

Biogeomorphology: Past, present and future

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Abstract

Since the 1970s there has been a considerable expansion in biogeomorphological research which considers the complex, two-way relationships between biological, ecological and geomorphological systems over a wide range of spatial and temporal scales. Advances have been made in theoretical, methodological, thematic and applied aspects of biogeomorphology. A review of key publications and symposia over the period illustrates growth in biogeomorphology with particular advances in quantitative understandings of biogeomorphic interactions, in interdisciplinary participation, and in theoretical framings. Theoretical advances have been influenced by the desire to answer four fundamental questions: How do ecological and geomorphological systems interact? Is there a geomorphological signature of life? How important is biodiversity to landscape evolution and vice versa? How have life and landscape co-evolved? A review of methodological advances in biogeomorphology confirms the continuing importance of field monitoring, and the increasingly tight collaboration between experimental and modelling-based research. Thematically, particularly strong progress has been made in disentangling the complex bidirectional biogeomorphic interactions in coastal sedimentary environments, and fluvial and riparian systems. It is increasingly obvious that variation in ecological traits leads to large differences in biogeomorphic impacts of different species in different circumstances. This poses challenges for applications of biogeomorphology to environmental management and conservation. Seven key topics emerge from this review and provide the basis for a biogeomorphological research agenda to usher in the next 50 yr of progress.

Keywords

Ecogeomorphology, zoogeomorphology, ecosystem engineering

1 What is the future for biogeomorphological studies? It appears ... that
2 there is a vast range of individual species-earth surface process
3 interactions which need further study and elucidation. Similarly, there
4 are many areas of community influences upon geomorphology which
5 deserve further study. Far more quantitative information must be
6 produced, in order to test specific hypotheses over the importance of
7 certain biological influences. It is vital that geomorphologists become
8 more aware of the ecology of landforms and landscapes, in order to
9 attempt to model the complex interactions which result. (Viles, 1988, p.
10 355).

12 It is just over 30 yr since I wrote the above concluding words to the 'Perspectives' section of
13 the edited volume on 'Biogeomorphology'. Over this time much has changed, and
14 significant progress has been made in addressing the complex web of interactions between
15 geomorphology and ecology. In both qualitative and quantitative terms, much more is now
16 known about how species and communities interact with earth surface processes and
17 landforms across a wide range of environments. The aims of this paper are to provide an
18 overview of developments in biogeomorphology since the 1988 volume, review the state of
19 the art of biogeomorphology today, and propose a research agenda for the future. The
20 discussion will focus on theoretical, methodological and thematic advances in
21 biogeomorphology and its practical application to environmental management and
22 conservation.

24 In 1988 biogeomorphology was a nascent concept introduced as being concerned with 'The
25 influence of landforms/geomorphology on the distributions and development of plants,
26 animals and micro-organisms; [and] the influence of plants, animals and micro-organisms on
27 earth surface processes and the development of landforms (Viles, 1988, p. 6). The longer
28 term history of ideas in biogeomorphology has been reviewed by Viles (2011). The term
29 'biogeomorphic response' had appeared over a decade earlier in the English-speaking

geomorphological literature in (Knox, 1972), and 'eco-geomorphology' featured in the mid-1980s in an important paper on the ecology of erosion (Thornes, 1985). Other terms such as 'phytogeomorphology' were also being coined around this time (Howard and Mitchell, 1985). In the German literature, 'geoecology' provided a comparable framework (Stablein, 1989) which has since been revived by Huggett (1995). Since that time, a plethora of other similar terms have been proposed to describe overlapping, cognate concepts such as 'zoogeomorphology' (Butler, 1995), 'ecogeomorphology', 'ecohydraulics', 'ecohydrology', 'biogeocomplexity' (Molau, 2008) and 'biomorphodynamics' (Murray et al., 2008). A particularly fertile body of ideas has come from the work of Don Johnson and colleagues, who have explored and developed concepts such as 'bioturbation', 'biomantle' and 'dynamic denudation' (Johnson et al., 2005a,b). Over evolutionary and geological timescales Cotterill and De Wit (2011) have proposed the term 'geoecodynamics'. Wheaton et al. (2011) provide a good review of the changing terminology. Within ecology, parallel developments have also occurred, with overlapping but rather broader concepts such as 'ecosystem engineering' becoming firmly rooted and widely utilised (Jones et al., 1994). At a larger scale and associated with the growth of Earth System Science, geobiology, geobotany, biocomplexity and biogeocomplexity have also gained some traction as overarching conceptual frameworks within which to integrate 'geo' and 'bio' concerns (Naylor, 2005). Definitions and explanations of key terms are given in Table 1. The development of these multiple concepts and frameworks can be seen as both a good and a bad thing. On the one hand it is evidence of creative thinking and interest in the field, whilst on the other hand it leads to some confusion and division and holds back the development of a coherent research community. This paper provides an overview and assessment of research within these overtly interdisciplinary conceptual frameworks using biogeomorphology as an

54 umbrella term which makes sense given its deliberately broad and inclusive meaning (Table
55 1).

56

57 Table 1: Key terminology in biogeomorphology and allied fields

Term	Definition	Source
Biogeocomplexity	"...the landscape should be used as the baseline unit for a fruitful amalgamation of geomorphology and ecology."	Molau, 2008, p. 54
Biogeomorphic resilience	"...can be summarized as the resilience properties generated by the functional capacity of organisms to shape biogeomorphic variability arising from disturbances such that the biogeomorphic conditions and processes that shape these capacities persist."	Stallins and Corenblit, 2018, p. 77
Bio-geomorphic systems	"The strong bi-directional coupling between ecological and geomorphological systems frames the concept of 'bio-geomorphic systems'"	Thoms et al., 2018a, p. 1
Biogeomorphology or Bio-geomorphology	"Biogeomorphology is ... used as an umbrella term to describe studies which focus on the linkages between ecology and geomorphology."	Viles, 2004, p. 83
Dynamic denudation	"...a unified process approach, a synthesis of various theories, models, and concepts that explain landform and soil evolution on slopes and level areas, wherein biomechanical processes and ranked equally with other key biotic, archaeogenic, geomorphic and pedologic processes."	Johnson, 2002, p. 15-16
Eco-geomorphology	"An interdisciplinary approach to the study of river systems that integrates hydrology, fluvial geomorphology and ecology."	Thoms and Parsons, 2002, p. 113
Ecohydraulics	"Aims to 'examine the linkages between physical processes and ecological functions within aquatic ecosystems..."	Rice et al., 2010, p. 363
Ecohydrology	"The study of the interaction of the water cycle with biota has been recently termed ecohydrology. This designation was initially used to denote an integrated study of ecological and hydrological processes in wetlands... The same approach was later extended to terrestrial ecosystems..."	D'Odorico et al., 2010, p. 899
Ecosystem engineering	The role of particular organisms (ecosystem engineers) in creating, modifying and maintaining habitats.	Jones et al., 1994
Geobiology	"Geobiology aims to study the interaction and coevolution between life and Earth environments, or between the biosphere and the geosphere..."	Benton and Xie, 2014, p. 483

