogeomorphic systems in two main ways (shown by the arrow coming in to the grey box from the left in Fig. 2): (1) by influencing geomorphological dynamics via regime shifts (e.g., the damming of rivers and climate change-driven changes in flood frequency; Brown et al., 2017; Slater et al., 2021), and (2) by affecting the composition of ecological communities via a range of synergistic impacts (e.g., extinctions and introductions). The nature of these community impacts is largely dictated by the response traits of the component species, some of which have biogeomorphic functions. For example, in response to anthropogenic climate change, physiological and behavioural traits determine the thermal tolerance, fitness (growth, reproduction and survival) and geographical range of ecosystem engineers (Butler, 2012; Estrada et al., 2016). By ‘selecting’ for certain individuals (i.e., those with the appropriate response traits), human activities shape communities and their collective trait pools (termed ‘trait filtering’ in Fig. 2, sensu Nock et al., 2016). Thus, the collective effect traits of the resulting communities dictate the ecosystem processes and functions they perform, including biogeomorphic types. For example, community shifts in coastal macroalgal communities in response to urban pollution and ocean warming (Schermer et al., 2013) are altering the composition and dominance of species with different functional traits (Gilson et al., 2021; Piñeiro-Corbeira et al., 2018), which in turn are likely to have different sediment-trapping, carbon-storage and wave-attenuating functions (Morris et al., 2020; Pessarrodona et al., 2019; Smale et al., 2013).

The double-ended arrows linking biogeomorphic systems and ecosystem processes and functions in Fig. 2 indicate that their alteration via human impacts can have biogeomorphic feedbacks, as has been considered over timescales ranging from successional to evolutionary (Corenblit et al., 2009, 2014a; Phillips, 2016a). The box on the far right of Fig. 2 indicates that some ecosystem processes and functions provide services to humans, some of which are biogeomorphological in nature including coastal protection in the case of wave attenuation by wetlands. The dotted arrows indicate that only some ecosystem processes and

functions are considered ‘services’, and the colours recognise that changes in the Anthropocene can both enhance (green) and reduce (red) the provision of ecosystem services. Finally, the dotted arrow connecting the far right and far left boxes indicates that some ecosystem services (arising from the management and manipulation of biogeomorphic systems) may mitigate human-driven environmental change and associated problems to some degree. Notably, quantification of how effective these impacts of improved ecosystem services might be in mitigating the impacts of global change is currently lacking.

More than theoretical, this framework helps identify and predict the ways in which environmental change in the Anthropocene is altering biogeomorphological systems (red pathway in Fig. 2) and how they could be managed and manipulated to maximise resilience (green pathway in Fig. 2). In direct parallel with a functional approach to biogeomorphology, ecologists have stressed how functional trait approaches aid understanding by focusing on the *mechanisms* that govern interactions between organisms and their environments (Nock et al., 2016).

Implicit within the conceptual framework in Fig. 2 is the recognition that conditions are not stationary, i.e., biogeomorphic systems are dynamic and evolving as both environmental conditions and phenotypic characteristics change. The lack of meaningful baselines from the past during periods of change complicates any simple deployment of NbS based on functional traits, as predicting outcomes is likely to be very challenging. We call for further experimentation with biogeomorphic trait-based interventional strategies in order to collect a more sophisticated evidence base on how biogeomorphologically important functional traits are affected by environmental change. Also implicit within our conceptual framework is an acknowledgement that, in many cases, the workings of biogeomorphic systems form more of a black box than being fully understood, and, thus, much remains to be discovered about how exactly functional traits contribute to resilience. Some important progress has been made in, for example, understanding the generation of biogeomorphic resilience in barrier dune systems as a form of emergent behaviour (Stallins and Corenblit, 2018) and the impacts of invasive species on resilience in zoogeomorphological systems (Butler et al., 2018).

Section 4 focuses on the red route in Fig. 2, illustrating how human impacts are modifying biogeomorphological systems via changes (largely unintentional) to the assembly of species traits and resulting ecosystem functions; and Section 5 links these to the green pathways in Fig. 2, illustrating (by use of three case studies) how by identifying, conserving, enhancing and adding species and communities with favourable functional traits, biogeomorphic systems can be manipulated and managed to help tackle environmental problems in the Anthropocene.

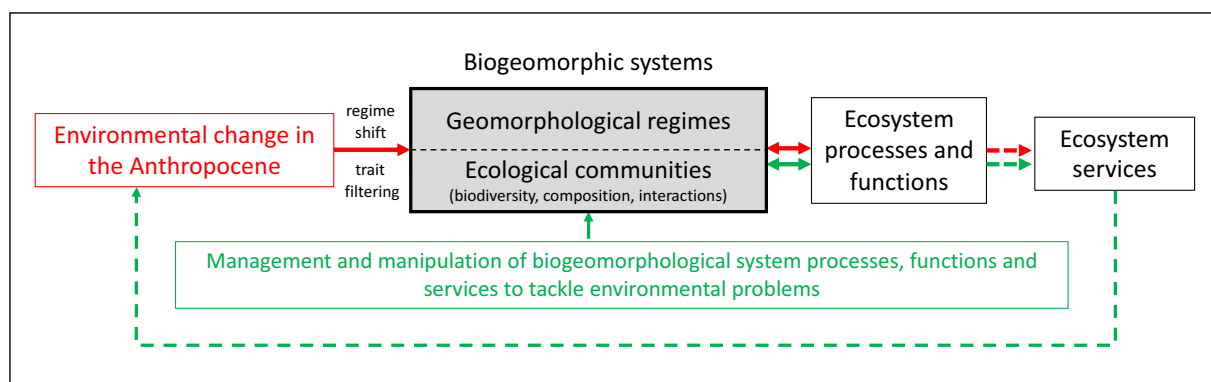


Fig. 2. A trait-based conceptual framework linking human impacts on biogeomorphic systems and resulting changes in ecosystem processes, functions and services. Red arrows indicate how conditions in the Anthropocene are having negative effects, and green arrows and text indicate positive responses to management of biogeomorphic systems. Dotted arrows imply potential but less well-established links.

