



ESEX Commentary

Biogeomorphology, quo vadis? On processes, time, and space in biogeomorphology

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ESPL

Earth Surface Processes and Landforms

ABSTRACT: Biogeomorphology has been expanding as a discipline, due to increased recognition of the role that biology can play in geomorphic processes, as well as due to our increasing capacity to measure and quantify feedback between biological and geomorphological systems. Here, we provide an overview of the growth and status of biogeomorphology. This overview also provides the context for introducing this special issue on biogeomorphology, and specifically examines the thematic domains of biogeomorphological research, methods used, open questions and conundrums, problems encountered, future research directions, and practical applications in management and policy (e.g. nature-based solutions). We find that whilst biogeomorphological studies have a long history, there remain many new and surprising biogeomorphic processes and feedbacks that are only now being identified and quantified. Based on the current state of knowledge, we suggest that linking ecological and geomorphic processes across different spatio-temporal scales emerges as the main research challenge in biogeomorphology, as well as the translation of biogeomorphic knowledge into management approaches to environmental systems. We recommend that future biogeomorphic studies should help to contextualize environmental feedbacks by including the spatio-temporal scales relevant to the organism(s) under investigation, using knowledge of their ecology and size (or metabolic rate). Furthermore, in order to sufficiently understand the ‘engineering’ capacity of organisms, we recommend studying at least the time period bounded by two disturbance events, and recommend to also investigate the geomorphic work done during disturbance events, in order to put estimates of engineering capacity of biota into a wider perspective. Finally, the future seems bright, as increasingly inter-disciplinary and longer-term monitoring are coming to fruition, and we can expect important advances in process understanding across scales and better-informed modelling efforts. © 2020 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd

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This Special Issue

Ecology in its strictest sense is the study of the relationships between biota and its physical environment and was already defined as such by geographer Alexander von Humboldt and botanist Aimé Bonpland (Humboldt and Bonpland, 1805). Around the same time, the discipline of geomorphology was also established, with its focus on the dynamics of the physical environment, by studying the processes forming landscapes and its landforms (Chorley *et al.*, 1964). The first biogeomorphic research was published by Darwin (1899), however, biogeomorphology as a defined sub-discipline of

geomorphology, which addresses the two-way interaction between biotic and dynamic abiotic landscape elements, only had its origins in the 1970s and has been growing considerably since then (e.g. Viles, 1988, 2019; Coombes, 2016). Significant theoretical, methodological and thematic advances have been made with the recognition of ecological factors affecting landform development. Similarly, the importance of geomorphology for ecological functioning and development has also been recognized by ecologists (e.g. Vaughan *et al.*, 2009; Vaughan and Ormerod, 2010). Yet, developing theory, methods and quantifying processes at the abiotic/biotic interface remains challenging due to the interdisciplinarity of

biogeomorphology, integrating concepts from ecology, evolutionary biology, engineering, geomorphology, geology and Quaternary science (e.g. Knox, 1972; Naylor, 2005; Wheaton *et al.*, 2011; Larsen *et al.*, 2018; Viles, 2019).

Viles (2019) recognizes three key thematic areas, which represent geomorphological units, for which a brief review of the state of science is given below. These key areas are also represented in this special issue:

- Coastal sedimentary environments (5 contributions to this special issue).
- Fluvial and riparian environments (12 contributions to this special issue).
- Hillslope (from alpine to arid) (7 contributions to this special issue).
- Biogeomorphological studies on coastal sedimentary environments, including a wide variety of coastal landforms and landscapes. Studies are being conducted on individual seagrass beds, salt marshes, mudflats, beaches and dunes. At the small scale, many contributions have focused on the contributions of individual or small groups of plants or animals on geomorphological processes within reefs (e.g. Salvador de Paiva *et al.*, 2018; Schotanus *et al.*, 2020), mudflats and marshes (e.g. Temmerman *et al.*, 2003; Townend *et al.*, 2011; Nolte *et al.*, 2013; Schwarz *et al.*, 2015; Coleman and Kirwan, 2019; Schepers *et al.*, 2020) and coastal dunes (e.g. Gao *et al.*, 2020). Larger-scale nested coastal landforms such as barrier islands, estuaries and deltas also often feature. A key focus of these larger-scale studies has been on the understanding of (multiple) ecological stable states (van de Koppel *et al.*, 2001; Marani *et al.*, 2013; Moffett *et al.*, 2015), how biogeomorphic coastal environments such as barrier islands, estuaries and deltas respond to (relative) sea-level rise and anthropogenic influences (e.g. Day *et al.*, 2008; van de Lageweg and Slangen, 2017; Nienhuis *et al.*, 2020), as well as evaluating carbon storage and exchange capabilities on a global scale (Kirwan and Mudd, 2012; Rovai *et al.*, 2018). A variety of methods to decipher coastal biogeomorphological feedback systems have been employed, including field observations (e.g. Neumeier and Amos, 2006; Turner *et al.*, 2006; Coleman and Kirwan, 2019; Schepers *et al.*, 2020), laboratory studies (e.g. Möller *et al.*, 2014; Spencer *et al.*, 2016; Lokhorst *et al.*, 2019; Yuan *et al.*, 2019), and numerical modelling (e.g. Fagherazzi *et al.*, 2012; D'Alpaos and Marani, 2016; Nardin *et al.*, 2018, 2020; Lera *et al.*, 2019).

Fluvial and riparian environments have long been a focus area for biogeomorphological research, with several reviews (e.g. Bätz *et al.*, 2015; Politti *et al.*, 2018; Polvi and Sarneel, 2018; O'Briain, 2019; Viles, 2019) and special issues (e.g. references in Coombes, 2016; Picco *et al.*, 2017; Thoms *et al.*, 2018) available. In agreement with the coastal sedimentary environment, a distinction between different scales and associated fluvial landforms can be made, although cross-scalar linkages are increasingly a focus area (Gurnell *et al.*, 2019; Kleinhans *et al.*, 2019; Rice *et al.*, 2019). At the small scale, work is done in understanding the role of vegetation, and particularly animals, on hydrodynamics and sediment dynamics (DeAnna and Wohl, 2019; Dong *et al.*, 2019; Grenfell *et al.*, 2019; Gurnell *et al.*, 2019; Mason *et al.*, 2019; Rice *et al.*, 2019; Jerin and Phillips, 2020). At larger spatial and temporal scales, GIS and remote sensing are increasingly used to monitor and evaluate the evolution of fluvial riparian environments (Gurnell *et al.*, 2019; Kleinhans *et al.*, 2019; Corenblit *et al.*, 2020; Mossa *et al.*, 2020). A particular focus is set on river bars and how their dynamics are affected by plant and ecological traits. Additionally, studies employing

geological records have demonstrated the substantial effect (land) that plants have had on fluvial systems on earth (e.g. Davies and Gibling, 2011; Larsen *et al.*, 2019). Numerical (e.g. Oorschot *et al.*, 2016; Kleinhans *et al.*, 2019) and physical (e.g. Tal and Paola, 2010; Lokhorst *et al.*, 2019) modelling work has further highlighted the key role vegetation can play in shaping fluvial environments across all scales. Finally, other freshwater environments such as lakes show a range of biogeomorphic processes (e.g. algal blooms affecting light penetration; Scheffer *et al.*, 2001), but these are not always labelled as such or studied by geomorphologists.

Biogeomorphic feedback systems have been studied on hillslopes also on various scales. At the small scale, research has focused on the relationships between bioweathering, bioerosion, and bioprotection (e.g. Naylor *et al.*, 2012; Coombes *et al.*, 2013; Coombes, 2016). At a larger scale, several efforts are aimed at investigating the effects of animal burrowing on sediment transport (e.g. Yoo *et al.*, 2005; Haussmann, 2017; Mauri *et al.*, 2019; Román-Sánchez *et al.*, 2019a, 2019b). Vegetation is also at the heart of hillslope research, with studies exploring the effects of trees and plants on soils and geomorphology (e.g. Pawlik *et al.*, 2016; Pawlik and Šamonil, 2018; Giaccone *et al.*, 2019). Biogeomorphic evolution and succession across the decadal to centennial scale have also been studied by contrasting hillslopes with different aspects (McAuliffe *et al.*, 2014; Stavi *et al.*, 2018; Carriere *et al.*, 2020).

This special issue builds on previous work (Viles and Naylor, 2002; Coombes, 2016; Viles, 2019) by covering the whole discipline of biogeomorphology with a particular focus on contributions exploring new research fields and conceptualizing and quantifying processes, rates, and feedback systems at different spatio-temporal scales.

First, this special issue was inspired by a series of European Geosciences Union (EGU) sessions on biogeomorphology (2017–2020). Over the last 4 years, a total of 116 exciting contributions were presented during these EGU sessions, covering a broad spectrum of biogeomorphological research. Some key contributions addressed, for example, the importance of biogeomorphic feedback for creating spatial heterogeneity (Wohl, 2017), how biogeomorphic feedback systems operate at the intra- and inter-species level (Corenblit *et al.*, 2017; Schulte Ostermann *et al.*, 2017), the sensitivity of biogeomorphic feedbacks to the considered spatio-temporal scale (Eichel, 2017; Balke, 2018), and the possibility of detecting a signature of life on the Martian landscape (Viles, 2020). Some of the papers presented during the biogeomorphology sessions at EGU are now part of this special issue. Some others were not presented at EGU but included via the special issue advertisement and review procedure. Additionally, a few contributions shedding light on spatio-temporal biogeomorphic processes not included yet were sourced from the *Earth Surface Processes and Landforms* journal.

The 25 contributions to this special issue cover a large range of landscape settings: mountains (3), hillslopes (3), fluvial (12), coastal (5), and deserts (1). Animals (7) and vegetation (16) are the most studied biological agents. One contribution looks at the effects of biofilms on rocky shores (1).