Geoecodynamics	"Geoecodynamics integrates relevant concepts and knowledge from the earth and life sciences into a cross-disciplinary synthesis.... Positioning the earth and life sciences in a novel association to study life as an earth surface process, geoecodynamics deciphers details of biodiversity dynamics to resolve tenures of landforms."	Cotterill and De Wit, 2011, p. 489
Geoecology	Term coined by Carl Troll as a synonym for landscape ecology. Study of landscape systems or geosystems.	Molina and Little, 1981; Huggett, 1995
Phytogeomorphology	"Investigates the influence of topography on plant communities."	Viles, 2004, p. 84
Zoogeomorphology	"Zoogeomorphology is the study of the geomorphic effects of animals...., and as such can be considered as a subset of biogeomorphology."	Butler, 2004, p. 1122

58

59 **1. Important precursors – the work of James Knox and John Thornes**

60 In 1972 James Knox published a paper on the Holocene history of valley alluviation in
61 southwestern Wisconsin which built on contemporary ideas of fluvial geomorphology and
62 hydrology to illustrate how changes in climate and vegetation have interacted to produce
63 changes in surface runoff and sediment yield which in turn have controlled channel and
64 floodplain evolution. Knox illustrates the non-linear responses of such systems to a change
65 in climate (Fig. 1). The novelty and importance of this paper lie in its clear conceptualization
66 and visualization of how these non-linearities arise from links between climate, vegetation
67 and fluvial processes.

68

69 John Thornes wrote an important and visionary paper in 1985 entitled 'The ecology of
70 erosion' in which he outlined a mathematical treatment of the dynamic interactions
71 between plant growth and soil erosion. He explained how varying the nature of the
72 dynamics of both or either process (erosion and plant growth) could lead to equilibrium or
73 non-equilibrium results (Fig. 2). As Wainwright and Parsons (2010) explain, the significance
74 of Thornes's paper is that it presents a much more interactive and dynamic view, and one

which is rooted in good mathematical understanding, than that outlined in other biogeomorphological research in the 1980s, and it foreshadows many recent important developments in the fields of biogeomorphology and the application of nonlinear dynamical systems ideas to geomorphology.

2. Developments in biogeomorphology since 1988

Over the past 30 yr there has been an acceleration in the scope, ambition and complexity of research activity on biogeomorphological topics as reflected in the growth in relevant conferences and conference sessions (including Binghamton symposia numbers 26, 36, 40, 42 and 48) and increasing numbers of publications (both books and journal articles).

2.1. Books and symposia - the changing nature of biogeomorphology

The 1988 edited volume on Biogeomorphology (Viles, 1988) focused mainly on the impacts of ecology on geomorphology, and used a categorisation into major geomorphic environments as a way of presenting the material. Three chapters focused on biogeomorphic interactions in temperate fluvial environments (rivers, soils and catchment erosion), two on tropical environments (rainforest processes and the geomorphological role of termites), and one on each of arid and semi-arid, periglacial, coastal and karst environments. There was no attempt to provide an overall theoretical framework or address scale, methodological or practical issues beyond a short 'Perspectives' chapter at the end. This lack, and the inclusion of some small scale oddities, provoked one reviewer to ask whether biogeomorphology was more fun than fundamental (Cox, 1989). According to Wainwright and Parsons (2010), the book presented a rather partial and static account of the complex web of ecological and geomorphological relationships. However, it did provide

a useful state of the art survey of the breadth of biogeomorphological interactions (involving the full spectrum of organisms – microbes, plants and animals) across many different environments, brought together geomorphologists, ecologists and soil scientists and acted as a stimulus for much further work.

In 1988 the British Geomorphological Research Group annual conference in Bristol, convened by John Thornes, focused on the links between vegetation and geomorphology. Twenty-eight papers presented at this meeting were published two years later in an edited book (Thornes, 1990) covering the impacts of vegetation on geomorphic processes largely within the context of drainage basins. As John Thornes notes in his Preface to the book most of these papers “...bring in vegetation only as an extrinsic variable, parameter or even constant rather than a highly dynamic and vital component which affects virtually all processes and therefore all geomorphological histories.” (Thornes, 1990, p. xii). Furthermore, as with the chapters in Viles (1988), most of the papers focus on the geomorphic effects of vegetation and not the effects of geomorphology on vegetation.

The five Binghamton symposia present a microcosm of developments in biogeomorphological research between 1995 and 2018. The first Binghamton symposium on biogeomorphological topics was held in 1995 under the title ‘Biogeomorphology, terrestrial and freshwater’ and the oral contributions were published as a special issue of *Geomorphology* the same year. As Hupp et al. (1995) noted in the preface, the meeting had been originally planned to focus on vegetation and geomorphology, but sufficient interest was generated in animal interactions with geomorphology to justify broadening the scope. Topics covered in 21 oral presentations included relations between vegetation, large woody

123 debris and river processes, the impacts of changing vegetation on slope processes in arid
124 and humid tropical environments, bioturbation in arid environments, ecology of rock
125 weathering, late Quaternary changes in climate, vegetation and river stability in Tasmania,
126 the roles of cows and beavers in geomorphology, modelling links between vegetation and
127 erosion, and scale problems in linking biogeomorphology and landscape evolution.

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129 The second Binghamton symposium on a broadly biogeomorphological topic was held in
130 2005 under the title of 'Geomorphology and ecosystems'. The edited collection of papers
131 appeared in *Geomorphology* in 2007 and is organised into three sections covering the role
132 of geomorphology in ecosystems, the role of ecology in geomorphic systems, and integrated
133 management of geomorphic ecosystems. Within these sections, topics covered include the
134 role of aeolian dust in ecosystems, landslides and biophysical diversity, feedbacks in fluvial
135 systems, beach nourishment and crab habitats, and stream ecosystems in the Antarctic dry
136 valleys. Several papers also tackled key challenges for interdisciplinary research on
137 geomorphic ecosystems, including issues of boundaries, conceptual frameworks and
138 nonlinear responses.

139

140 The third Binghamton symposium was entitled 'Geomorphology and vegetation:
141 interactions, dependencies and feedback loops' and took place in 2009 with the collection
142 of papers appearing in *Geomorphology* in 2010. The intent, as explained in the preface, was
143 to revisit the 1995 symposium but with a tighter focus on vegetation and geomorphology.
144 The papers are organised into three sections addressing vegetation/geomorphic coupling in
145 uplands, floodplains and channels. The fourteen substantive papers cover topics including
146 mosses and slope processes on Hawai'i, land degradation in drylands, vegetation and

147 topography, the interactions between fire, floods and woody debris, and between logjams
148 and floodplains, and riverine vegetation and bank stability.