4. How is human activity filtering biogeomorphic traits, and thus biogeomorphic processes and functions?

The impacts (often synergistic and complex) of overexploitation, species introductions, climate change, pollution and habitat destruction on community composition have made significant, widespread alterations to ecological communities (Brook et al., 2008). In many cases, this includes changes to the presence and abundance of species with functional traits that underpin biogeomorphic system functions (Table 1). Thus, as conceptualised in Fig. 2, human impacts filter species based on their response traits, which in turn alters the prevalence of effect traits in the resulting communities, leading to altered ecosystem processes and functions. Within this 'filtering' process, the traits and functions of a range of geomorphologically relevant species are being altered, not only over management/ engineering timescales but also over evolutionary time via niche construction effects (Corenblit et al., 2021; Phillips and Van Dyke, 2017). This has consequences for the occurrence and resilience of biogeomorphological system functions and services.

For example, overexploitation and hunting of animals has caused the extirpation of some species. Bison (known to be important biogeomorphological agents through wallowing, trampling and grazing) were extirpated from USA by the late nineteenth century and replaced by domesticated grazing animals, which have very different biogeomorphic impacts because of traits such as body size, weight and feeding behaviour. The loss of bison also had knock-on biogeomorphic effects, as prairie dog habitats were destroyed as a consequence. Prairie dogs are important burrowing animals, which contribute significantly to bioturbation and sediment movement, and now only occupy ~1.5 % of their original area (Butler, 2018). While it has not yet been possible to quantify the impacts of these events on erosion rates, it is likely that the extirpation of bison made a considerable difference to the functioning of the biogeomorphic system across wide swathes of the USA. As another example, the near extirpation of Eurasian beaver (*Castor fiber*) across Europe (including extinction within the UK) some 400 years ago was largely caused by hunting and likely contributed to the simplification of many river systems (Brazier et al., 2021).

Introductions and invasions (deliberate or accidental) of species with particular biological traits have also been shown to have important consequences for biogeomorphic systems. For example, the North American beaver (*Castor canadensis*) was introduced into Patagonia in 1946. Beavers have many traits that make them particularly effective biogeomorphic agents (such as buoyancy, herbivory, dam-building behaviours, etc.; see Brazier et al., 2021). Because there were no natural predators, the population boomed, and the beaver caused extensive changes to fluvial systems. A recent remote sensing study identified over 200,000 beaver dams in a 73,000 km² area of the Tierra del Fuego archipelago in South America (Herrera et al., 2020), with associated widespread shifts in hydrogeomorphological processes, nutrient dynamics and riparian vegetation (Westbrook et al., 2017).

Burrowing rodents introduced to many islands have also caused many biogeomorphic effects, as recorded on the sub-Antarctic Marion Island where the invasive house mouse (*Mus musculus*) is now well established. Because of its functional traits (high reproduction rates, small size and burrowing behaviour), *M. musculus* has produced up to 6000 burrows per hectare here and moves an estimated 2.4–8.4 t ha⁻¹ of sediment. Additionally, this species prefers to burrow under cushions of *Azorella selago*, which is a bioprotective species growing on the lava fellfields. Thus, mouse-induced disturbance of *Azorella* cushions enhances surface erosion and also negatively affects their plant facilitation roles (Eriksson and Eldridge, 2014).

Several studies have noted that invasive species can have particularly negative impacts on biogeomorphic systems. Fei et al. (2014) give many examples of the complex effects that the introduction of invasive plant species (such as *Tamarix* and *Casuarina*) can have, and Butler et al. (2018) notes that the introduction of exotic flora in turn influences zoogeomorphic processes, although evidence of these impacts remains

lacking. Not all invasive species have deleterious effects in all places, however. Recent research in North Carolina, USA, for example, demonstrated that the invasive reed *Phragmites australis* has a neutral impact on the shoreline stabilisation capacity of saltmarsh (Theuerkauf et al., 2017). Furthermore, climate change can enhance the dominance of invasive species and in turn influence biogeomorphic systems. In the Wadden Sea, for example, alien oysters (originally introduced in 1986 for oyster farming) have replaced native mussels in response to recent shifts in the climate regime. While the two species might be functionally equivalent as consumers, a field experiment demonstrated that they had very different impacts on habitat structures and associated organisms (Kochmann et al., 2008).