The contributions use a variety of methods to quantify biogeomorphic processes, rates, and feedbacks at different spatio-temporal scales. A total of 16 papers assess processes and feedbacks by conducting field work, whereas 6 contributions use numerical model simulations to obtain a better understanding of biogeomorphological feedbacks. Two studies performed controlled laboratory experiments.

The above summary of landscape settings and applied methods covered in this special issue illustrates the great

variety of environments in which interactions between abiotic and biotic systems are taking place, as well as the manifold of techniques required to better understand them. As also illustrated in this special issue, some of these interactions take place across small spatio- and temporal scales (e.g. biofilms affecting grain sediment transport), whereas others happen across entire landscapes.

In order to go beyond a basic summary of these published articles, we use the 22 contributions in this special issue in combination with new literature to analyse where the field is heading, and which challenges arise across the discipline of biogeomorphology. We discuss these challenges first in general, and then more specifically with regards to the publications in this special issue. We anticipate that by using the articles in this special issue as examples, the conceptual considerations become less abstract to the reader, and we can derive a state-of-the-art in biogeomorphology, identify future research gaps, and most importantly facilitate the continuation of the fascinating discussions for which this discipline is known.

Conceptualizing and Quantifying Biogeomorphological Processes, Rates, and Feedbacks

Understanding feedback between biological and geomorphological processes is becoming increasingly important as new 'nature-based solutions' (NbS) projects emerge and also increasingly find their way into management (i.e. restoration projects). Despite recent advances, the conceptualization and quantification of the processes, rates, and feedbacks between geomorphology and ecology often remain limited (Baptist, 2001), particularly in systems that are sensitive to human-induced or natural environmental change (e.g. high-mountain and polar environments, deserts, hillslopes, rivers and wetlands, salt marshes and deltas). In this sense, Mossa *et al.* (2020) point out that the anthropogenic impact usually covers the entire length of river corridors and, as shown by Corenblit *et al.* (2020), may shift biogeomorphic system state. Hence, when it comes to NbS in river management, it is essential to understand how human activities may dominate, and may even be considered as a key zoogeomorphic agent, placed within the biogeomorphic systems of the Anthropocene.

Substantial advances have been made in understanding, quantifying, and modelling feedbacks between vegetation, fluvial, and coastal dynamics. In this issue, Jerin and Phillips (2020) focus on the influence of mature tree species in creating pools in bedrock channels, while Kleinhans *et al.* (2018, 2019), Gurnell *et al.* (2019), and Corenblit *et al.* (2020) focus on the relationship between successional vegetation and sediment transport in fluvial systems. Stavi *et al.* (2018), Dong *et al.* (2019), Larsen *et al.* (2019) and Carriere *et al.* (2020) investigate landscape stability and evolution due to the influence of vegetation on surface processes (and vice versa). Within most of these studies, the feedback systems between the shallow groundwater and soil water, and vegetation dynamics, emerges as important in driving geomorphic feedbacks. In contrast, Giaccone *et al.* (2019) find that in alpine environments, morphodynamic processes and soil moisture are important to vegetation species distribution, yet temperature plays the dominant role. Vegetation is also an important factor controlling the dynamics in coastal areas. Coleman and Kirwan (2019), Lera *et al.* (2019), Nardin *et al.* (2020) and Schepers *et al.* (2020) find that salt marsh and submerged aquatic vegetation impacts sediment transport and morphological evolution of coastal features, such as tidal

marsh platform or river mouth bar. In particular, they showed ecological feedbacks on sediment transport facing sea-level rise, with different approaches such as field survey, numerical modelling, and satellite image analysis. Microbial communities are often overlooked as biotic engineers. A study of Yuan *et al.* (2019) finds that lithobiotic biofilms contribute to shoreline rock decay through intensified magnitude and an increased number of cycles of expansion and contraction.

Discoveries can still be made on how animals change surface processes through environmental feedback systems, like beavers causing long-lasting vegetation change in riparian corridors (DeAnna and Wohl, 2019). Mason *et al.* (2019) and Rice *et al.* (2019) explore the potential of case-building caddisfly larvae and fish feeding behaviour in changing in-channel sediment transport, while Grenfell *et al.* (2019) show for the first time how the ecosystem engineering of earthworms changes surface processes in riparian wetlands in South Africa.

Mauri *et al.* (2019) and Román-Sánchez *et al.* (2019a, 2019b) employ new techniques in quantifying the contribution of biota on sediment transport. Both studies indicate a surprising contribution of biota to the overall hillslope and river sediment flux.

Time and Space in Biogeomorphology

Geomorphology is undoubtedly within a new era, one that recognizes the role of biotic factors in governing geomorphic processes across a wide range of spatial and temporal scales (Larsen *et al.*, 2018). In ecology, scales of space and time are considered as being coupled. Resources for biota are available in multiple forms, and time is available at multiple scales (Post, 2019), from milliseconds, seconds, minutes, hours, days, weeks, years to decades (*x*-axis in Figure 1b). These are to a great extent related to metabolic rates and body size, or mass of the organism (*y*-axis in Figure 1b) (Schmidt-Nielsen, 1984; West *et al.*, 1997; Brown *et al.*, 2004; Allen and Holling, 2010).

In contrast, geomorphologists traditionally divide time into steady (here: steady state), graded (here: dynamic equilibrium), and cyclic (here: cyclical state) (Schumm and Lichty, 1965) (Figure 1a). Temporal and spatial scale levels are also coupled in geomorphology, described as the hierarchy of scales (De Vriend, 2001). Cyclic, also referred to as geologic time, considers for example one sedimentary cycle of a mountain range or an entire coast (Figure 1b). Within graded time, surfaces are in dynamic equilibrium and adjust, for example, to base-level lowering or a changing climate. Hence, investigated time scales range from river reaches/hillslopes/shorefaces to entire landscapes or coastal margins (Figure 1b). During steady time periods, larger spatial scale morphology is considered as stable, and finer scale processes are investigated. Mechanistic modelling addresses mostly the scale of the steady state (Figure 1g). The longer the time period and the larger the spatial scale considered, the more drivers and processes are involved, and complexity increases (Figure 1d). This results in a more statistical or rule-based modelling approach towards the investigation of biogeomorphic systems (Figure 1g).

The close coupling of time and spatial scale in both ecology and geomorphology has, for example, set the base for the widely used river continuum concept (Vannote *et al.*, 1980) and its derivatives. When combining observations of ecologic and geomorphic time and space (Figure 1b), Baptist (2001) summarizes that there is evidence for feedbacks between biota and physical (river) processes on all spatio-temporal scales, however the influence of biota seems to become stronger the smaller the scales (green shading in Figure 1b). In turn, this means that at larger spatio/temporal scales, tracking the signature of biota on the earth's surface is more challenging (Dietrich

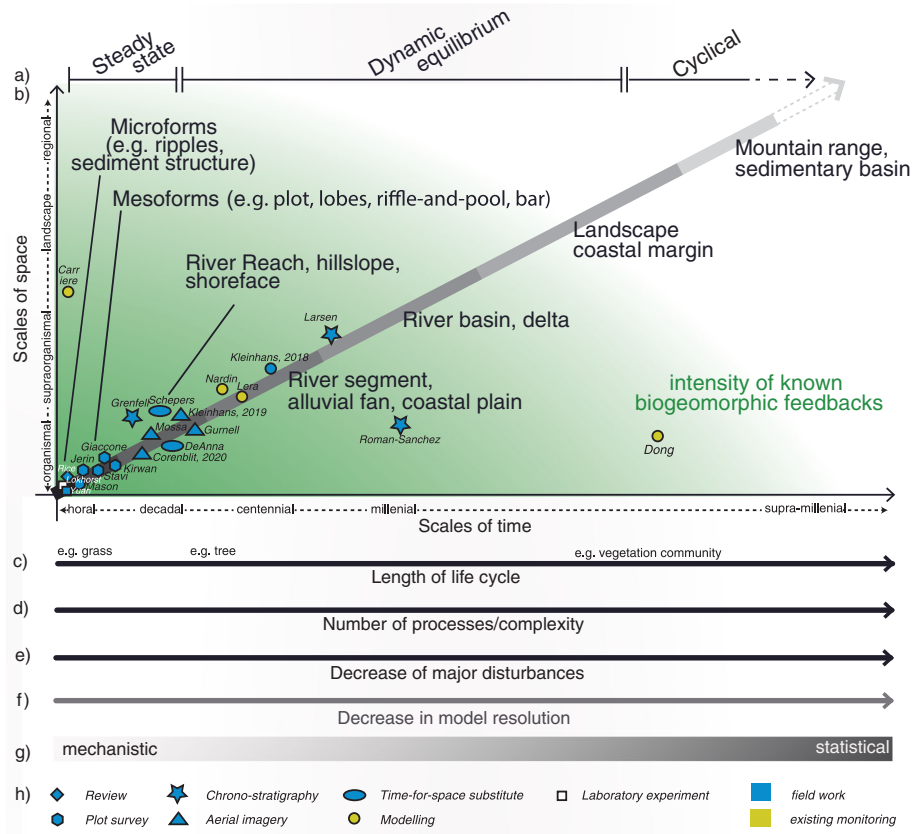


Figure 1. Relationship between representative timescales over which biological, ecological, and evolutionary processes occur, and the spatial scaleover which they operate (based on Post, 2019). This is based on the relationship between geomorphic time spans (a) and geomorphic units (e.g. ripples to mountain range) (b), across which specific geomorphic processes are relevant (modified from Baptist, 2001). Note that they- and x-axes in b) are dimensionless, and the description (horal–supra-millennial and organismal–regional) is only indicative. The processes occurring over the shortest time scale (hourly–annual) tend to occur at the scale of individual organisms within the smallest geomorphic unit (microforms, bottom left of b). Processes unfolding beyond annual time scales tend to represent supra-organismal dynamics, including community dynamics and distributional shifts (b, c). These are typical for the geomorphic units including river reach/hillslope/shoreface up to the landscape, coastal margin, mountain range, and sedimentary basin geomorphic units (top right end of b). Studies included in this special issue are added to the plot in b) (as different shapes) which also refer to the methods used for spatio-temporal analysis (h). With increasing spatio-temporal scale, the number of processes involved increases (d), however, the number of major disturbances decrease with increasing spatio-temporal scales (e). The increasing number of processes also increases complexity (d), which in turn leads to a relative decrease in model process resolution with increasing spatio-temporal scale (f), and therefore to an increasing reliance on statistical rather than mechanistic models (g).

and Perron, 2006). One reason for this could be that with increasing scale, the number of processes (and drivers; Figure 1d) in (bio)geomorphic systems makes identification of process-response increasingly difficult.