149

150 The fourth biogeomorphologically-orientated Binghamton symposium, entitled
151 ‘Zoogeomorphology and ecosystem engineering’, was held in 2011 with the collection of
152 fifteen papers appearing in *Geomorphology* in 2012. The aim of the symposium was to
153 bridge the gap between geomorphological and ecological approaches, in particular to link
154 those who study zoogeomorphology with people who research on ecosystem engineering.
155 The collection of papers is divided into three sections covering microbial/ hydrosphere
156 communities, larger animals and ecosystem engineering, and varied animal impacts on
157 sediment movement and erosion. Topics covered include microbes and geomorphology,
158 organisms and erosion on rocky coasts, ecosystem engineers in the benthic zone, the
159 geomorphic signatures of ecosystem engineering, the impacts of elephants, gopher
160 tortoises and armadillos, and the roles of small animal foraging in sediment and nutrient
161 movements in deserts, warfare as a zoogeomorphic agent, and the impacts of climate
162 change on zoogeomorphology.

163

164 The most recent biogeomorphological Binghamton symposium, held in 2017, was entitled
165 ‘Resilience and bio-geomorphic systems’ and published in 2018 in a special issue of
166 *Geomorphology* consisting of 19 papers. This has the widest scope and most ambitious
167 remit of any of the five symposia – trying to articulate linkages and bridge gaps between
168 socio-ecological resilience thinking, biogeomorphology and geomorphology. Papers cover a
169 diverse array of topics including the resilience of wetlands in drylands, niche construction in
170 riparian corridors, coastal wetlands and sea level rise, impacts of evolution in fish species on

landscape evolution, impacts of urbanisation on stream geomorphology and ecology, zoogeomorphology and resilience, and the interdependence of geomorphic and ecological resilience.

The edited collections reviewed above record three key areas of progress in biogeomorphological research over the past 30 yr – a move away from qualitative studies of individual species/process interactions to quantitative studies of more complex interdependencies, an enhanced level of interdisciplinarity and diversity in research traditions, and a growing focus on developing biogeomorphological theory within the broader frameworks of earth and environmental sciences and global change. Progress has not been linear, with the wider geomorphological community not taking biogeomorphological interactions seriously until well into the 1990s. Some continuity and deepening of scope is also obvious – with major persistent foci of research on fundamental sediment/vegetation/fluid dynamics at the small scale, and the river/ floodplain/ hillslope nexus at the larger scale. It is also apparent that biogeomorphological research is still open to explorations of new, often quite unusual examples of the mutual interdependencies of the living and non-living on Earth's surface, such as in cryoconite hollows in glacial surfaces, nest tumuli of alkali bees (Cane, 2003), and the action of penguin feet (Ercolano et al., 2016). Whilst such bizarre and small-scale examples can seem peripheral, as with cryoconite biofilms they can have global significance (Anesio et al., 2009).

2.2. Growth in biogeomorphological publications

What is the scale and significance of biogeomorphological research today? A partial answer can be gained from looking at the numbers of publications and their citation profiles. A

Scopus search [29/9/2018] of article titles, abstracts and keywords using the terms 'biogeomorph* OR bio-geomorph* OR ecogeomorph* OR eco-geomorph* OR zoogeomorph* OR zoo-geomorph* found 635 unique references since 1972, which have in turn received close to 8700 citations, with rapid growth in both since around 2000 (Fig. 3). These papers appear in more than 100 different journals covering many areas of the earth and environmental sciences, showing the range of interest in biogeomorphological research. These references are a mere tip of the iceberg as many important publications on biogeomorphological topics do not have those particular words in the title, abstract or keywords. Looking more broadly, Scopus searches [29/9/2018] using 'vegetation AND geomorphology' and 'vegetation AND erosion' returned 3098 and 11,419 unique references respectively between 1972 and 2018. Even given the underlying growth in scientific activity over the past 30 yr, it is clear that there is rapidly developing interest in this cross-cutting and interdisciplinary area of research.

3. Major advances in biogeomorphology since 1988

3.1. Theoretical advances

Much effort has gone into creating a set of foundation concepts to encapsulate the important components of biogeomorphic systems, as well as into developing a coherent explanatory framework to allow analysis of the interactions between components, and then exploring different outcomes across a range of temporal and spatial scales. Developing theory in interdisciplinary areas is challenging, as it often relies on borrowing or expanding concepts and frameworks from one or more disciplines. There can be a lack of shared understanding of these elements as well as difficulties in putting them together

219 meaningfully. The motivating force for developing theory is often the need to answer
220 fundamental questions and in biogeomorphology and cognate fields four key questions
221 have emerged:

- 222 a) How do ecological and geomorphic systems interact?
- 223 b) How important are such interactions in shaping the landscape (or, to put it another
224 way: Is there a geomorphological signature of life? And if so, what form does it take
225 (topographical, geochemical?) and at what scale(s) is it manifest?)
- 226 c) How important is biodiversity to landscape evolution, and conversely how important
227 is landscape evolution to biodiversity?
- 228 d) Have life and landscape co-evolved?

229 These fundamental questions form a nested hierarchy and, in essence, deal with bio/geo
230 interactions over a spectrum of spatio-temporal scales, from the process-response or
231 ecological scale to the evolutionary or geological scale (Phillips, 1995). They require
232 interdisciplinary consideration which links ideas from geomorphology, Quaternary science,
233 geology, ecology, and evolutionary biology.

234

235 In order to answer the question 'How do ecosystems and geomorphic systems interact?' it is
236 first necessary to conceptualise what the possible relationships and interactions might be,
237 and then consider how they may be produced. Fei et al. (2014), building on earlier work by
238 (Naylor et al., 2002; Carter and Viles, 2005; Naylor, 2005) and others, neatly categorise the
239 major biogeomorphic processes as bioweathering, bioerosion, bioturbation, bioprotection
240 and bioconstruction. An amplified and modified version of these ideas, informed by
241 Corenblit et al. (2009) is shown in Fig. 4. These processes represent current understanding
242 of the fundamental ways in which biological/ ecological processes (eating, growing, making

243 a home, competing, reproducing) influence the basic geomorphological processes
244 (weathering, erosion, transport and deposition). The first three (bioweathering, bioerosion
245 and bioturbation) can be viewed as different ways in which biota can enhance the
246 breakdown and movement of material on the earth's surface, whereas the last two
247 (bioprotection and bioconstruction) can be seen as ways in which biota reduces these. An
248 interesting extension of ideas on bioerosion, with a new conceptual framework, is
249 presented in Davidson et al. (2018), whilst examples of bioprotection are given in Carter and
250 Viles (2005) and Gowell et al. (2015). Often, the activities of individual species can involve
251 more than one of these biogeomorphological processes.