Community composition is also altered by shifts and losses of species and their functional traits in response to altered physico-chemical landscape properties, including climate change, physical disturbance regimes and pollution. For example, widespread loss of the flow-altering and sediment-retaining functions of coastal seagrass meadows has recently been documented, largely in response to human impacts (Duarte, 2002; Duarte et al., 2008; Vacchi et al., 2017). Warming of ocean waters has already been found to have negatively influenced *Posidonia oceanica* meadows in the Balearic Islands, Spain, causing shoot mortality rates to increase (Marba and Duarte, 2010), and modelling indicates that future climate change will have dramatic effects on *Posidonia* meadows across the Mediterranean, leading to functional extinction by around the middle of the twenty-first century (Jordà et al., 2012). In Morro Bay in California, USA, another seagrass (*Zostera marina* or eelgrass) has experienced a sharp decline over the last decade likely caused by multiple human impacts, shifting the biogeomorphological system from one that favours accretion to one that favours erosion (Walter et al., 2020). While it is not clear what caused the dramatic collapse in eelgrass beds, the ecological and geomorphological impacts have been pronounced, with over 90 % of locations that previously supported eelgrass suffering from erosion.

The synergistic action of anthropogenic stressors is demonstrated by dryland soils covered with biological soil crusts (BSCs) made up of a range of photoautotrophic organisms (cyanobacteria, algae, lichens and mosses) and heterotrophic organisms (bacteria, archaea and fungi). BSCs have a range of traits that make them important soil-surface-stabilising agents (such as size and shape, drought tolerance, N-fixation ability, etc.), and recent calls have been made for a trait-based approach to understanding BSCs (Bowker et al., 2018). BSCs are known to protect soil surfaces from wind erosion and play a key role in surface hydrology in many dryland areas (Eldridge et al., 2020). They are affected by physical disturbance (such as caused by vehicles and trampling by grazers), and experimental studies on the Colorado Plateau have shown that climatic change (warming and altered precipitation patterns) produces similar deleterious impacts on BSCs as physical disturbance (Ferrenerg et al., 2015). Currently, around 12 % of the world's land surface is thought to be covered by BSCs, and recent modelling shows that climate change is likely to result in reductions in coverage, notably in hyper-arid, semiarid and dry sub-humid areas, with hyper-arid areas likely to lose 40 % of BSC cover by 2070 under some scenarios (Rodríguez-Caballero et al., 2018). Field experimental studies over eight years at a dryland site in Spain illustrate that climatic warming leads to reduced species diversity and richness as well as declining cover, with concomitant reductions in the ability of BSCs to sequester carbon and limit erosion (Ladrón de Guevara et al., 2018).

Over the Anthropocene, human impacts on biogeomorphic systems such as those reviewed above have been widespread and serious, often causing significant changes to the landscape. In recent years, it has also become increasingly apparent that such landscape-scale changes are of global significance given that many biogeomorphological functions offer important ecosystem services critical for regulating and mitigating detrimental environmental change. These services are sustained by the functional (effect) traits of the species and communities they comprise. Loss of these services is occurring worldwide via a range of adverse

human impacts, which act as trait filters, reducing or removing beneficial biogeomorphic functions (Fig. 2). In turn, human activities are also introducing alien species, with different functional (effect) traits into many ecosystems, often producing unwanted biogeomorphic functions. There is still a dearth of reliable, quantitative information about the global effects of human impacts over the Anthropocene on biogeomorphic functions and ecosystem services. With the increase in global datasets of all kinds, this is an important opportunity for future biogeomorphological research to investigate and predict the roles of functional traits in mediating biogeomorphological responses to global change.

5. How can biogeomorphic processes and functions be used to tackle the impacts of global change?

Enhancing the functional resilience of biogeomorphic systems can provide effective NbS to tackle problems of erosion, flooding and soil degradation in many different environments. This is well recognised in conservation ecology, where the focus has shifted from conserving ‘keystone species’ based on trophic interactions to ‘key engineers’ based on functional roles in ecosystems (Boogert et al., 2006); thus, “conservation efforts may be most effective if they ensure the survival of the key engineers in an ecosystem” (Odling-Smee et al., 2003, p. 384). It is worth emphasising that biogeomorphological processes and outcomes underpin many of these key engineering functions via the transformation of energy and matter. Table 3 provides some examples of the major ecosystem services that biogeomorphological systems contribute to, and shows the types of functions, processes and traits involved. Note that the underpinning systems/ environments listed in Table 3 often support multiple ecosystem services. For example, coastal salt marshes are known to contribute to shoreline stabilisation, carbon storage and plant diversity (Theuerkauf et al., 2017). In the rest of this section we focus on three more detailed examples to illustrate the links between biological traits, ecosystem functions and ecosystem services, and the potential for manipulating biogeomorphic systems to contribute to large-scale environmental restoration in the Anthropocene. We have chosen the examples to reflect the breadth of biogeomorphological systems.

5.1. Species reintroductions for river restoration

River flooding affects lives and livelihoods in many parts of the

world, and causes major economic problems. According to a recent report, 25 % of the current global population live in freshwater inundation zones, and 23 % of the world’s croplands are also affected (Smith et al., 2021). Fig. 3a shows a global map of river reaches, highlighting both their widespread nature and the degree of interruption to their flows (as represented by their connectivity status index, or CSI). In recent years, environmental managers have become much more interested in working with nature to tackle these problems, rather than seeking hard engineering solutions in all cases. A whole suite of interventions to fluvial and riparian systems can be made that utilise the ecosystem engineering traits of a range of plant and animal species (Polvi and Sarneel, 2018). Fig. 3b illustrates the major types of ecosystem engineers in fluvial systems, their functional traits and their potential roles, and Fig. 3c portrays, in simplified form, how biogeomorphic system restoration may help counteract some of the damage caused to ecosystem function and ecosystem services provision in the Anthropocene. Not all species of riparian vegetation and benthic invertebrates have similarly strong ecosystem engineering roles, depending on their functional traits and the influence of contingency and phenotypic plasticity, and work needs to be done to establish relevant trait and function databases. For example, Polvi and Sarneel (2018) note that smaller streams with lower discharges, finer sediments and medium levels of disturbance might be particularly amenable biogeomorphic systems to restoration through working with nature.