Recurrence intervals and intensity of disturbance events are highly variable between ecosystems. Disturbances often originate in extreme geomorphic events (the type of disturbance on which we focus here), where the magnitude increases with decreasing frequency. Most geomorphic work is performed during such events. When relating this to the observation that time and metabolic rates and body size of organisms relate to each other (see above), one can hypothesize that the larger the metabolic rate/body size of an organism, the less frequently a relevant disturbance occurs (Figure 1b). For example, for a macroinvertebrate which lives for 1 year in a river pool, an annually recurring summer thunderstorm followed by a sudden flood event is a relevant disturbance, while an established tree living for several hundred years may be disturbed by a 100-year recurring flood event. In turn, this means that when investigating biogeomorphic systems, the minimum time window that needs to be considered is that between and including two extreme events relevant to the species investigated. And this time window generally increases with the metabolic rate and life span of the organism investigated. It is, however, important

to note that when investigating environmental feedbacks including a strong component of trophic cascade, this relationship might break down, as small processes can then also affect larger organisms.

In a first window, termed the *window of opportunity* (Balke *et al.*, 2011), the time between two disturbance events needs to be large enough to allow bio-engineers (e.g. plants) to settle. After establishment, a *biogeomorphic feedback window* is entered, in which biogeomorphic feedbacks can be established (Eichel *et al.*, 2016; Hortobagyi, 2018). Within this time period, organisms can thrive and engineer their environment, so that they become more resilient to disturbances (Stallins and Corenblit, 2018; Corenblit *et al.*, 2020). If this window is too short, the long-term (e.g. decades) establishment of organisms is generally less successful (Corenblit *et al.*, 2020). However, the rate, success, and engineering activity of organisms between two disturbance events may also depend on low-magnitude and high-frequency extreme events, in this context termed *pulses* (Junk *et al.*, 1989). These pulses may provide essential resources (e.g. nutrients, water) that may be necessary for successful organism establishment and growth in biogeomorphic systems (Bätz *et al.*, 2015, 2016).

In other words, biota have the ability to change surface processes within the time window between two relevant

geomorphic disturbance events. The rate at which organisms engineer their environment during this window may depend on the resource fluxes originating in pulses. Though not necessarily the case, such modifications then have the potential to also change surface processes, even during disturbance events, which then increases the resilience to disturbance events. It becomes increasingly clear that the processes and feedbacks invoked by both phases, the geomorphic disturbance events and the biotic-driven processes within biogeomorphic feedback windows, depend on each other, and the biogeomorphic evolution of the surface can only be understood when researching both phases. This approach requires us to cross scale boundaries. For example, in this issue, Larsen *et al.* (2019) point out that the incision of a river segment, driven by physical thresholds and processes, can only happen because of a biotic-driven phase of stability and aggradation beforehand. Hence, stretching biogeomorphic studies on larger scales to cover full disturbance cycles, or even beyond, remains one main challenge for the discipline. This challenge has been recognized, and an increasing amount of studies in this special issue and beyond (Figure 2) tackle the decadal and centennial time scale. Studies employ a variety of methods to stretch enquiries, including chrono-stratigraphical approaches, modelling, space-for-time substitutes, and laboratory experiments.

(Bio)geomorphic microforms (1–10 m in size)

Discoveries can still be made about the influence of variable animal species on surface processes. In this special issue, the influence of aquatic animals on river sediment transport is described at the scale of geomorphic microforms (1–10 m in size) (Mason *et al.*, 2019; Rice *et al.*, 2019). Mason *et al.* (2019) collected data on the mineral sediment use of caddisfly larvae in river riffles. Different species used different ranges of grain sizes (mostly coarse sand and fine gravel) and might influence river processes by directly affecting the distribution and mobility of this sediment size range. Rice *et al.* (2019) summarize how fish disturb and condition bed materials, which has implications for sediment mobility. By coupling these geomorphological effects with monitoring data on species occurrence, or species distribution models, a first estimation can be made about the influence of species on sediment dynamics on a larger spatial scale (e.g. entire catchments) (Rice *et al.*, 2019). However, it remains important to validate these models, as the geomorphic effect of biota is

highly context dependent, and the intensity of feedback systems might decrease with increasing spatio-temporal scale (Figure 1b). Lokhorst *et al.* (2019) identify small plant species which were argued to exhibit similar hydraulic characteristics on a microscale to plant vegetation species in the natural environment. These results could help to recreate diverse vegetation communities in flume experiments, mimicking real-world applications and hence facilitating upscaling of results from flume experiments. Yuan *et al.* (2019) use an environmental chamber to simulate variable isolated environmental factors acting on rock surfaces of a supratidal sandstone colonized by biofilm. This not only allows investigation of processes separately, but also over a much shorter time period. The study indicates that light exposure is one of the main drivers of biofilm-induced weathering of supratidal sandstone.

(Bio)geomorphic mesoforms (10–100 m)

Stavi *et al.* (2018) and Giaccone *et al.* (2019) investigate vegetation–environment interaction on a bi-annual basis using repeated plot surveys. Plot scales are very common in ecological and soil erosion studies that focus on hillslopes. This approach allows the authors to investigate seasonal and annual variability. Both studies find geomorphology to be an important factor within a wider range of environmental factors (green shading in Figure 1b, intensity of known biogeomorphic feedbacks).

Decadal time scale

Most studies in this special issue (Figure 1), and in biogeomorphology in general (Figure 2), are conducted on a decadal time scale. This is likely because the decadal time scale is associated with a frequently investigated geomorphic spatial scale and associated geomorphic units (river reach, hillslope, shoreface) (Figure 1). There are a variety of techniques that support research at a decadal time scale, and most of them involve some type of remote sensing. However, there are also other methods, for example DeAnna and Wohl (2019) substitute space for time in analysing a series of beaver reaches, in order to gain an insight into how river floodplain heterogeneity, which is a function of beaver modification, changes through time. They find that even after abandonment, beaver-induced heterogeneity may persist for up to about 30 years even after beaver abandonment. Similarly, Schepers

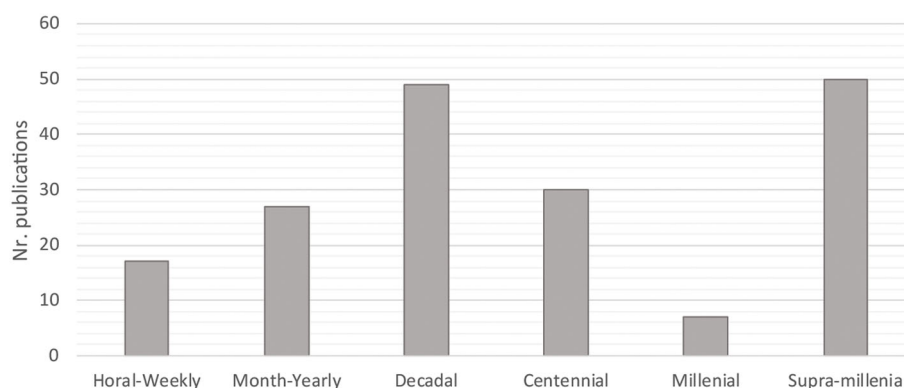


Figure 2. Number of publications on biogeomorphology with respect to their time scale. A Web of Science search on ‘Biogeomorphology’ (June 2020, keywords can be found in Annex 1) was filtered with the respective keywords for a particular time scale. Note that a search using the keywords for ‘Biogeomorphology’ only would have led to a higher number of publications (778 instead of 180). Even though this is a rough analysis of the published literature, we hypothesize that it gives a representative view of how biogeomorphic publications spread along the temporal scale. Also note that the supra-millennial column covers time periods from 100 000 years up to geological eras, and hence is over-proportionally large.

et al. (2020) use a spatial gradient of decreasing marsh area and increasing shallow open water area in a salt marsh system (USA) to investigate early warning signs of marsh vulnerability to sea-level rise. Grenfell *et al.* (2019) find that earthworms create a hummock–hollow microtopography in seasonal wetlands in South Africa. The authors were able to quantify the slow ecosystem engineering of earthworms by using a combination of field observations of earthworm activity and Pb210 sediment dating technique. The role of vegetation in dynamic river channels and floodplains on a decadal scale is addressed by Gurnell *et al.* (2019), Kleinhans *et al.* (2019) and Corenblit *et al.* (2020). These studies apply remote sensing methods to archival aerial images amongst other imagery to facilitate analysis on a decadal scale. Corenblit *et al.* (2020) also have a dataset of an older survey available, with which they relate vegetation bar succession to historic changes in gravel mining and flooding frequency and magnitude. Kleinhans *et al.* (2019) find a surprising consistency of vegetation patches in a dynamically meandering river reach. Gurnell *et al.* (2019) determine conditions and feedbacks for the establishment of river islands in a braided river reach by combining remote sensing with field observations, and a seed bank experiment. Through Delft3D, Nardin *et al.* (2020) quantify the evolution of a coastal bay colonized by salt marsh and submerged aquatic vegetation. They investigated feedback between ecology and sediment transport in an erosional system. The study shows the delicate equilibrium between internal bay processes and offshore waves.