252

253

254 Ecologists have approached the essential nature of bio/geo interactions in a very different
255 way, with Jones et al. (1994) proposing the concept of 'ecosystem engineering'. Ecosystem
256 engineers are defined by Jones et al. (1994, p. 374) as: "...organisms that directly or
257 indirectly modulate the availability of resources...to other species, by causing physical state
258 changes in biotic or abiotic materials." A subset of ecosystem engineers may have a clear
259 effect on geomorphology and thus be biogeomorphic in nature. Another approach has been
260 to explore the links between biodiversity and geodiversity, in particular how geomorphic
261 processes can provide favourable or unfavourable conditions for different organisms to
262 colonise and thrive (Hjort et al., 2012). A useful paper by Allen et al. (2014) sets out three
263 important ecological principles which the ecogeosciences need to take on board to avoid
264 portraying the impact of biological processes on the environment in too simplistic a way.
265 First, biological traits in nature are variable because of species diversity. Second, biological
266 traits are dynamic, and third, dynamically coupled bidirectional relationships between

species and their environments generate feedback cycles. They use these principles to generate testable hypotheses which should inform biogeomorphological research.

Conceptualisations of the relationships between biological/ ecological and geomorphological processes often start by investigating their dynamics independently and then together, as illustrated by the analysis of Thornes (1985) who developed mathematical expressions for both plant growth and soil erosion and then added feedbacks between them. The biogeomorphic processes thus emerge from the interactions. A slightly different approach has been followed by Viles et al. (2008) who built on the geomorphological work of Bull (1991) to produce simple conceptualisations of the impacts of disturbances (such as droughts) on biogeomorphic systems through changes over time in growth and activity of vegetation, microorganisms and animals, and in earth surface processes (Fig. 5). A more complex conceptual approach has been followed by Stallins (2006) who uses the framework of complexity theory to characterise biogeomorphic systems as complex adaptive systems with multiple causality, which are influenced by ecosystem engineers, and possess an ecological topology and an ecological memory (where ecological topology refers to the geometry of stability domains and phase transitions, and ecological memory is defined by Stallins (2006, p. 212 as “...how a subset of abiotic and biotic components are selected and reproduced by recursive constraints on each other”).

Further conceptual advances in biogeomorphology have come through the development of the biogeomorphic succession concept (Corenblit et al., 2007, 2009) which, applied originally to fluvial corridors, outlines four stages (geomorphic, pioneer, biogeomorphic,

ecological) with differing interactions between species, water flow, sedimentation and erosion predicted to occur within each phase. This concept links the evolution of fluvial landforms and riparian vegetation within a bi-directional model based on reciprocal interactions and adjustments and uses the approach of adaptive cycles. An expansion of this framework to more complex sequences is provided by Phillips et al. 2017). Further theoretical explorations of the functioning of biogeomorphic systems have focused on the concept of biogeomorphic resilience (based on adaptive cycles, panarchy and resilience theory ideas) as shown in Fig. 6 (Stallins and Corenblit, 2018; Atkinson et al., 2018; Butler et al., 2018). The idea of biogeomorphic resilience is summarised as “...the resilience properties generated by the functional capacity of organisms to shape biogeomorphic variability arising from disturbances such that the biogeomorphic conditions and processes that shape these capacities persist.” (Stallins and Corenblit, 2018, p. 77).

Theoretical advances in biogeomorphology have also arisen in relation to attempts to answer the question ‘Is there a topographical signature of life?’. Phillips (1995), for example, explores a number of mathematical approaches including comparing the transient form ratios for landforms and vegetation – where $TFR = t_a/t_f$ (given t_a = relaxation time of landform or vegetation and t_f = recurrence interval of a disturbance affecting landforms or vegetation). Jones (2012) takes a similar approach, but starts from an ecological perspective rooted in the approach of ecosystem engineering. He develops a similar ratio (F/D) to compare rates of formation and decay of structures engineered by species (such as beaver dams, termite mounds, etc.) within patches across a landscape. In this case F = the rate of formation of a set of biogenic structures and D = rate of decay of those structures. Where

315 F/D < 1 the structures are likely to be transient and of less geomorphological importance.
316 These ideas build on, but do not directly acknowledge, the transient form ratio idea as
317 originally developed in the 1970s by Denys Brunsden and John Thornes (Brunsdn and
318 Thornes, 1979). The concept of the 'biogeomorphological feedback window' (Eichel et al.,
319 2016) is a useful addition to the biogeomorphic succession ideas reviewed above which
320 addresses the question of a topographical signature of life. It encapsulates the notion that
321 within a biogeomorphic succession there are particular conjunctions of conditions which
322 permit biogeomorphic feedbacks to establish and operate, in this case within lateral
323 moraines. Within these windows of opportunity a geomorphological signature of life is most
324 likely to occur and be most clearly expressed on the earth's surface.

325

326 The question of how important landscape evolution is to biodiversity has generated several
327 important theoretical insights, largely within the emerging field of geodiversity and
328 biodiversity research. Matthews (2014), for example, reviews the literature on geodiversity
329 and biodiversity and proposes that conservation should focus on 'natural diversity'
330 (geodiversity and biodiversity) because of the fundamental links between them. Lawler et
331 al. (2015) introduce the concept of 'Nature's stage' (geophysical diversity, including
332 geomorphological processes and topography) and how important it is to conserve the stage
333 as well as the actors (biodiversity) in order to conserve the 'ecological play' (the interactions
334 between biodiversity and geophysical diversity).

335

336 A rich recent vein of theoretical biogeomorphological research relates to the question 'Have
337 life and landscape coevolved?' and demonstrates extensive interchange of ideas between
338 biology and geomorphology. Building on the ecological idea of 'ecosystem engineering'

various authors have utilised the concepts of ‘niche construction’ and ‘extended phenotypes’ to develop a macroevolutionary biogeomorphological framework (Corenblit et al., 2011). In these long-term approaches, the evolutionary benefits of biogeomorphic processes or ecosystem engineering activities result in changes to both biotic and geomorphic components of the system. Phillips (2016a) provides a review of evolutionary concepts and their application to karst landscapes, identifying a spectrum of biogeomorphic interactions on seven levels from indirect impacts of organisms on landforms up to extended phenotype landforms. He notes that the special nature of karst geomorphology permits some species to play ecosystem engineering roles that they do not play in other geomorphic environments – he names these ‘contingent ecosystem engineers’.

Phillips (2016b) explores these evolutionary ideas in geomorphology in general, outlining pathways of ecosystem engineering, niche construction and landform biogenesis (Fig. 7). He proposes that some landforms can be regarded as extended composite phenotypes because of the strong, evolutionarily significant biogeomorphic contributions to their formation and maintenance (e.g., insect mounds, salt marshes, mangrove swamps and coral reefs). Phillips (2016b) suggests that biological evolution will continue to drive landscape metamorphosis, leading to new landform types, and the loss of extended phenotypes when species extinction occurs.