In Europe and the USA, the reintroduction of beavers has been a particular focus of many river management schemes, although restoration of instream wood (to create leaky dams) and riparian vegetation (to stabilise channel banks and islands) are also very important methods of ‘slowing the flow’. Brazier et al. (2021) provide a full summary of how beavers ‘slow the flow’ and enhance biodiversity through their ecosystem engineering roles in low-order streams where their dams, canals and burrows have major impacts on geomorphology, hydrology and aquatic ecology. What is as yet unclear, as Brazier et al. (2021) note, is whether research findings from North America (where the native beaver species is *C. canadensis*) are directly applicable to Europe (where the native beaver species is *C. fiber*), and what the long-term (20+ years) performance of the restored biogeomorphic system might be. Nevertheless, there is growing evidence to suggest that the biogeomorphic and wider functional impacts of *C. fiber* are indeed significant in European rivers. This includes increased geomorphic and habitat heterogeneity following beaver reintroductions and population expansion in

Table 3

Examples of how biogeomorphological systems can contribute to ecosystem services using a hierarchy of biological traits, and biogeomorphic processes and functions.

Ecosystem service	Underpinning biogeomorphic system	Biogeomorphic processes and functions	Example biogeomorphic species/ organisms	Relevant biogeomorphic species traits
River flood alleviation	Fluvial and riparian systems	Flow interception and sediment retention	Riparian vegetation Macrophytes Instream wood Beavers Benthic invertebrates	Colonisation & growth rates (e.g., Schwarz et al., 2018) Dam-building behaviour, size, buoyancy, morphology. Foraging habit
Coastal protection (erosion control & flood alleviation)	Vegetated coastal wetlands	Flow interception and sediment retention	Saltmarsh communities/seagrass beds/mangroves	Blade morphology/density/stiffness Root depth and root architecture Life-history traits
Biogeochemical cycling (carbon sequestration)	Terrestrial soils and rock surfaces	Biogeochemical cycling	Soil microflora/fauna and Biocrusts	Population size/abundance/growth rates Metabolic pathway & rate/C fixation
Drylands erosion control	Dryland hillslopes	Flow interception and surface stabilisation	Patchy vegetation	Canopy structure and density Root depth and root architecture
Soil fertility maintenance	Forested hillslopes	Bioturbation	Biological soil crusts Treefall Digging vertebrates Burrowing invertebrates	Growth rates & morphology Root depth and root architecture Body size, abundance/density Foraging habit