Centennial time scale

The number of biogeomorphic studies drops off sharply when moving onto the centennial time scale (Figures 1 and 2). This is likely because instrumental records are mostly limited to recent decades, and only very rarely expand further back in time. At the same time, most sedimentary dating tools are not accurate enough to cover this time period accurately. Nevertheless, some studies using a modelling approach have focused on this comparably difficult time period. Kleinhans *et al.* (2018) analyse the longer-term feedback between cohesive floodplain deposition, vegetation and river channel pattern change in a Delft3D modelling study. For example, on this time scale, hysteretic loops can develop in model runs in which vegetation and mud increase over time. Also making use of Delft3D, Lera *et al.* (2019) quantify the evolution of a river mouth bar colonized by submerged aquatic vegetation. They studied feedback among ecology and sediment transport, which reveals the important role of submerged aquatic vegetation on sediment sorting in estuarine environments.

Millennial time scale

Without doubt, identifying biogeomorphic feedbacks on a millennial time scale is very challenging, because most sedimentary records alone do not yield enough information to do so. Unfortunately, similar to the centennial time scale, geomorphic cyclicality and hysteresis have been observed mostly over longer time scales, and hence there is a clear need to investigate these time scales in order to increase our understanding of biogeomorphic systems. One promising approach is to use the chronostratigraphy of sedimentary archives including palaeo-environmental information through, for example, botanical remains, in combination with analysis of aerial imagery and field observation from shorter time scales. For example, Larsen *et al.* (2016, 2019) show that vegetation controls sediment aggradation in a tropical river floodplain during periods

of low disturbance. A short (decadal) alluvial knickpoint then causes widespread erosion, dewatering of peat layers, and finally fire, which in combination destroys the ecosystem. The authors argue that this evolution is part of a cyclical behaviour, in which aggradation and erosion depend on each other. In a coastal environment, Coleman and Kirwan (2019) investigate the role of vegetation diebacks on a smaller area in a marsh environment, which caused local subsidence and erosion because of a loss of surface and subsurface stability on an annual basis. The authors show that erosion originating in vegetation dieback is only one part of a complex marsh-wide history, in which erosion and sediment redistribution is necessary to maintain overall marsh elevation above sea level (Hopkinson *et al.*, 2018).

Crossing Spatio-temporal Scales in Biogeomorphology

In biogeomorphology, datasets of biologic and physical forms and processes are being combined. As a comparatively young sub-discipline of geomorphology, there is still a need to develop models to simply conceptualize the interactions between biology and geomorphology over variable spatio-temporal scales (Stavi *et al.*, 2018; Dong *et al.*, 2019; Gurnell *et al.*, 2019; Larsen *et al.*, 2019; Corenblit *et al.*, 2020). In the same sense, observations between biological and physical data at smaller scale are often used in simple rule-based models that allow extrapolation of the general magnitude of effects to large scales (Mason *et al.*, 2019; Rice *et al.*, 2019). Concepts of scale breaks and cross-scale dynamics are well established in ecology, and slowly find their way into biogeomorphology, for example Panarchy (Eichel, 2017; Hortobagyi, 2018; Stallins and Corenblit, 2018). Panarchies are hierarchically nested and mutually reinforcing sets of processes that operate at different spatial and temporal scales, ranging, for example, from a leaf up to the biosphere from days to geological epochs (Gunderson and Holling, 2002). Scale levels are separated by discontinuities in key variables and the set of processes subject to adaptive cycles of collapse and renewal (Allen and Holling, 2008). Cross-scale dynamics are then related through *Remembering* (*sensu* memory), which allows cascading legacies and instabilities from the upper to the lower scales. The opposite of remembering is *Revolt* (*sensu* disruption/change of a cycle), which allows the lower cycle to exert its influence on a vulnerable phase of the upper scales (Allen and Holling, 2010; Stallins and Corenblit, 2018). By understanding the characteristics and inter-relations of these cycles and their scales, it may be possible to evaluate system stability and resilience with particular utility for developing sustainable process-based management strategies (see next section). Most interestingly, it may be possible to identify the points at which a biogeomorphic system is capable of positive change, and to indicate the points where it is vulnerable or favourable for change. The likely challenge here is going to be the availability of data over sufficiently long time scales and large spatial scales but at sufficient spatial granularity and temporal resolution to illustrate these processes concretely.

Biologic datasets often originate in monitoring, and contain data on a single species or on a species community. Species distribution models are often used for upscaling monitoring data. The analysis, and also the modelling and hence upscaling and the crossing of spatio-temporal scales, is mostly based on statistical principles. Similarly, the analysis and monitoring of physical processes are based on field data, but then modelled and upscaled based on the physics of the processes involved.

This poses two main challenges to the discipline: firstly, bridging the gap between modelling studies and field data collection is undoubtedly one of the largest issues that the biogeomorphic community encounters; secondly, modelling of biophysical systems additionally suffers from the fact that geomorphology, as a physical science, models mechanistically, while biological processes are most often treated as stochastic or with simple correlations (Vaughan *et al.*, 2009; Figure 1g). Due to the complexity of modelling physics and biological processes together, often a simplification of one or both disciplines reduces the accuracy of the results. The modelling combination of both scientific disciplines is widely used in this special issue on biogeomorphology. In fact, numerical models are used to couple vegetation and sediment transport through different modelling approaches and environments in this special issue: Kleinhans *et al.* (2018, 2019), Lera *et al.* (2019), Carriere *et al.* (2020), and Nardin *et al.* (2020) use available mechanistic models (Delft3D and Landlab); Dong *et al.* (2019) and Román-Sánchez *et al.* (2019a) use analytical models to solve a diffusion–advection equation and calculate the diffusivity constant and erosion–deposition rates; while Stavi *et al.* (2018), Coleman and Kirwan (2019), Corenblit *et al.* (2019), and Giaccone *et al.* (2019) take a more ecology-based approach and employ statistical models. In order to analyse the influence of explanatory environmental variables (e.g. elevation, temperature) on species cover and species richness, Giaccone *et al.* (2019) used generalized linear and generalized additive models. Then, additional environmental factors (a morphodynamics index and the type of earth surface processes) were added to the baseline model to test their additional effect in an advanced model. Corenblit *et al.* (2019) present a statistical approach (CLPM: cross-lagged panel model) which may be used to identify and characterize causal relationships between different variables measured at different points in time in biogeomorphologically evolving systems. The method consists of a series of correlations between a variable at time t with itself at $t+1$ and other variables at respectively t and $t+1$. This process is repeated for all variables.

Biogeomorphological models must couple biological and geomorphological changes at different time scales. Increasing the time scale of predictions magnifies errors and models can develop to an unrealistic landscape state. Numerical models are playing an increasingly important role, because they can provide future scenarios of landscape evolution, including biogeomorphic feedbacks under different forcings. Following Murray's (2003) model classification, numerical models can be arrayed along an axis having at the two extremes simulation models, like Kleinhans *et al.* (2019), Lera *et al.* (2019) and Nardin *et al.* (2020), and exploratory models, like Dong *et al.* (2019). Simulation models aim to reproduce the natural system as accurately as possible. On the contrary, highly simplified exploratory models aim to understand the general behaviour of the system, by purposely avoiding the representation of as many processes as possible, and by following the emergent property viewpoint (e.g. Goldenfeld and Kadanoff, 1999).

Models are used to reveal specific physical parameters governing the landscape dynamics, and this knowledge can be tested and adapted, and then transferred to other areas worldwide. Kleinhans *et al.* (2018, 2019), Lera *et al.* (2019), and Nardin *et al.* (2020) apply a hydrogeomorphological modelling tool, Delft3D, that includes a complexity of physical and ecological parameters. These can reproduce closely the system modelled. However, a miscalibration of one parameter might lead to unrealistic results. As a result, care must be taken during the initial calibration of these models, including field surveys and readily available data, and a sensitivity analysis of the most critical variables. These initial steps are critical for

upscaling the results to a larger time and spatial scale. Field surveys must be linked with modelling needs and focus on certain key parameters which might help to strongly validate numerical models. An intensive communication between field researchers and modellers will boost the precision of numerical model forecast. Coleman and Kirwan (2019) and Schepers *et al.* (2020) are examples of field studies and data analysis that can offer different modelling applications.

Biogeomorphological Research and Nature-Based Solutions

NbS involve working with natural processes and enhancing nature to address societal challenges (e.g. Cohen-Shacham *et al.*, 2016; Faivre *et al.*, 2017; Seddon *et al.*, 2020). They involve a broad range of actions, such as the protection and management of natural and semi-natural ecosystems, the incorporation of green and blue infrastructure in urban areas, and the application of ecosystem-based principles to agricultural systems. The concept is based on the understanding that healthy natural and managed ecosystems produce a wide range of services on which human wellbeing depends, from controlling floods and stabilizing shorelines and slopes, to providing clean air and water, food, fuel, medicines, and storing carbon. NbS are an 'umbrella concept' for other established 'nature-based' approaches, such as ecosystem-based adaptation (EbA) and ecosystem-based mitigation, eco-disaster risk reduction and green infrastructure.

NbS are increasingly used in the management of coastal, fluvial, and hillslope environments. For example, mega-nourishments employing waves and currents to naturally redistribute sand along the coast are implemented for coastal safety as well as creating opportunities for ecology and society (e.g. Stive *et al.*, 2013; De Vriend *et al.*, 2015; Cooke *et al.*, 2020). Similarly, many NbS have been tested and implemented in fluvial environments, ranging from catchment-scale natural flood management (e.g. Rijke *et al.*, 2012; Edelenbos *et al.*, 2017; Lane, 2017; Polvi *et al.*, 2020) programmes involving at a local or regional level, amongst others, lowering of groins, removing hydraulic obstacles, as well as creating retention reservoirs or woody dams as a means to slow the flow (Dixon *et al.*, 2016). On hillslopes, NbS are proving a cost-effective long-term solution for hydrological risks and land degradation (e.g. Keesstra *et al.*, 2018).

The attractiveness of NbS comes from their potential to protect society from climate change impacts while slowing further warming, supporting biodiversity, and securing ecosystem services. Yet, many NbS have not rigorously been assessed in terms of reliability, cost-effectiveness, and resilience to climate change (Lane, 2017; Firth *et al.*, 2020). It is important to understand the value and limitations of NbS for proper use (e.g. Firth *et al.*, 2020; Seddon *et al.*, 2020).