Whilst geomorphologists are often nervous about theory, and geomorphology, ecology and evolutionary biology have quite distinctive theoretical traditions, there is an increasingly coherent and significant body of ideas being developed in and around biogeomorphology. There are two key areas which require additional work in order to strengthen and develop this theoretical corpus. First, it is important to develop a coherent and shared

understanding of underpinning concepts and terms, by bringing together people who have developed and pursued different biogeomorphological research directions over the past few years. Second, and building on the first area, it is now timely to develop a shared theoretical corpus within which testable hypotheses can be explored. Such hypotheses should build on the work reviewed above to address the four fundamental questions, but in a more coordinated and articulated fashion than has previously been possible.

3.2. Methodological advances

There have been many advances in biogeomorphological research methods since 1988, despite many challenges. Lack of shared theoretical vision between geomorphologists, ecologists and evolutionary biologists has posed problems for developing shared methodologies, although recent theoretical advances should help overcome these. Haussmann (2011) makes some very pertinent observations about the methodological differences between ecologists and geomorphologists which are, in her view, holding back biogeomorphology. As she explains, many ecologists focus on statistical explanations of patterns, whilst geomorphologists often focus on theoretically-informed, case study based detailed explanations of process. Furthermore, ecologists usually deploy controlled experiments, whereas geomorphologists often use uncontrolled field observations. Such different approaches feed into modelling frameworks, where ecological models are usually based on statistical analysis of datasets, whilst geomorphological models are often built from mathematical relationships between variables. Molau (2008) makes some useful contributions to discussions about how to improve the relationship between ecologists and geomorphologists. He advocates a focus on the landscape rather than ecosystem scale (c.f. (Post et al., 2007), and a shared methodology utilising the ‘three Ms’ – monitoring,

manipulation (field and laboratory-based) and modelling which he regards as together providing the essence of modern ecology.

In fact, both geomorphology and ecology are largely now based on the ‘three Ms’ – although the nature of each ‘M’ and the balance and relationships between them may vary between the two disciplines. Furthermore, each ‘M’ covers a diversity of approaches. For example, many geomorphological and ecological studies use mapping and measurement (i.e., snapshot or static data collection) or palaeo-evidence (using characteristics of dated samples to infer change over time) rather than strict monitoring over time. Meta-analysis has also become more popular as a methodology in many environmental sciences in recent years (and so could increasingly provide a fourth ‘M’). Naylor (2005) and Reinhardt et al. (2010) provide good reviews of the methodological toolkits available to today’s biogeomorphologists drawn from recent advances in the three ‘Ms’ in both geomorphology and ecology – including remote sensing, radiometric dating, and isotopic proxies as well as various approaches to modelling. A survey of 50 biogeomorphological papers (published between 1994 and 2018, with the bulk in the last 10 yr) helps quantify the situation, and shows a preponderance of studies using monitoring methods (Fig. 8), with various forms of mapping and measurement also popular, followed closely by modelling methods. Field and laboratory manipulations are less commonly used but can provide extremely valuable information.

Monitoring in biogeomorphology covers a very wide range of temporal and spatial scales, and has been revolutionised by recent developments in remote sensing technologies,

411 including aerial and ground-based LIDAR and UAV-mounted sensors (Viles, 2016). For
412 example, Meitzen (2009) used air photos and GIS to monitor lateral channel migration and
413 riparian vegetation change, Schwarz et al. (2018) used air photography to corroborate
414 modelling findings on the biogeomorphology of the western Scheldt delta, and Aguiar et al.
415 (2016) used LIDAR surveys to investigate the impacts of dams on river ecology and
416 geomorphology. Doyle and Woodroffe (2018) demonstrate the utility of LIDAR in providing
417 wide and rapid assessment of the biogeomorphic status of foredunes in Australia.
418 Monitoring in a wider sense encompasses longer term proxies of environmental change,
419 such as the use of isotopes in soil profiles to investigate changing soil nutrient status by
420 Chadwick et al. (2007) in Hawaii and the use of ^{137}Cs surveys to investigate redistribution of
421 organic carbon across a landscape (Ritchie et al., 2007). Environmental DNA has recently
422 been proposed as novel potential proxy for long term monitoring of the changing role of
423 fauna in fluvial biogeomorphology (Larsen et al., 2018). The particular monitoring needs of
424 biogeomorphological research, with special reference to coastal sedimentation rates, are
425 critically reviewed by Nolte et al. (2013).

426

427 Manipulation in biogeomorphology involves both laboratory and field experiments.
428 Examples of laboratory experimentation include flume-based studies of the impacts of fish
429 such as Barbel on fluvial sediments (Pledger et al., 2014) as well as the use of compressive
430 strength testing equipment to assess the strength of intertidal sediments cemented by
431 Sabellaria polychaete worms (Le Cam et al., 2011). Field experiments in biogeomorphology
432 utilise a range of different approaches, from paired catchments with and without grazing
433 ungulates (Grudzinski et al., 2018), to experimental removal of vegetation from salt marshes
434 to simulate disturbance (Temmerman et al., 2012). Scaling issues in biogeomorphological

435 experiments are discussed by Kleinhans et al. (2015), but they have proven to be extremely
436 important in recent years in providing empirical data for modelling studies.

437

438 Modelling in biogeomorphology encompasses many different approaches, from detailed
439 mathematical landscape evolution models (e.g., CHILD used by Yetemen et al. (2015) to
440 investigate the impact of differences in solar radiation receipt on slope asymmetry) to
441 simplified cellular automata models. An example of the latter is the ViSTA model which
442 simulates vegetation, wind and sediment dynamics in arid and semi-arid areas (Mayaud et
443 al., 2017). Some studies also use statistical modelling to explore trends in data collected in
444 the field from measurement, mapping and monitoring, such as Eichel et al. (2016) and Bätz
445 et al. (2015). Murray et al. (2008) discuss the difficulties of quantifying biological and
446 ecological processes within morphodynamic models, and the need for new
447 parameterizations.

448

449 Some biogeomorphological studies are methodologically innovative, often using established
450 methods in new ways – such as Kinlaw and Grasmueck (2012) who used Ground Penetrating
451 Radar to investigate the 3D architecture of burrows created by Gopher tortoises. Tools have
452 also been borrowed from many other disciplines, such as microbial ecology where DNA
453 sequencing and other methods are increasingly being deployed to probe more deeply into
454 microbial contributions to geomorphic processes. Biogeomorphological investigations
455 usually require multiscalar data (Atkinson et al., 2018), and as Urban and Daniels (2006)
456 pointed out, many geomorphological tools are scale dependent and thus new techniques
457 may need to be developed. Renschler et al. (2007) suggest that whilst GIS methods can
458 provide common ground between geomorphological and ecological studies, critical

appraisal of the accuracy of data sets and model outputs is required before GIS tools can be used for environmental management.