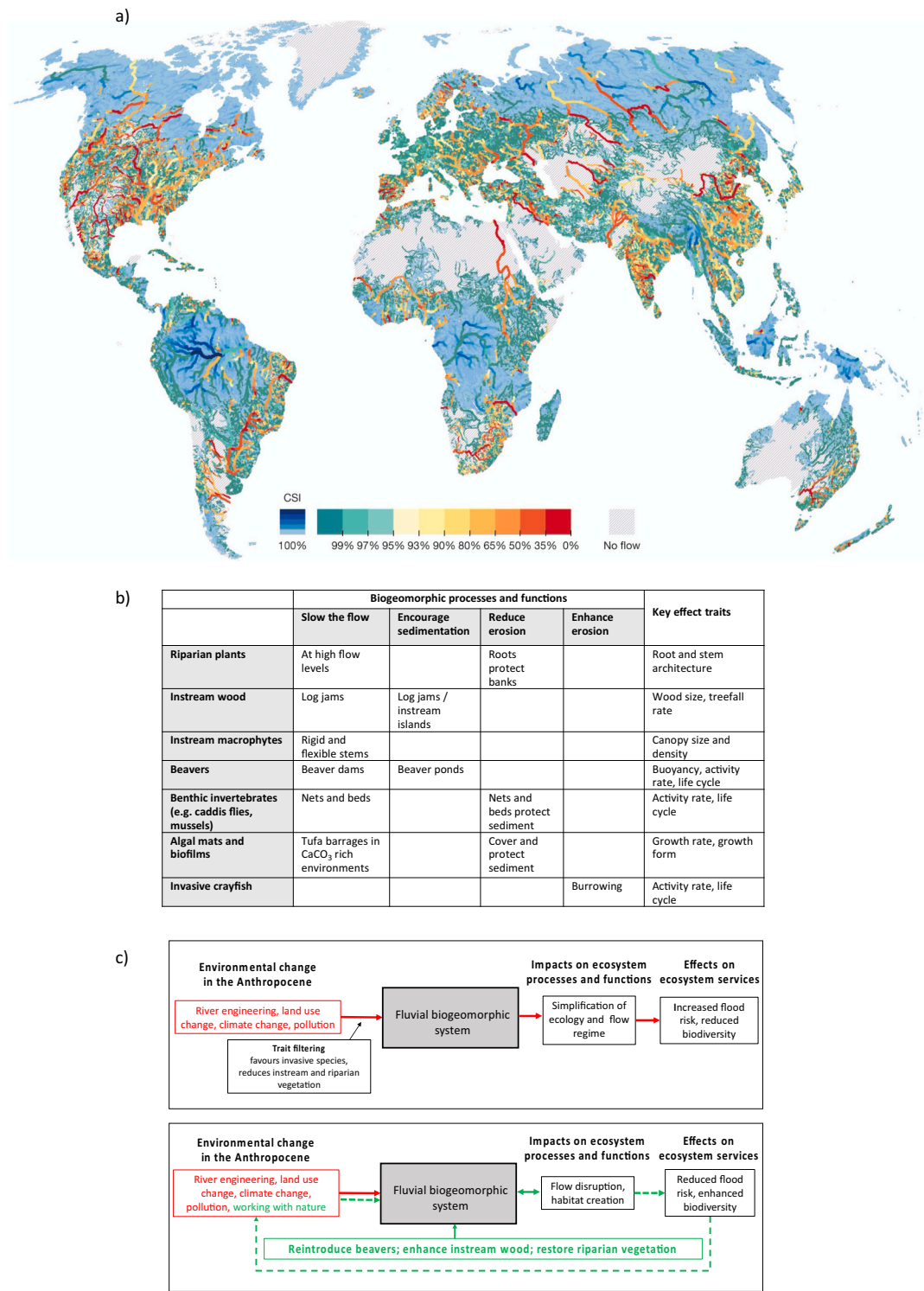


Fig. 3. (a) Map of world river reaches showing connectivity status index (CSI, 0–100 %). The blue shades represent the magnitude of river discharge for river reaches with CSI = 100 % (that is, darker shades for larger rivers). Source: [Grill et al., 2019](#). (b) Examples of biogeomorphic functions played by ecosystem engineers in fluvial systems. (c) Conceptual diagram (also see [Fig. 2](#)) of impacts on fluvial biogeomorphic systems and their ecosystem services in the Anthropocene (upper panel) and of the potential restorative impacts of manipulating fluvial biogeomorphic systems and their ecosystem services (lower panel).

approximately 25 European countries ([Halley et al., 2021](#)). There is also increasing effort to better understand the key behavioural traits of this species (e.g., territoriality and sociality) to better predict population changes and linked biogeomorphic dynamics at a landscape scale ([Campbell-Palmer et al., 2021](#)).

Studies such as those reviewed above are proving ever more

important for evaluating the success of beaver reintroductions as well as managing the potential conflicts that can arise ([Ulicsni et al., 2020](#)). Collectively, these and other works demonstrate that the active reintroduction of *C. fiber* in Europe is increasingly seen as an effective form of working with nature in human-modified river systems, helping restore biogeomorphic functions and deliver associated ecosystem

services (Thompson et al., 2021; Fig. 3c).

According to Polvi and Sarneel (2018, p. 7) "...there is potential for multiple other ecosystem engineers to be used systematically as a holistic tool for restoration in appropriate river systems; however, care should be taken so that ecosystem engineers do not become invasive in non-native areas, as with tamarix in North America and beaver in South America." Challenges for such fluvial biogeomorphic system restorations are also posed by future climatic change, which may induce non-stationarity and cause non-analogue conditions, i.e., negatively influencing the reintroduced native species, causing other species with different and less beneficial functional traits to take over. As with all environmental restoration projects, impacts on human populations also need addressing, as in most parts of the world today, biogeomorphic systems are socio-ecological systems, with important human dimensions (Gaywood, 2018; Blewett et al., 2021).

5.2. Restoring biological soil crusts for tackling land degradation in drylands

Drylands cover more than 40 % of Earth's land surface and are prone to soil erosion and loss of soil fertility as a result of many human impacts, such as over-grazing, land-use change, over-irrigation and urbanization increasingly exacerbated by climate change. Dryland ecosystems are often characterised by patchy vegetation cover and dynamism over time. A recent review of dryland biogeography notes the 'functional paradox' of drylands, i.e., that there is a much higher than expected functional diversity in dryland plants despite the dynamic and often harsh environmental conditions (Maestre et al., 2021). Grasslands are the most abundant land-cover type found in drylands, and a major feature of many drylands is discontinuous plant cover with patchy shrubs and trees.

BSCs are known to be an important ecosystem engineer in many drylands and play key roles in the biogeomorphic system. In particular, BSCs perform ecosystem functions such as stabilising soil surfaces to prevent erosion, fixing nitrogen and carbon from the atmosphere, and mediating the dryland hydrological system (Antoninka et al., 2020; Eldridge et al., 2020). Fig. 4a illustrates the global extent of different types of BSCs, which vary in function depending on community composition. Dryland BSCs are variable in composition and morphology, with, for example, those in hyper-arid areas often dominated by cyanobacteria whilst lichen-dominated BSCs are found in fog deserts and many arid and semi-arid areas. As noted in Section 4, dryland BSCs are easily damaged by physical disturbance and climate change, affecting their biogeomorphic functions. Many efforts have been made to restore dryland soils either by encouraging the natural recovery of BSCs or via active restoration (Antoninka et al., 2020). Their functional roles need to be viewed within the context of the whole biogeomorphic system, however, as patchy vegetation and animals also play important roles and their interactions are, as yet, not well understood (Fig. 4b). Fig. 4c (top panel) gives a simplified illustration of how trait filtering in the Anthropocene is influencing dryland biogeomorphic systems and, as a consequence, their ecosystem functions and ecosystem services. Fig. 4c (bottom panel) suggests potential ways in which these impacts could be mitigated. However, such restoration attempts are, so far, small-scale and in their infancy.