NbS can be employed across a variety of spatial and temporal scales. Ranging from local woody dams to entire river reaches (Dixon *et al.*, 2016; Lane, 2017), and from individual replanted seagrass patches to coastal mega-nourishments (De Vriend *et al.*, 2015). This issue demonstrates that biogeomorphological feedback systems (i.e. the feedback systems NbS are employing) are inherent for all spatial and temporal scales (Figure 1). Yet, many contributions within this issue highlight that our understanding of biogeomorphic feedback systems is incomplete and, importantly, differs depending on the scale considered. For the smallest scales, a mechanistic understanding is established for some feedback systems (Grenfell *et al.*, 2019; Mason *et al.*, 2019) but many other

feedback systems at the smallest scales remain unresolved to date (e.g. microbial effects on sediment dynamics, microbial effects on extraterrestrial bodies). For intermediate scales (decadal to centennial), the literature shows a peak in contributions (Figure 2), likely related to the rise of numerical modelling (Kleinbans *et al.*, 2019; Lera *et al.*, 2019; Nardin *et al.*, 2020), as well as remote sensing techniques (Gurnell *et al.*, 2019; Corenblit *et al.*, 2020) for biogeomorphological research. At the largest scales, a more rule-based understanding of system behaviour is established (Larsen *et al.*, 2019; Carriere *et al.*, 2020). In other words, biogeomorphological research is conducted at many scales and elucidating many feedback systems, but there is now a particular need for research into cross-scalar effects and how biogeomorphology can contribute further to environmental management, for example by employing NbS.

In the context of space and time, and inspired by the panarchy approach, we propose three ways forward for a better application of biogeomorphic research and findings in NbS:

- 1 Explicit definition of scale(s) of interest and accounting for cross-scale dynamics. When searching for adequate NbS, it is essential to define the scale(s) of interest and assess the strength of cross-scale dynamics (e.g. Allen and Holling, 2010; Naylor *et al.*, 2017; Gurnell *et al.*, 2019; Johnson *et al.*, 2020; Polvi *et al.*, 2020). This may allow weighting how changes at one level may propagate across scales, or how legacies at the higher scale may hinder/reinforce desired management goals.
- 2 Allow for the cyclicity of natural processes. When applying NbS, it is important to be aware of the cyclic nature of biogeomorphic processes (Allen and Holling, 2010; Larsen *et al.*, 2019). For managers of coastal, fluvial and hillslope environments, a stable system may be preferable. However, for long-term cost-effective and sustainable application of NbS (Johnson *et al.*, 2020), it is important to recognize the importance of naturally occurring unstable phases in biogeomorphic systems (e.g. succession after disturbance; Toone *et al.*, 2014) and therefore account for the associated uncertainties during planning (Darby and Sear, 2008).
- 3 Set up integrated (long-term) biogeomorphic monitoring campaigns as part of NbS. Monitoring of NbS can greatly improve our understanding of biogeomorphic feedback systems across a variety of scales and for a range of environments, adding to the scientific knowledge base. Many monitoring campaigns focus on a limited number of parameters but to better understand and evaluate biogeomorphic feedback systems, programmatic, richer, and smarter (matched in space and time) monitoring design is required (Weber *et al.*, 2018; Firth *et al.*, 2020; Johnson *et al.*, 2020; Seddon *et al.*, 2020; Viles, 2020). By including these requirements in the NbS project proposal, evaluation of the effectiveness of the NbS will be better informed and, importantly, in doing so lessons may be learned on biogeomorphic feedback systems facilitating the NbS. Setting up long-term monitoring campaigns observing ecological as well as biogeomorphical parameters of biogeomorphic environments would be a win for scientists, practitioners, and policy-makers involved in biogeomorphology and NbS.

In relation to point 3 of the list above in particular, a biogeomorphological toolkit (Viles, 2019) may help further bridge the gap between the scientific discipline of biogeomorphology and the application of NbS. Such a toolkit may serve as a nucleus for biogeomorphological knowledge and methodologies and would benefit from setting up data

and model repositories. Importantly, such a toolkit could also aid in building a stronger biogeomorphology community with shared resources. Inspiring examples are provided by the CSDMS modelling community (https://csdms.colorado.edu/wiki/Main_Page) as well as the Ecoshape initiative (<https://www.ecoshape.org/en/>), developing and sharing knowledge and, in doing so, building invested communities. The next step for the biogeomorphology community?

Conclusions

This special issue on biogeomorphology may serve as a state-of-the-art, but above all it will hopefully also serve as a starting point for uncovering more biogeomorphic feedbacks in the coming years. This article summarizes and analyses the publications of the special issue on biogeomorphology. We identify the relation of time and space in biogeomorphology as a topic that is at the heart of the biogeomorphic research frontier. It is well established that time and spatial scales in both ecology and geomorphology are closely coupled, and can hence be combined. Even though there is evidence for feedback systems between biota and physical processes on all spatio-temporal scales, the influence of biota seems to become stronger the smaller the scales. This article also connects the metabolic rate or size of organisms to spatio-temporal considerations. When linking this evidence to disturbance cycles (note, only disturbances originating in geomorphic events), and biotic recovery in between these events, it becomes clear that the minimum time period of biogeomorphic interest is relative to the size of the organism investigated, and involves at least two disturbance events and one phase of recovery in between the two. Modelling and remote sensing are currently used to cross spatio-temporal scales, but especially on longer time scales this proves challenging. In part this originates in missing data from long-term monitoring of physical processes and biota for model validation. This article thus highlights the importance of the establishment of long-term, coupled physical-biotic environmental monitoring.

We also find that there is still a disconnect between the scientific discipline of biogeomorphology and the application of biogeomorphological knowledge and methodologies in coastal, fluvial, and hillslope environments, for example by NbS. An effort from the scientific community is therefore needed to transfer their knowledge on biogeomorphic processes to practitioners and policy-makers and to shape them into practical tools. As such, the setup of a toolkit with biogeomorphological repositories for data and models may serve as a nucleus for biogeomorphological knowledge and methodologies, help bridge the gap between scientists and practitioners, and build a stronger biogeomorphology community.

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Conflict of interest

The authors declare no conflict of interest.

Data availability statement

All data will be shared on request to the corresponding author.