This survey of methods used in biogeomorphological research shows great diversity, richness and innovation. It also reveals increasing evidence of cross-fertilization and linkages – with field and lab experimentation being used to generate data which can be used for parameterization within models, and field observations of new, often complex interactions between biological and geomorphological processes helping to stimulate improvements in the realism, complexity and fidelity of models.

There are two key areas which require further work in order to develop a coherent biogeomorphological methodology. First, it would be good to develop a ‘modelling toolkit’ for future biogeomorphological investigations, bringing together the best recent approaches and applying them to under-studied biogeomorphic systems. Such a toolkit, informed by the theoretical developments proposed at the end of Section 3.1, would enable easier comparison of results between studies and permit a broader scale assessment of the functioning of biogeomorphic systems. Second, there is a clear need for rigorous meta-analyses of existing and new biogeomorphological process datasets in order to test key biogeomorphic hypotheses. Such meta-analyses would help demonstrate the relative importance of biogeomorphic processes (as opposed to inorganic processes and those directly related to human activity) in environmental systems around the world.

3.3. Thematic advances

As publications on biogeomorphological topics have multiplied over the past 10 yr (Fig. 3), this section focuses on the state-of-the-art of knowledge within key thematic areas over this

period. Within the length constraints of a journal article such a review is of necessity partial and selective, and many important areas are neglected in the following paragraphs. As the bulk of publications over this period focus on coastal sedimentary environments and fluvial/riparian environments, with a smaller number of contributions focusing on hillslopes (across a wide range of environments from Alpine to arid, and including rocky and soil-covered slopes) these are the main areas focused on below.

3.3.1. Coastal sedimentary environments

Biogeomorphological studies on coastal sedimentary environments cover the whole spatial hierarchy of landforms and landscapes from individual seagrass beds, salt marshes, mudflats, mangrove swamps, beaches and vegetated foredunes, to larger, compound features such as barrier islands, estuaries and deltas. The term ‘ecogeomorphology’ is often used to describe the research, although biogeomorphology also features strongly. The full spectrum of methods reviewed in Section 3.2 are found in coastal biogeomorphological publications and many of the theoretical approaches reviewed in Section 3.1 are also explored.

At the small scale, an important body of research has recently focused on the ecological and biological controls on plant and animal contributions to geomorphological processes within reefs, marshes and coastal dunes. Looking at individual species behaviour, Salvador de Paiva et al. (2018) find that oyster reefs play a contingent ecosystem engineering role in stabilizing sediment, with stabilisation only resulting under certain environmental conditions. Focusing on more than one species, Schwarz et al. (2018) elucidate the role of plant traits (fast or slow colonizers) in controlling channel patterns and landscape within marshes of the Western Scheldt using a combined field and modelling approach. Such control has a knock-on effect on the resilience of these marshes. In a similar vein, Ameen et

al. (2017) demonstrate that different vegetation communities have varying effects on delta sediment shear strength which in turn causes local differences in erosion rates. The importance of individual species characteristics is also explored by Charbonneau et al. (2017) who show that invasive sedge plants stabilised coastal foredunes more effectively than native grasses during Hurricane Sandy.

Several small scale studies also investigate interlinkages between different components of biogeomorphic systems. Van Regteren et al. (2017), for example, show that oligochaete bioturbation retards the establishment of *Salicornia* seedlings in marsh front environments, with inferred impacts on sedimentation and marsh development, whilst Harris et al. (2017) use a glasshouse study to demonstrate the importance of interactions between two foredune plant species, and Escapa et al. (2015) illustrate how the links between crab bioturbation and *Sarcocornia perennis* growth on Argentinian saltmarshes leads to the production of salt pans.

At a larger scale, several recent papers have improved understanding of the functioning and wider importance of previously neglected coastal biogeomorphic systems, such as seagrass beds (Montefalcone et al., 2016; De Muro et al., 2017; Vacchi et al., 2017). Other studies have investigated bistable or multiple stable states in coastal biogeomorphic systems such as marshes and mudflats, through combined modelling and observational methods (Da Lio et al., 2013; Marani et al., 2013; Wang and Temmerman, 2013). However, the dominant focus has been on providing a fuller understanding of how well-studied biogeomorphic systems such as barrier islands, mixed saltmarsh and mangrove wetlands and deltas behave when forced by sea level rise and human interference (e.g., Day et al., 2008; Deaton et al., 2017; Fagherazzi et al., 2017; Sandi et al., 2018). At the largest scale, ecogeomorphological frameworks have been started to be applied to global scale assessments of the carbon

storage capabilities of delta sediments, with Rovai et al. (2018) noting the importance of coastal environmental settings to the quantity of carbon stored. Much of the recent research on coastal sedimentary environments demonstrates strong cross-scalar linkages, often viewed within the frameworks of complex systems and resilience.

3.3.2. Fluvial and riparian environments

River channels, banks and floodplains have always been a key focus for biogeomorphological research, and several good reviews have recently been published summarising progress in these areas (Murray et al., 2008; Thomas et al., 2014; Atkinson et al., 2018). As with coastal sedimentary environments, the state-of-the-art shows a flowering of research at different scales and an increasing focus on cross-scalar linkages, and consideration of biogeochemical as well as biophysical impacts, often framed in terms of concepts such as biogeomorphic succession and biogeomorphic resilience. The terms ecogeomorphology and ecohydraulics are often used to describe the orientation of these studies, as well as biogeomorphology.

At the small scale, recent research in fluvial biogeomorphology has made huge progress in quantifying the impacts of large woody debris (LWD) and in-channel fauna on sediment dynamics, as well as those of riparian plants and animals, both individually and in combination. Bendix and Cowell (2010) and Curran (2010), for example, carried out observational studies of LWD and its dynamics showing, respectively, the combined role of fire and floods in delivering LWD and the mobility of LWD in low gradient rivers. Many laboratory and field experiments have been carried out on the geomorphic roles of in-channel fauna on bed and bank sediment, including foraging fish (Pledger et al, 2017), insect

555 larvae (Savrda, 2017), and invasive signal crayfish (Johnson et al., 2011; Faller et al., 2016).
556 Studies continue to be carried out on the reverse situation, i.e., the impact of flow and
557 sediment regimes on biota (see for example the work of Katz et al. (2018) on the impacts of
558 bed mobility on benthic algae, and the modelling study of Perona and Crouzy (2018) on
559 vegetation uprooting by flowing water).