Patchy vegetation is known to play a key role in surface hydrology, ecology and geomorphology in dryland areas, through altering local infiltration rates and acting as 'fertile islands' (Goudie, 2022; Okin et al., 2015). A wide range of animal species in drylands contribute to soil disturbance through burrowing, scraping and mound-building. A recent global meta-analysis reveals some widespread ecosystem functions of soil-disturbing vertebrates, with significant reductions in water runoff, enhancement of soil nitrogen levels and increases in vascular plants; however, they were also found to commonly decrease the abundance of BSCs (Mallen-Cooper et al., 2019). Soil-disturbing animals and their positive ecosystem functions have declined in some areas, for example in

dryland Australia where native species including burrowing bilby, bet-tong and wallaby have been replaced by invasive rabbits and pigs. The native species have positive impacts on soil formation, water infiltration and soil microbial activity while the invasive species do not (Eldridge and James, 2009). Reintroducing native burrowing fauna is increasingly being seen as a form of environmental restoration or NbS, although care needs to be taken to ensure that future, non-analogue conditions do not cause unintended consequences. Invertebrates also play important biogeomorphological roles in many dryland areas, with ants and termites particularly effective agents of bioturbation and soil movement, whose activities in creating surface mounds and subterranean galleries play a range of biogeomorphic functions. Complex interactions between these different biogeomorphic agents are likely as, for example, ant foraging is known to contribute to the formation of patterned vegetation (Viles et al., 2021). The practical implications of these interactions for success or failure of environmental restoration and 'rewilding' schemes in drylands require further investigation, although significant progress is being made (e.g., Lohr et al., 2021).

5.3. Replanting seagrass meadows for coastal protection

Seagrass meadows cover some 0.1 to 0.2 % of the global ocean (Fig. 5a), although there is a lack of data from many areas. These are highly productive, largely subtidal ecosystems found 0–30 m below sea level along temperate and tropical coastlines (Duarte, 2002; Short et al., 2007). They are known to provide several ecosystem services, including climate regulation through carbon sequestration, biodiversity enhancement and coastal protection via sediment stabilisation and wave attenuation. Seagrasses, which include *Z. marina* (eelgrass), *P. oceanica* and *Thalassia testudinum*, are prone to damage through physical disturbance from dredging and anchoring as well as eutrophication, climate change and cyclones. Many seagrasses are slow-growing, making recovery from disturbance challenging. Globally, it has been estimated that 29 % of known seagrass areas have been lost since initial records in 1879, with accelerated losses of up to 7 % p.a. in recent years (Waycott et al., 2009). Green et al. (2021) estimate with a high degree of certainty that the British Isles has lost at least 44 % of its seagrass since 1936, with losses of up to 90 % possible over longer time spans. Vacchi et al. (2017) provides an assessment of the biogeomorphology of *P. oceanica* in the Mediterranean, where it occupies ~1.5 % of the sea surface, noting that the seagrass mat (a tangled association of roots, rhizomes and sediment) is a form of bioconstruction that stores fine sediment, and that seagrass influences nearshore hydrodynamics and vice versa.

Seagrass meadows are important biogeomorphic systems, with different seagrass species having different functional traits (such as canopy and root/ rhizome architecture) that affect their ability to trap and store sediment. James et al. (2021) discuss the 'biogeomorphic landscapes' produced by seagrasses along tropical coastlines and the valuable contribution they make to coastal protection (see also Fig. 5b). They also note the ability of some seagrass species, particularly *T. testudinum*, to withstand hurricane force storm events. Within seagrass meadows, a range of other biogeomorphologically active organisms are found, such as calcifying species, burrowers and bioturbators, whose effects often interact with those of the seagrasses. A recent study, for example, found some complex relationships between the stabilising roles of *Z. marina* and those of associated bivalves (Meysick et al., 2022), whilst Siebert and Branch (2006) found experimentally that the burrowing action of sand prawns were mutually antagonistic with the sediment-stabilising role of *Z. capensis*. Seagrass restoration, as a form of NbS to coastal erosion, has been trialled in several places around the world with increasing success rates over recent years (van Katwijk et al., 2016). Modelling has also been used to infer that 'green nourishment' (i.e., combining beach nourishment with seagrass restoration) might be particularly effective (Chen et al., 2022). Fig. 5c illustrates how seagrass restoration might manipulate biological traits to produce changes in ecosystem function and, thereby, enhance ecosystem services provision.