References

- Allen CA, Holling CS. 2008. *Discontinuities in Ecosystems and Other Complex Systems*. Columbia University Press: New York.
- Allen CR, Holling C. 2010. Novelty, adaptive capacity, and resilience. *Ecology and Society* **15**(3): 1–15. <https://doi.org/10.5751/ES-03720-150324>.
- Balke T. 2018. Critical Transitions and the Effects of timing in biogeomorphic ecosystems. EGU General Assembly Conference Abstracts.
- Balke T, Bouma TJ, Horstman EM, Webb EL, Erfemeijer PLA, Herman PMJ. 2011. Windows of opportunity: thresholds to mangrove seedling establishment on tidal flats. *Marine Ecology Progress Series* **440**: 1–9.
- Baptist MJ. 2001. *Review on biogeomorphology in rivers: processes and scales*. Delft University of Technology: Delft.
- Bätz N, Colombini P, Cherubini P, Lane SN. 2016. Groundwater controls on biogeomorphic succession and river channel morphodynamics. *Journal of Geophysical Research – Earth Surface* **121**(10): 1763–1785. <https://doi.org/10.1002/2016JF004009>.
- Bätz N, Verrecchia EP, Lane SN. 2015. The role of soil in vegetated gravelly river braid plains: more than just a passive response? *Earth Surface Processes and Landforms* **40**: 143–156. <https://doi.org/10.1002/esp.3631>.
- Brown JH, Gillooly JF, Allen AP, Savage VM, West GB. 2004. Toward a metabolic theory of ecology. *Ecology* **85**: 1771–1789. <https://doi.org/10.1890/03-9000>.
- Carriere A, Le Bouteiller C, Tucker GE, Klotz S, Naaim M. 2020. Impact of vegetation on erosion: insights from the calibration and test of a landscape evolution model in alpine badland catchments. *Earth Surface Processes and Landforms* **45**: 1085–1099. <https://doi.org/10.1002/esp.4741>.
- Chorley R, Dunn A, Beckinsale R. 1964. *The History of the Study of Landforms: Volume 1 – Geomorphology Before Davis (Routledge Revivals)*. Routledge: London.
- Cohen-Shacham E, Walters G, Janzen C, Maginnis S. 2016. *Nature-Based Solutions to Address Global Societal Challenges*. IUCN: Gland.
- Coleman DJ, Kirwan ML. 2019. The effect of a small vegetation dieback event on salt marsh sediment transport. *Earth Surface Processes and Landforms* **44**: 944–952. <https://doi.org/10.1002/esp.4547>.
- Cooke SJ, Bergman JN, Nyboer EA, Reid AJ, Gallagher AJ, Hammerschlag N, Van De Riet K, Vermaire JC. 2020. Overcoming the concrete conquest of aquatic ecosystems. *Biological Conservation* **247**: 1–12, 108589. <https://doi.org/10.1016/j.biocon.2020.108589>.
- Coombes MA. 2016. Biogeomorphology: diverse, integrative and useful. *Earth Surface Processes and Landforms* **41**: 2296–2300. <https://doi.org/10.1002/esp.4055>.
- Coombes MA, Naylor LA, Viles HA, Thompson RC. 2013. Bioprotection and disturbance: seaweed, microclimatic stability and conditions for mechanical weathering in the intertidal zone. *Geomorphology* **202**: 4–14. <https://doi.org/10.1016/j.geomorph.2012.09.014>.
- Corenblit D, Roussel E, Steiger J, Walcker R. 2019. A bivariate model for estimating reciprocal causality within biogeomorphic ecosystems: the cross-lagged panel model. *Earth Surface Processes and Landforms* **44**: 667–671. <https://doi.org/10.1002/esp.4535>.
- Corenblit D, Steiger J, Till-Bottraud I. 2017. Biogeomorphic feedbacks within riparian corridors: the role of positive interactions between riparian plants. *EGU General Assembly Conference Abstracts*.
- Corenblit D, Vautier F, González E, Steiger J. 2020. Formation and dynamics of vegetated fluvial landforms follow the biogeomorphological succession model in a channelized river. *Earth Surface Processes and Landforms* **45**: 2020–2035. <https://doi.org/10.1002/esp.4863>.
- D'Alpaos A, Marani M. 2016. Reading the signatures of biologic-geomorphic feedbacks in salt-marsh landscapes. *Advances in Water Resources* **93**: 265–275. <https://doi.org/10.1016/j.advwatres.2015.09.004>.
- Darby SE, Sear D. 2008. *River Restoration: Managing the Uncertainty in Restoring Physical Habitat*. Wiley: Chichester.
- Darwin C. 1899. *Die Bildung der Ackererde durch die Thätigkeit der Würmer mit Beobachtung über deren Lebensweise. Charles Darwin's gesammelte Werke; aus dem Englischen übersetzt von J. Victor Carus*. Schweizerbart: Stuttgart.
- Davies NS, Gibling MR. 2011. Evolution of fixed-channel alluvial plains in response to carboniferous vegetation. *Nature Geoscience* **4**: 629–633. <https://doi.org/10.1038/ngeo1237>.
- Day JW, Christian RR, Boesch DM, Yáñez-Arancibia A, Morris J, Twilley RR, Naylor L, Schaffner L, Stevenson C. 2008. Consequences of climate change on the ecogeomorphology of coastal wetlands. *Estuaries and Coasts* **31**: 477–491. <https://doi.org/10.1007/s12237-008-9047-6>.
- De Vriend H. 2001. Long-term morphological prediction. In *River, Coastal and Estuarine Morphodynamics*, Seminara G, Blondeaux P (eds). Springer: Berlin; 163–190.
- De Vriend HJ, Van Koningsveld M, Aarninkhof SGJ, De Vries MB, Baptist MJ. 2015. Sustainable hydraulic engineering through building with nature. *Journal of Hydro-Environment Research* **9**: 159–171. <https://doi.org/10.1016/j.jher.2014.06.004>.
- Deanna L, Wohl E. 2019. The persistence of beaver-induced geomorphic heterogeneity and organic carbon stock in river corridors. *Earth Surface Processes and Landforms* **44**: 342–353. <https://doi.org/10.1002/esp.4486>.
- Dietrich WE, Perron JT. 2006. The search for a topographic signature of life. *Nature* **439**: 411–418.
- Dixon SJ, Sear DA, Odoni NA, Sykes T, Lane SN. 2016. The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surface Processes and Landforms* **41**: 997–1008.
- Dong X, Murray AB, Heffernan JB. 2019. Ecohydrologic feedbacks controlling sizes of cypress wetlands in a patterned karst landscape. *Earth Surface Processes and Landforms* **44**: 1178–1191. <https://doi.org/10.1002/esp.4564>.
- Edelenbos J, Van Buuren A, Roth D, Winnubst M. 2017. Stakeholder initiatives in flood risk management: exploring the role and impact of bottom-up initiatives in three 'Room for the River' projects in the Netherlands. *Journal of Environmental Planning and Management* **60**: 47–66. <https://doi.org/10.1080/09640568.2016.1140025>.
- Eichel J. 2017. Linking biogeomorphic feedbacks from ecosystem engineer to landscape scale: a panarchy approach. *EGU General Assembly Conference Abstracts*.
- Eichel J, Meyer N, Draebing D, Schmidlein S, Dikau R. 2016. Controls on small-scale biogeomorphic interactions on lateral moraine slopes and their linkage to large-scale geomorphic and vegetation patterns. *EGU General Assembly Conference Abstracts*.
- Fagherazzi S, Kirwan ML, Mudd SM, Guntenspergen GR, Temmerman S, D'Alpaos A, Van De Koppel J, Rybczyk JM, Reyes E, Craft C, Clough J. 2012. Numerical models of salt marsh evolution: ecological, geomorphic, and climatic factors. *Reviews of Geophysics* **50**: 1–28. <https://doi.org/10.1029/2011RG000359>.
- Faivre N, Fritz M, Freitas T, De Boissezon B, Vandewoestijne S. 2017. Nature-based solutions in the EU: innovating with nature to address social, economic and environmental challenges. *Environmental Research* **159**: 509–518. <https://doi.org/10.1016/j.envres.2017.08.032>.
- Firth LB, Airoldi L, Bulleri F, Challinor S, Chee S-Y, Evans AJ, Hanley ME, Knights AM, O'Shaughnessy K, Thompson RC, Hawkins SJ. 2020. Greening of grey infrastructure should not be used as a Trojan horse to facilitate coastal development. *Journal of Applied Ecology* **57**: 1762–1768. <https://doi.org/10.1111/1365-2664.13683>.

- Gao J, Kennedy DM, Konlechner TM. 2020. Coastal dune mobility over the past century: a global review. *Progress in Physical Geography: Earth and Environment* **44**: 814–836. <https://doi.org/10.1177/0309133320919612>.
- Giaccone E, Luoto M, Vittoz P, Guisan A, Mariéthoz G, Lambiel C. 2019. Influence of microclimate and geomorphological factors on alpine vegetation in the Western Swiss Alps. *Earth Surface Processes and Landforms* **44**: 3093–3107. <https://doi.org/10.1002/esp.4715>.
- Goldenfeld N, Kadanoff LP. 1999. Simple lessons from complexity. *Science*, **284**: 87–89.
- Grenfell MC, Aalto R, Grenfell SE, Ellery WN. 2019. Ecosystem engineering by hummock-building earthworms in seasonal wetlands of eastern South Africa: insights into the mechanics of biomorphodynamic feedbacks in wetland ecosystems. *Earth Surface Processes and Landforms* **44**: 354–366. <https://doi.org/10.1002/esp.4497>.
- Gunderson LH, Holling CS. 2002. *Panarchy: Understanding Transformations in Human and Natural Systems*. Island Press: Washington, D.C.
- Gurnell AM, Bertoldi W, Francis RA, Gurnell J, Mardhiah U. 2019. Understanding processes of island development on an island braided river over timescales from days to decades. *Earth Surface Processes and Landforms* **44**: 624–640. <https://doi.org/10.1002/esp.4494>.
- Hausmann NS. 2017. Soil movement by burrowing mammals: a review comparing excavation size and rate to body mass of excavators. *Progress in Physical Geography: Earth and Environment* **41**: 29–45. <https://doi.org/10.1177/0309133316662569>.
- Hopkinson CS, Morris JT, Fagherazzi S, Wollheim WM, Raymond PA. 2018. Lateral marsh edge erosion as a source of sediments for vertical marsh accretion. *Journal of Geophysical Research – Biogeosciences* **123**: 2444–2465. <https://doi.org/10.1029/2017jg004358>.
- Hortobagyi B. 2018. *Multi-scale interactions between riparian vegetation and hydrogeomorphic processes (the lower Allier River)*. PhD thesis, Université Clermont Auvergne.
- Humboldt AV, Bonpland A. 1805. *Essai sur la géographie des plantes: accompagné d'un tableau physique des régions équinoxiales, fondé sur des mesures exécutées, depuis le dixième degré de latitude boréale jusqu'au dixième degré de latitude australe, pendant les années 1799, 1800, 1801, 1802 et 1803*. Chez Levrault, Schoell & Co.: Paris.
- Jerin T, Phillips J. 2020. Biogeomorphic keystones and equivalents: examples from a bedrock stream. *Earth Surface Processes and Landforms* **45**: 1877–1894. <https://doi.org/10.1002/esp.4853>.
- Johnson MF, Thorne CR, Castro JM, Kondolf GM, Mazzacano CS, Rood SB, Westbrook C. 2020. Biomic river restoration: a new focus for river management. *River Research and Applications* **36**: 3–12. <https://doi.org/10.1002/rra.3529>.
- Junk W, Bayley PB, Sparks RE. 1989. The flood pulse concept in river-floodplain systems. In *International Large River Symposium (LARS)*, Dodge DP (ed). Canadian Special Publication of Fisheries and Aquatic Sciences: Ottawa.
- Keesstra S, Nunes J, Novara A, Finger D, Avelar D, Kalantari Z, Cerdà A. 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. *Science of the Total Environment* **610–611**: 997–1009. <https://doi.org/10.1016/j.scitotenv.2017.08.077>.
- Kirwan ML, Mudd SM. 2012. Response of salt-marsh carbon accumulation to climate change. *Nature* **489**: 550–553. <https://doi.org/10.1038/nature11440>.
- Kleinhans M, Douma H, Addink EA. 2019. Fate of pioneering vegetation patches in a dynamic meandering river. *Earth Surface Processes and Landforms* **44**: 1618–1632. <https://doi.org/10.1002/esp.4596>.
- Kleinhans MG, De Vries B, Braat L, Van Oorschot M. 2018. Living landscapes: muddy and vegetated floodplain effects on fluvial pattern in an incised river. *Earth Surface Processes and Landforms* **43**: 2948–2963. <https://doi.org/10.1002/esp.4437>.
- Knox JC. 1972. Valley alluviation in southwestern Wisconsin. *Annals of the Association of American Geographers* **62**: 401–410. <https://doi.org/10.1111/j.1467-8306.1972.tb00872.x>.
- Lane SN. 2017. Natural flood management. *WIREs Water* **4**: 1–4, e1211. <https://doi.org/10.1002/wat2.1211>.
- Larsen A, Alvarez N, Sperisen C, Lane SN. 2018. Biotic drivers of river and floodplain geomorphology – new molecular methods for assessing present-day and past biota. *Earth Surface Processes and Landforms* **43**: 333–338. <https://doi.org/10.1002/esp.4238>.
- Larsen A, May J-H, Carah X. 2019. Late Quaternary biotic and abiotic controls on long-term sediment flux in a northern Australian tropical river system. *Earth Surface Processes and Landforms* **44**: 2494–2509. <https://doi.org/10.1002/esp.4652>.
- Larsen A, May J-H, Moss P, Hacker J. 2016. Could alluvial knickpoint retreat rather than fire drive the loss of alluvial wet monsoon forest, tropical northern Australia? *Earth Surface Processes and Landforms* **41**: 1583–1594. <https://doi.org/10.1002/esp.3933>.
- Lera S, Nardin W, Sanford L, Palinkas C, Guercio R. 2019. The impact of submersed aquatic vegetation on the development of river mouth bars. *Earth Surface Processes and Landforms* **44**: 1494–1506. <https://doi.org/10.1002/esp.4585>.
- Lokhorst IR, De Lange SI, Van Buiten G, Selaković S, Kleinhans MG. 2019. Species selection and assessment of eco-engineering effects of seedlings for biogeomorphological landscape experiments. *Earth Surface Processes and Landforms* **44**: 2922–2935. <https://doi.org/10.1002/esp.4702>.
- Marani M, Da Lio C, D'Alpaos A. 2013. Vegetation engineers marsh morphology through multiple competing stable states. *Proceedings of the National Academy of Sciences* **110**: 3259–3263. <https://doi.org/10.1073/pnas.1218327110>.
- Mason RJ, Rice SP, Wood PJ, Johnson MF. 2019. The zoogeomorphology of case-building caddisfly: quantifying sediment use. *Earth Surface Processes and Landforms* **44**: 2510–2525. <https://doi.org/10.1002/esp.4670>.
- Mauri L, Sallustio L, Tarolli P. 2019. The geomorphologic forcing of wild boars. *Earth Surface Processes and Landforms* **44**: 2085–2094. <https://doi.org/10.1002/esp.4623>.
- McAuliffe JR, McFadden LD, Roberts LM, Wawrzyniec TF, Scuderi LA, Meyer GA, King MP. 2014. Non-equilibrium hillslope dynamics and irreversible landscape changes at a shifting pinyon-juniper woodland ecotone. *Global and Planetary Change* **122**: 1–13. <https://doi.org/10.1016/j.gloplacha.2014.07.008>.
- Moffett KBNW, Silvestri S, Wang C, Temmerman S. 2015. Multiple stable states and catastrophic shifts in coastal wetlands: progress, challenges, and opportunities in validating theory using remote sensing and other methods. *Remote Sensing* **7**: 10184–10226. <https://doi.org/10.3390/rs70810184>.
- Möller I, Kudella M, Rupprecht F, Spencer T, Paul M, Van Wesenbeeck BK, Wolters G, Jensen K, Bouma TJ, Miranda-Lange M, Schimmels S. 2014. Wave attenuation over coastal salt marshes under storm surge conditions. *Nature Geoscience* **7**: 727–731. <https://doi.org/10.1038/ngeo2251>.
- Mossa J, Chen Y-H, Kondolf GM, Walls SP. 2020. Channel and vegetation recovery from dredging of a large river in the Gulf coastal plain, USA. *Earth Surface Processes and Landforms* **45**: 1926–1944. <https://doi.org/10.1002/esp.4856>.
- Murray AB. 2003. Contrasting the goals, strategies, and predictions associated with simplified numerical models and detailed simulations. *Prediction in geomorphology*, 151–165.
- Nardin W, Larsen L, Fagherazzi S, Wiberg P. 2018. Tradeoffs among hydrodynamics, sediment fluxes and vegetation community in the Virginia Coast Reserve, USA. *Estuarine, Coastal and Shelf Science* **210**: 98–108. <https://doi.org/10.1016/j.ecss.2018.06.009>.
- Nardin W, Lera S, Nienhuis J. 2020. Effect of offshore waves and vegetation on the sediment budget in the Virginia Coast Reserve (VA). *Earth Surface Processes and Landforms* **30**: 3055–3068. <https://doi.org/10.1002/esp.4951>.
- Naylor LA. 2005. The contributions of biogeomorphology to the emerging field of geobiology. *Palaeogeography, Palaeoclimatology, Palaeoecology* **219**: 35–51. <https://doi.org/10.1016/j.palaeo.2004.10.013>.
- Naylor LA, Coombes MA, Viles HA. 2012. Reconceptualising the role of organisms in the erosion of rock coasts: a new model. *Geomorphology* **157–158**: 17–30. <https://doi.org/10.1016/j.geomorph.2011.07.015>.
- Naylor LA, Spencer T, Lane SN, Darby SE, Magilligan FJ, Macklin MG, Möller I. 2017. Stormy geomorphology: geomorphic contributions in an age of climate extremes. *Earth Surface Processes and Landforms* **42**: 166–190. <https://doi.org/10.1002/esp.4062>.