560

561 Riparian vegetation and the differential impact of individual species on the development of
562 alluvial bars as a result of different plant traits has been studied by Hortobágyi et al. (2018),
563 and a broader exploration of the role of ecological traits in riparian biogeomorphology
564 carried out by Diehl et al. (2017). Allen et al. (2018) find a clear correlation from a field
565 observational study between increased riparian plant biodiversity and decreased erosion
566 rate. The role of animal grazing on stream sediment concentrations and bank erosion
567 continues to be a topic of interest, with Grudzinski et al. (2018) providing a neat comparison
568 between bison and cattle grazing impacts, using a paired catchment design field
569 experiment. Beschta and Ripple (2012) use the extirpation of large predators in USA
570 National Parks as a field experiment to study the indirect impact on fluvial sediment
571 dynamics.

572

573 At larger spatial and temporal scales, methods such as remote sensing and GIS have been
574 used to monitor change in fluvial biogeomorphic systems over five decades by Kui et al.
575 (2017), over decadal to century timescales by Little et al. (2013), and over a century by Diaz-
576 Redondo et al. (2017). Over geological and evolutionary timescales, some interesting recent
577 research has shown the fundamental importance of biogeomorphological interactions in
578 fluvial systems to the Earth system. Fremier et al. (2018), for example, use modelling to

explore whether a speciation event could have a significant influence on the evolution of upland mountain streams. Ielpi et al. (2018) investigated the nature of fluvial systems before the advent of land plants, and Davies and Gibling (2010) illustrated the phenomenal changes in alluvial systems during the period when land plants evolved. Much of the smaller scale recent biogeomorphological research in fluvial and riparian environments has obvious applications to environmental management, and there is increasing evidence that these small scale studies need to be situated in larger scale and longer term contexts.

3.3.3. Hillslopes – from alpine to arid

A smaller body of work has been produced in recent years on biogeomorphological interactions outside coastal sedimentary and fluvial environments. However, many significant findings have resulted which together illustrate the nature and larger scale significance of many relatively small scale biogeomorphic interactions on vegetated land surfaces in diverse climatic zones across the globe. I focus here on hillslopes (in a broad sense, including rocky outcrops such as cliffs and shore platforms).

At the very small scale, research has continued on the relationship between microbial biofilms, lichens and rock weathering, and biological soil crusts and slope sediments. Favero-Longo et al. (2015) and Morando et al. (2017), for example, provide detailed assessments of the differential impact of endolithic and epilithic lichens on gneiss and limestone outcrops respectively, and Williams et al. (2013) investigate the bidirectional relationships between sediment types and biological soil crust types on Mojave desert surfaces. Further research has been carried out on the interplay between bioweathering, bioerosion and bioprotection

602 on rocky outcrops (Coombes et al., 2013, 2017; Mayaud et al., 2014) and a new model of
603 biological contributions to rocky coastal evolution proposed (Naylor et al., 2012).

604

605 At a larger scale, several studies have continued the tradition of investigating the impacts of
606 animal burrowing and sediment movement on hillslopes. Research on burrowing by *Mus*
607 *musculus* on sub Antarctic islands (Eriksson and Eldridge, 2014) and ant mounds as a source
608 of erodible sediment in tropical rainforest in Panama (Schmidt et al., 2014) both confirm the
609 quantitative importance of these animals. Interactions between species are crucial. Winchell
610 et al. (2016) find that gopher burrows are significant in alpine meadows but not adjacent
611 forests, whilst the useful review of Haussmann, (2017) indicates that larger animals produce
612 larger burrows, but smaller ones move more sediment. The importance of having ecological
613 information about population dynamics to aid longer term quantification of the bioturbating
614 role of key ecosystem engineers is noted by Coombes and Viles (2015) in their study of
615 badger impacts over a 17 yr period.

616

617 Several papers focus on the biomechanical effects of trees on forest soils and
618 geomorphology, including soil creep (Pawlik and Šamonil, 2018), slope processes (Phillips et
619 al., 2017) and landscape and ecosystem dynamics (Šamonil et al., 2018). Pawlik et al. (2016)
620 provide a good review of the range of biomechanical and biochemical impacts of trees.
621 Some of the studies are extremely comprehensive – for example, Šamonil et al. (2017)
622 studied ~55,000 trees over 3-4 decades over 161 ha of old growth forest. The key finding of
623 many researchers is that different trees behave in different ways, and that different
624 environmental conditions also play a significant role in the biogeomorphological outcomes
625 making generalisations difficult.

626

627 Studies have also focused on investigating combinations of processes, such as the work of
628 Louw et al. (2017) who investigated the combined effect of aardvark burrowing and
629 hueweltjie mounds on landscape heterogeneity in arid environments. Biogeomorphic
630 feedback systems have also been well-studied on hillslopes at various scales, including plant
631 growth and solifluction within paraglacial and periglacial environments (Annandale and
632 Kirkpatrick, 2017; Draebing and Eichel, 2018), and plant and landscape mosaics within the
633 Mojave Desert, USA (Pietrasiak et al., 2014). Biogeomorphic successions over decadal to
634 centennial scales have also been studied by Klaar et al. (2015) in rapidly deglaciating
635 environments, and by McAuliffe et al. (2014) on slopes of contrasting aspect in Arizona in
636 which soil temperature appears to play a key role in determining biogeomorphic processes
637 and their landscape significance.

638

639 *3.3.4. Thematic overview*

640 The examples of recent biogeomorphological research presented above show that
641 considerable advances have been made since 1988. Much quantitative evidence now exists
642 of interactions between ecology and geomorphology in many different environments
643 (through field and laboratory studies). Great progress has been made in linking these data
644 to landscape and ecological dynamics through modelling. Reflecting the quantitative
645 dominance of scientific outputs in fluvial and coastal environments noted in other recent
646 studies (see for example Table 2 in Chaffin and Scown, 2018), these two areas have shown
647 particularly strong progress. Key advances include linking results across scales and between
648 thematic areas, and a much more balanced participation in biogeomorphological research
649 by ecologists as well as geomorphologists.

Two thematic areas require further research. First, there are some specific knowledge gaps which require filling include a fuller specification of the role of microbial life in biogeomorphic systems noted by Viles (2012). Exciting progress is being made in this area (Hemingway et al., 2018), but much more needs to be done. Closer collaboration between microbial ecologists and geomorphologists is required in order to design projects which utilise cutting edge techniques ideas from both ecological and geomorphological traditions. Second, there is an excellent opportunity now for geomorphologists to explore the possibilities of a geomorphological signature of life on other planetary bodies based on an enhanced understanding of microbial contributions to biogeomorphic systems on Earth (see initial work of Corenblit et al., In Press).