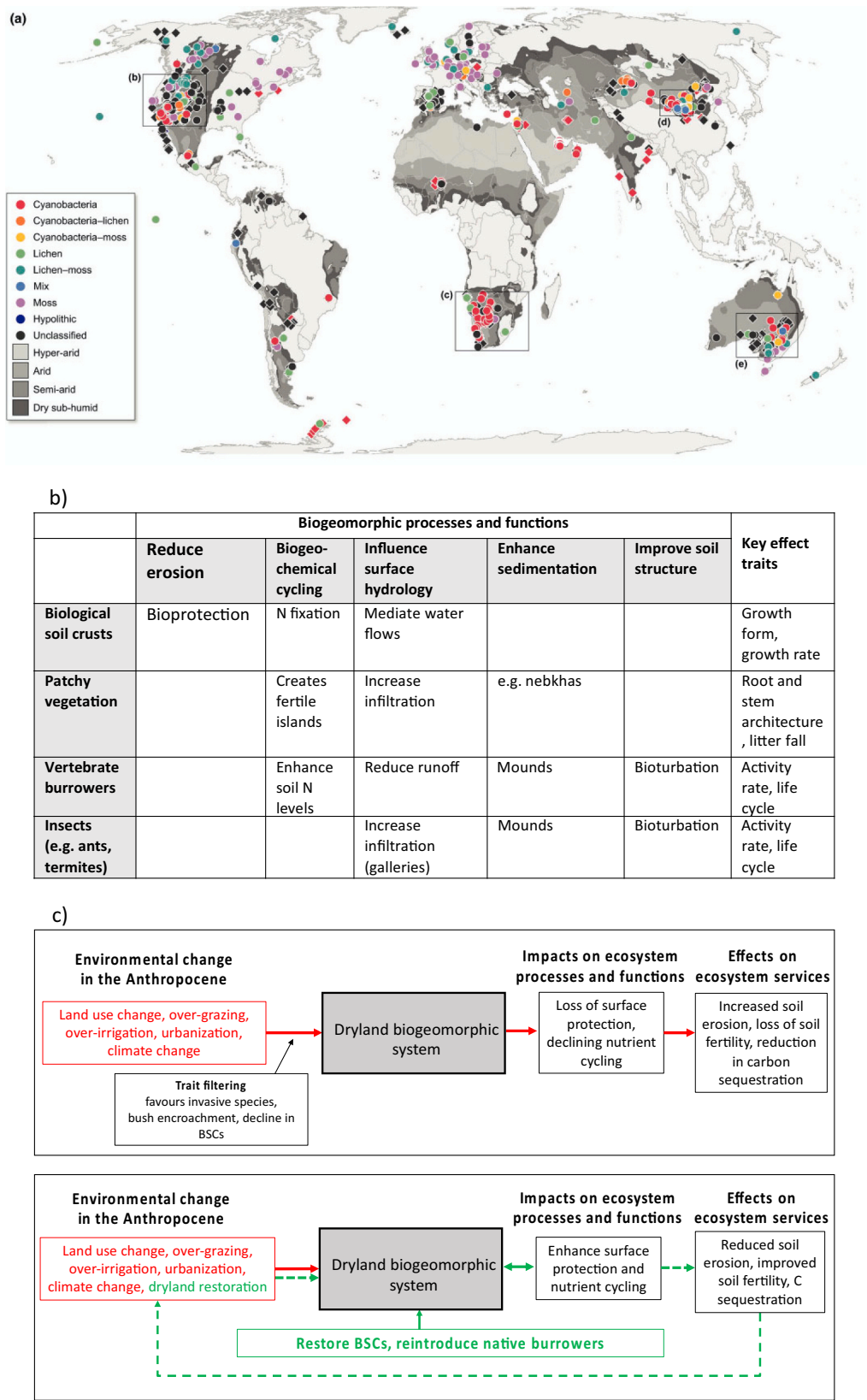


Fig. 4. (a) Distribution of biological soil crust (BSC) communities across global drylands. Different colours indicate the dominant BSC components (i.e., cyanobacteria, hypolithic, lichens and mosses) at each study site. Source: [Maestre et al., 2021](#). (b) Examples of biogeomorphic functions played by ecosystem engineers in dryland environments. (c) Conceptual diagram (also see [Fig. 2](#)) of impacts on dryland biogeomorphic systems and their ecosystem services in the Anthropocene (top panel) and of the potential restorative impacts of manipulating dryland biogeomorphic systems and their ecosystem services (bottom panel).