- Neumeier U, Amos CL. 2006. The influence of vegetation on turbulence and flow velocities in European salt-marshes. *Sedimentology* **53**: 259–277. <https://doi.org/10.1111/j.1365-3091.2006.00772.x>.
- Nienhuis JH, Ashton AD, Edmonds DA, Hoitink AJF, Kettner AJ, Rowland JC, Törnqvist TE. 2020. Global-scale human impact on delta morphology has led to net land area gain. *Nature* **577**: 514–518. <https://doi.org/10.1038/s41586-019-1905-9>.
- Nolte S, Koppenaal EC, Esselink P, Dijkema KS, Schuerch M, De Groot AV, Bakker JP, Temmerman S. 2013. Measuring sedimentation in tidal marshes: a review on methods and their applicability in biogeomorphological studies. *Journal of Coastal Conservation* **17**: 301–325. <https://doi.org/10.1007/s11852-013-0238-3>.
- O'Briain R. 2019. Climate change and European rivers: an eco-hydromorphological perspective. *Ecohydrology* **12**: 1–18, e2099. <https://doi.org/10.1002/eco.2099>.
- Oorschot MV, Kleinhans M, Geerling G, Middelkoop H. 2016. Distinct patterns of interaction between vegetation and morphodynamics. *Earth Surface Processes and Landforms* **41**: 791–808. <https://doi.org/10.1002/esp.3864>.
- Pawlik Ł, Phillips JD, Šamonil P. 2016. Roots, rock, and regolith: bio-mechanical and biochemical weathering by trees and its impact on hillslopes – a critical literature review. *Earth-Science Reviews* **159**: 142–159. <https://doi.org/10.1016/j.earscirev.2016.06.002>.
- Pawlik Ł, Šamonil P. 2018. Soil creep: the driving factors, evidence and significance for biogeomorphic and pedogenic domains and systems – a critical literature review. *Earth-Science Reviews* **178**: 257–278. <https://doi.org/10.1016/j.earscirev.2018.01.008>.
- Picco L, Bertoldi W, Comiti F. 2017. Dynamics and ecology of wood in world rivers. *Geomorphology* **279**: 1–2. <https://doi.org/10.1016/j.geomorph.2016.11.020>.
- Politti E, Bertoldi W, Gurnell A, Henshaw A. 2018. Feedbacks between the riparian Salicaceae and hydrogeomorphic processes: a quantitative review. *Earth-Science Reviews* **176**: 147–165. <https://doi.org/10.1016/j.earscirev.2017.07.018>.
- Polvi LE, Lind L, Persson H, Miranda-Melo A, Pilloto F, Su X, Nilsson C. 2020. Facets and scales in river restoration: nestedness and interdependence of hydrological, geomorphic, ecological, and biogeochemical processes. *Journal of Environmental Management* **265**: 1–15, 110288. <https://doi.org/10.1016/j.jenvman.2020.110288>.
- Polvi LE, Sarneel JM. 2018. Ecosystem engineers in rivers: an introduction to how and where organisms create positive biogeomorphic feedbacks. *WIREs Water* **5**: 1–10, e1271. <https://doi.org/10.1002/wat2.1271>.
- Post E. 2019. *Time in Ecology. A Theoretical Framework*. Princeton University Press: Princeton, NJ.
- Rice S, Pledger A, Toone J, Mathers K. 2019. Zoogeomorphological behaviours in fish and the potential impact of benthic feeding on bed material mobility in fluvial landscapes. *Earth Surface Processes and Landforms* **44**: 54–66. <https://doi.org/10.1002/esp.4541>.
- Rijke J, Van Herk S, Zevenbergen C, Ashley R. 2012. Room for the river: delivering integrated river basin management in the Netherlands. *International Journal of River Basin Management* **10**: 369–382. <https://doi.org/10.1080/15715124.2012.739173>.
- Román-Sánchez A, Laguna A, Reimann T, Giráldez JV, Peña A, Vanwallegghem T. 2019a. Bioturbation and erosion rates along the soil-hillslope conveyor belt, part 2: quantification using an analytical solution of the diffusion–advection equation. *Earth Surface Processes and Landforms* **44**: 2066–2080. <https://doi.org/10.1002/esp.4626>.
- Román-Sánchez A, Reimann T, Wallinga J, Vanwallegghem T. 2019b. Bioturbation and erosion rates along the soil-hillslope conveyor belt, part 1: insights from single-grain feldspar luminescence. *Earth Surface Processes and Landforms* **44**: 2051–2065. <https://doi.org/10.1002/esp.4628>.
- Rovai AS, Twilley RR, Castañeda-Moya E, Riul P, Cifuentes-Jara M, Manrow-Villalobos M, Horta PA, Simonassi JC, Fonseca AL, Pagliosa PR. 2018. Global controls on carbon storage in mangrove soils. *Nature Climate Change* **8**: 534–538. <https://doi.org/10.1038/s41558-018-0162-5>.
- Salvador De Paiva JN, Walles B, Ysebaert T, Bouma TJ. 2018. Understanding the conditionality of ecosystem services: the effect of tidal flat morphology and oyster reef characteristics on sediment stabilization by oyster reefs. *Ecological Engineering* **112**: 89–95. <https://doi.org/10.1016/j.ecoleng.2017.12.020>.
- Scheffer M, Straile D, Van Nes EH, Hosper H. 2001. Climatic warming causes regime shifts in lake food webs. *Limnology and Oceanography* **46**(7): 1780–1783. <https://doi.org/10.4319/lo.2001.46.7.1780>.
- Schepers L, Kirwan ML, Guntenspergen GR, Temmerman S. 2020. Evaluating indicators of marsh vulnerability to sea level rise along a historical marsh loss gradient. *Earth Surface Processes and Landforms* **45**: 2107–2117. <https://doi.org/10.1002/esp.4869>.
- Schmidt-Nielsen K. 1984. *Scaling: Why is Animal Size so Important?* Cambridge University Press: Cambridge.
- Schotanus J, Capelle JJ, Parez E, Fivash GS, Van De Koppel J, Bouma TJ. 2020. Restoring mussel beds in highly dynamic environments by lowering environmental stressors. *Restoration Ecology* **28**(5): 1124–1134. <https://doi.org/10.1111/rec.13168>.
- Schulte Ostermann T, Heuner M, Bouma T. 2017. Traits of estuarine marsh plants affect wave dissipation. *EGU General Assembly Conference Abstracts*.
- Schumm SA, Lichty RW. 1965. Time, space, and causality in geomorphology. *American Journal of Science* **263**: 110–119. <https://doi.org/10.2475/ajs.263.2.110>.
- Schwarz C, Bouma TJ, Zhang LQ, Temmerman S, Ysebaert T, Herman PMJ. 2015. Interactions between plant traits and sediment characteristics influencing species establishment and scale-dependent feedbacks in salt marsh ecosystems. *Geomorphology* **250**: 298–307. <https://doi.org/10.1016/j.geomorph.2015.09.013>.
- Seddon N, Chausson A, Berry P, Girardin CAJ, Smith A, Turner B. 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society, B: Biological Sciences* **375**: 1–12, 20190120. <https://doi.org/10.1098/rstb.2019.0120>.
- Spencer T, Möller I, Rupprecht F, Bouma TJ, Van Wesenbeeck BK, Kudella M, Paul M, Jensen K, Wolters G, Miranda-Lange M, Schimmels S. 2016. Salt marsh surface survives true-to-scale simulated storm surges. *Earth Surface Processes and Landforms* **41**: 543–552. <https://doi.org/10.1002/esp.3867>.
- Stallins AJ, Corenblit D. 2018. Interdependence of geomorphic and ecologic resilience properties in a geographic context. *Geomorphology* **305**: 76–93. <https://doi.org/10.1016/j.geomorph.2017.09.012>.
- Stavi I, Rachmilevitch S, Hjazin A, Yizhaq H. 2018. Geodiversity decreases shrub mortality and increases ecosystem tolerance to droughts and climate change. *Earth Surface Processes and Landforms* **43**: 2808–2817. <https://doi.org/10.1002/esp.4412>.
- Stive MJF, De Schipper MA, Luijendijk AP, Aarninkhof SGJ, Van Gelder-Maas C, Van Thiel De Vries JSM, De Vries S, Henriquez M, Marx S, Ranasinghe R. 2013. A new alternative to saving our beaches from sea-level rise: the sand engine. *Journal of Coastal Research* **29**: 1001–1008.
- Tal M, Paola C. 2010. Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments. *Earth Surface Processes and Landforms* **35**: 1014–1028. <https://doi.org/10.1002/esp.1908>.
- Temmerman S, Govers G, Wartel S, Meire P. 2003. Spatial and temporal factors controlling short-term sedimentation in a salt and freshwater tidal marsh, Scheldt estuary, Belgium, SW Netherlands. *Earth Surface Processes and Landforms* **28**: 739–755. <https://doi.org/10.1002/esp.495>.
- Thoms MC, Meitzen KM, Julian JP, Butler DR. 2018. Bio-geomorphology and resilience thinking: common ground and challenges. *Geomorphology* **305**: 1–7. <https://doi.org/10.1016/j.geomorph.2018.01.021>.
- Toone J, Rice SP, Piégay H. 2014. Spatial discontinuity and temporal evolution of channel morphology along a mixed bedrock-alluvial river, upper Drôme River, southeast France: contingent responses to external and internal controls. *Geomorphology* **205**: 5–16. <https://doi.org/10.1016/j.geomorph.2012.05.033>.
- Townend I, Fletcher C, Knappen M, Rossington K. 2011. A review of salt marsh dynamics. *Water Environment Journal* **25**: 477–488. <https://doi.org/10.1111/j.1747-6593.2010.00243.x>.
- Turner RE, Baustian JJ, Swenson EM, Spicer JS. 2006. Wetland sedimentation from Hurricanes Katrina and Rita. *Science* **314**: 449–452. <https://doi.org/10.1126/science.1129116>.
- Van De Koppel J, Herman PMJ, Thoolen P, Heip CHR. 2001. Do alternate stable states occur in natural ecosystems? Evidence from a tidal

- flat. *Ecology* **82**: 3449–3461. [https://doi.org/10.1890/0012-9658\(2001\)082\[3449:DASSO\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2001)082[3449:DASSO]2.0.CO;2).
- van de Lageweg WI, Slangen ABAA. 2017. Predicting dynamic coastal delta change in response to sea-level rise. *Journal of Marine Science and Engineering* **5**: 1–12. <https://doi.org/10.3390/jmse5020024>.
- Vannote RL, Minshall GW, Cummins KW, Sedell JR, Cushing CE. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* **37**: 130–137. <https://doi.org/10.1139/f80-017>.
- Vaughan IP, Diamond M, Gurnell AM, Hall KA, Jenkins A, Milner NJ, Naylor LA, Sear DA, Woodward G, Ormerod SJ. 2009. Integrating ecology with hydromorphology: a priority for river science and management. *Aquatic Conservation: Marine and Freshwater Ecosystems* **19**: 113–125. <https://doi.org/10.1002/aqc.895>.
- Vaughan IP, Ormerod SJ. 2010. Linking ecological and hydromorphological data: approaches, challenges and future prospects for riverine science. *Aquatic Conservation: Marine and Freshwater Ecosystems* **20**: S125–S130. <https://doi.org/10.1002/aqc.1104>.
- Viles H. 1988. *Biogeomorphology*. Basil Blackwell: Oxford.
- Viles H. 2019. Biogeomorphology: past, present and future. *Geomorphology* **366**: 1–15, 106809. <https://doi.org/10.1016/j.geomorph.2019.06.022>.
- Viles H. 2020. Biogeomorphological research frontiers: from ant mounds to Mars. *EGU General Assembly Conference Abstracts*.
- Viles HA, Naylor LA. 2002. Editorial. *Geomorphology* **47**: 1–2. [https://doi.org/10.1016/S0169-555X\(02\)00136-8](https://doi.org/10.1016/S0169-555X(02)00136-8).
- Weber C, Åberg U, Buijse AD, Hughes FMR, McKie BG, Piégay H, Roni P, Vollenweider S, Haertel-Borer S. 2018. Goals and principles for programmatic river restoration monitoring and evaluation: collaborative learning across multiple projects. *WIREs Water* **5**: 1–15, e1257. <https://doi.org/10.1002/wat2.1257>.
- West GB, Brown JH, Enquist BJ. 1997. A general model for the origin of allometric scaling laws in biology. *Science* **276**: 122–126. <https://doi.org/10.1126/science.276.5309.122>.
- Wheaton JM, Gibbins C, Wainwright J, Larsen L, McElroy B. 2011. Preface: multiscale feedbacks in ecogeomorphology. *Geomorphology* **126**: 265–268. <https://doi.org/10.1016/j.geomorph.2011.01.002>.
- Wohl E. 2017. Biotic drivers of spatial heterogeneity and implications for river ecosystems. *EGU General Assembly Conference Abstracts*.
- Yoo K, Amundson R, Heimsath AM, Dietrich WE. 2005. Process-based model linking pocket gopher (*Thomomys bottae*) activity to sediment transport and soil thickness. *Geology* **33**: 917–920. <https://doi.org/10.1130/g21831.1>.
- Yuan R, Kennedy DM, Stephenson WJ, Gómez-Pujol L. 2019. Experimental investigations into the influence of biofilms and environmental factors on short-term microtopographic fluctuations of supratidal sandstone. *Earth Surface Processes and Landforms* **44**: 1377–1389. <https://doi.org/10.1002/esp.4581>.

Appendix

Annex A1. List of keywords used for a Web of Science search (June 2020, plotted in Figure 2). Wildcard symbols (i.e. *, ?) were used to check for different spellings and variations of the root of a keyword (e.g. week, weekly). The search was conducted by filtering the results on ‘Biogeomorphology’ (no. 778) with the keywords of the respective time scale. Keywords of the lower and higher time scale were actively excluded in the search function. This led to a total of 180 publications.

Category	Keywords
Biogeomorphology	biogeomorph*; zoogeomorph*; phytogeomorph*; ecogeomorph*; ecosystem engineer*; bio-geomorph*; eco-geomorph*
Houral–Weekly	minut*; day*; hour*; week*; horal* one year; annual*; inter-annual*; interannual*; inter annual*; month*; intra-annual*; season*; intra annual* [excluding: annual
Month–Yearly	flow; Annual Meeting; Binghamton]
Decadal	decad*; decennium*; decennary; 1?-years; 2?-years; 3?-years; 4?-years; 5?-years; 6?-years; 7?-years; 8?-years
Centennial	centenary; century; 1??-years; 2??-years; 3??-years; 4??-years; 5??-years; 6??-years; 7??-years; 8??-years
Millennial	millen*; 1???-years; 2???-years; 3???-years; 4???-years; 5???-years; 6???-years; 7???-years; 8???-years
Supra-millennia	paleo*; Quaternar*; Holocene; Devonian; Pleistocene; Silurian; Ordovician; Carboniferous; geologic time