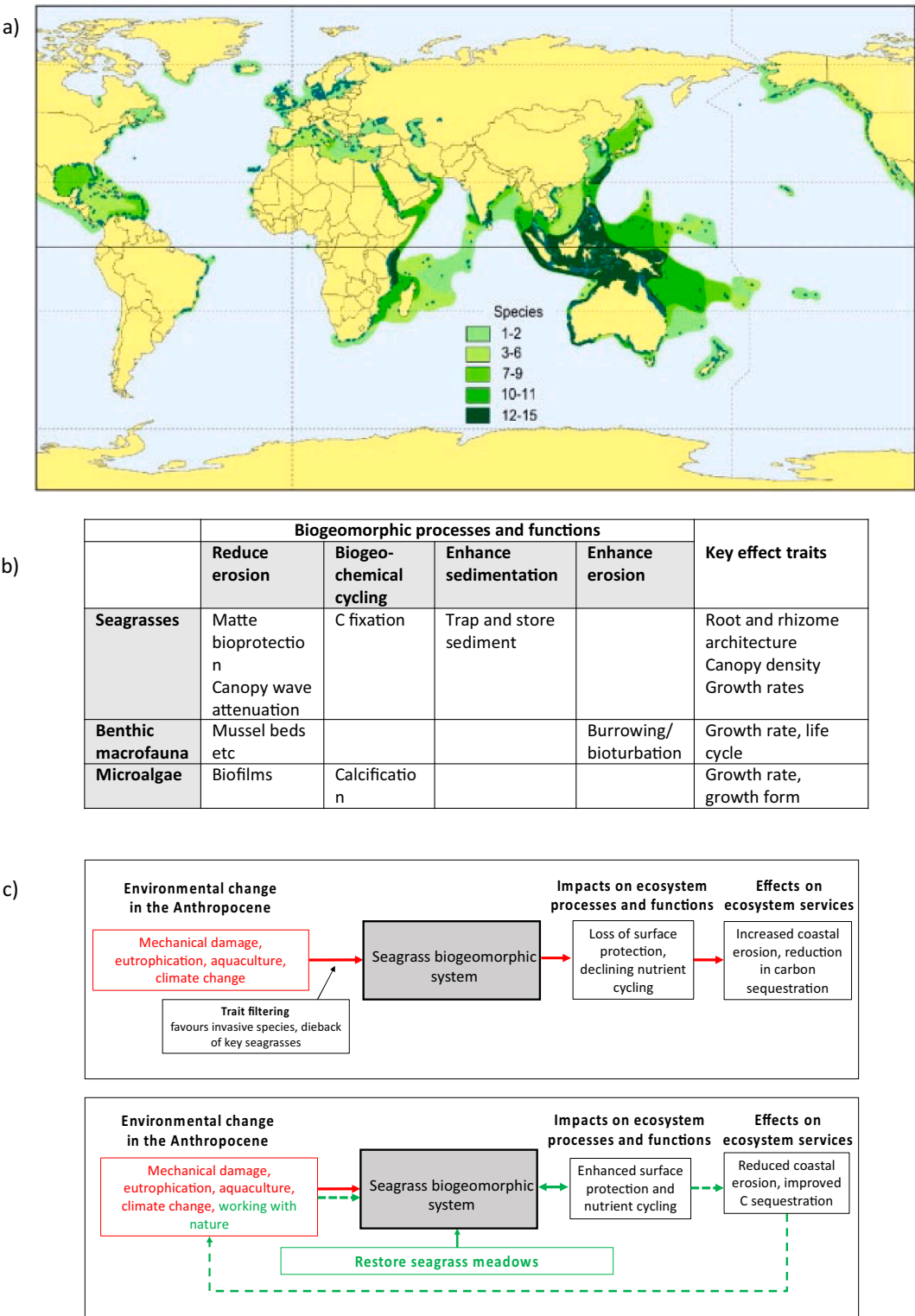


Fig. 5. (a) Global seagrass diversity and distribution. Shades of green indicate numbers of species reported for an area; blue points and polygons indicate documented reports of seagrass occurrence (from 2005 UNEP-WCMC). Source: [Short et al., 2007](#). (b) Examples of biogeomorphic functions played by ecosystem engineers in seagrass meadows, (c) Conceptual diagram (also see [Fig. 2](#)) of impacts on seagrass biogeomorphic systems and their ecosystem services in the Anthropocene (top panel) and of the potential restorative impacts of restoring seagrass meadows and their ecosystem services (bottom panel).

6. Discussion and conclusions

A trait-based approach to biogeomorphology has both shorter-term practical implications for environmental management and restoration and also offers one route to examining biogeomorphology over larger

space scales and longer timescales. For example, there is some evidence that more easily measured ‘soft’ traits can be used to predict hard traits that more typically equate to species’ functional roles (e.g., [Belluau and Shipley, 2018](#)). In this sense, measuring and modelling how humans are altering the prevalence of those more easily measured ‘soft’ traits (e.g.,

morpho-anatomical characteristics) could be a useful starting point for studies of large-scale biogeomorphic system within which function may be inherently difficult to quantify based on a priori knowledge of the system and assumed causal linkages.

With the advent of ‘big data’ on physical and biological components of the landscape at scales ranging from square metres to global, there are many opportunities now to explore our conceptual framework with quantitative data. It will remain a challenge to conclusively establish how human activities within the Anthropocene have disrupted or altered many biogeomorphic systems because of the difficulty of knowing what the baseline (pre-human influence) conditions were. Nevertheless, the three case studies explored in Section 5 all demonstrate profound alterations to biogeomorphic systems over the past few centuries. All three cover biogeomorphic systems that are prone to disturbance, and all three illustrate the intertwining of physical and ecological processes and functions based on the suite of response and effect traits of the component species. For all three biogeomorphic systems (fluvial, dryland and seagrass), potential ecological restoration techniques are available and being deployed at sites across many parts of the world. These offer ways in which to work with and restore nature, as part of improving environmental stewardship. What is yet unclear is what the longer-term impacts on the biogeomorphic functions will be, and how this might affect their success in terms of enhancing ecosystem services and resilience in the face of ongoing human disturbance. It is also unclear to what extent future climate change will affect the success of such NbS as, along with other modes of human impact, changing climatic conditions are linked to shifts in ecological community composition and trait filtering.

In conclusion, the work reviewed in this paper and the conceptual framework presented has shown that:

- Humans can (unintentionally) alter the type, intensity, spatial pattern and longevity of biogeomorphic processes by changing species assemblages and their association functional traits.
- Biogeomorphic processes can be (intentionally) manipulated by adding, enhancing and conserving biogeomorphic functions to tackle human-driven environmental problems.
- Conserving and enabling biogeomorphic processes and functions (e.g., certain working with nature/NbS) can contribute to environmental resilience in the face of ongoing human impacts.
- Opportunities for larger scale/longer-term study using the growing availability of big datasets and modern monitoring techniques is important for understanding the resilience of biogeomorphic systems over different space/timescales.
- A functional/ trait-based approach to biogeomorphology that adopts ecological concepts and understandings should help inform the identification, conservation and manipulation of key biogeomorphic species communities for environmental management in the face of anthropogenic impacts.

Declaration of competing 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

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

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