660

3.4. Applications

Considerable progress has been made in the practical application of biogeomorphological research since 1988. Naylor (2005) noted three key areas of potential application of biogeomorphological research, i.e., to studies of carbon sequestration and climate change impacts, to astrobiology and the search for life on other planetary bodies, and to bioengineering. To date, most progress has been made in applying biogeomorphology to environmental management and environmental restoration. Such progress is set within a broader context of concerns about human impacts on the Earth system in the Anthropocene (Goudie and Viles, 2016), and developing interest in social-ecological systems and resilience thinking (Wohl et al., 2014; Thoms et al., 2018a). The Anthropocene provides two, linked challenges to biogeomorphology. First, biogeomorphic process interactions have been and continue to be affected by the changing global conditions in the Anthropocene. Many landscapes are now so altered by human activity that they might be called ‘genetically

674 modified' (following Naylor et al., 2016), and the biogeomorphic process interactions that
675 result may be very different from pre-Anthropocene ones. Vast areas of landscapes are now
676 dominated by biogeomorphologically important invasive species, which often have very
677 different impacts to the original inhabitants (Fei et al., 2014). In turn, the
678 biogeomorphological impacts of invasive and native species, such as rates of bioerosion, are
679 likely to be highly influenced by recent global change, as explored by Davidson et al. (2018).
680 Second, local biogeomorphic process interactions influence many important global
681 Anthropocene changes. For example, the complex and spatially differentiated dynamics of
682 many paraglacial biogeomorphic systems may determine whether or not rapid warming
683 leads to significant release of stored greenhouse gases. Better understanding of these two
684 challenges is required to improve environmental management and restoration. As Thoms et
685 al. (2018b) point out, there are substantial challenges facing attempts to link
686 biogeomorphology and resilience ideas to help manage social-ecological systems, in
687 particular a lack of shared understanding of resilience terminology, lack of agreement about
688 whether humans are external drivers or internal components of the systems of concern, and
689 unresolved questions about scale and scale linkages. Wohl et al. (2014) present a helpful
690 summary of the core themes in geomorphological, ecological and social systems thinking
691 and identify common concerns with thresholds, connectivity, feedbacks and resiliency.
692
693 The key question for applied biogeomorphology today is whether manipulating
694 biogeomorphic interactions can lead to more resilient landscapes and social-ecological
695 systems and if so, under what conditions? Biogeomorphological approaches to
696 environmental management and restoration may be attractive, given widespread
697 recognition of the failure of many hard engineering solutions (e.g., dams and coastal

698 protection schemes). Manipulation of, for example, LWD in rivers, forests on floodplains,
699 plants on coastal foredunes and saltmarshes might provide better solutions to problems of
700 flooding and erosion. Furthermore, rewilding schemes and reintroduction of extirpated
701 animals (e.g., beavers) should consider the likely biogeomorphological (as well as ecological)
702 outcomes. Biogeomorphological insights can also be deployed in improving the
703 conservation of heritage sites and urban buildings, where biofilms, lower plants, incipient
704 soils and higher plant communities can play protective roles. Properly designed and
705 controlled experiments should be carried out to assess the resilience of manipulated
706 biogeomorphic systems before implementation, such as those of on the impacts of storms
707 on vegetated saltmarsh surfaces and those of Hanssen and Viles (2014) and Coombes et al.
708 (2018) on the impacts of soil, turf and ivy on walls.

709 Practical applications of biogeomorphic ideas to environmental management and
710 conservation have so far been only partly successful. This is largely because of the key
711 features of biogeomorphic systems elucidated by much recent research – i.e., their
712 emergent properties, spatial differentiation and scale linkages. Such features make
713 biogeomorphic systems difficult to control and predict. Dixon et al. (2016), for example, use
714 reduced complexity modelling to explore the success of LWD and floodplain reforestation in
715 managing flood risk, noting highly variable outcomes. A key research need for the future is
716 to explore the multi-scalar characteristics of adaptive cycling within biogeomorphic systems
717 and investigate how biogeomorphology might contribute further to environmental
718 management, conservation and risk reduction. Whilst progress is being made in individual
719 environments (e.g., river channels, coastal sedimentary environments, heritage sites) we are
720 not as yet grappling in a concerted manner with the grand challenges facing humanity in the

Anthropocene and how biogeomorphological insights could help environmental management at length scales from metres to hundreds of kilometres.

4. Conclusions

The past fifty years have seen the birth, growth and flowering of biogeomorphology as an interdisciplinary research arena. The importance of biological and ecological factors to landscape processes and evolution is now clearly recognised by geomorphology. As Larsen et al. (2018, p. 335) put it, “Geomorphology is within a new era, one that recognises the role of biotic factors in governing geomorphic processes across a wide range of spatial and temporal scales”. The importance of geomorphology is also clearly recognised by ecologists. Many of the needs for further study in biogeomorphology that I outlined in 1988 have been met – there is now a huge body of knowledge and quantitative information on the interactions between species, communities and earth surface processes in many environments. This information is being used to test hypotheses about the interactions of life and landscape over a wide range of spatial and temporal scales, largely through modelling approaches. We now have clear evidence of the significance and complexity of the bidirectional relationships between ecology and geomorphology in many environmental settings, and are starting to use this information to help manage environmental change in the Anthropocene. As I have suggested throughout this paper, seven challenges relating to theoretical, methodological, thematic developments in biogeomorphology and their application to environmental management are now ripe for exploration over the coming 50 yr. These challenges could form a coherent research agenda for the future, prioritising on developing the following:

1. A coherent and shared understanding of underpinning concepts and terms.

2. A shared theoretical corpus within which testable hypotheses can be proposed and explored.
3. A multipurpose ‘modelling toolkit’ for analysing biogeomorphic systems.
4. Meta analyses of existing biogeomorphological process datasets to test key biogeomorphic hypotheses.
5. An interdisciplinary approach to filling key knowledge gaps, e.g., on microbial contributions to geomorphic systems.
6. An exploration of the geomorphological signature of life on other planetary bodies.
7. Practical application of understanding of multi-scalar, adaptive cycling in biogeomorphic systems to environmental management, conservation and risk reduction.

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1216 Figure captions
1217

1218 Figure 1: Suggested biogeomorphic response to abrupt changes in climatic regimes (Source:
1219 Knox, 1972).
1220

1221 Figure 2: One of the vegetation-erosion competition models discussed in ‘The ecology of
1222 erosion’, shown as isoclines in phase space (Source: Wainwright and Parsons, 2010, Fig. 2).
1223

1224 Figure 3: Cumulative growth in (a) publications and (b) citations on biogeomorphological
1225 topics, 1972-2018.
1226

1227 Figure 4: Types of biogeomorphic processes (Source: Modified after Corenblit et al., 2011).

Figure 5: Conceptual models of biogeomorphic disturbance regimes as a response to climate change (a) Vegetated dunes, (b) Rocky paraglacial environments (Source: Viles et al., 2008).

Figure 6: Conceptualisation of the adaptive cycles found in biogeomorphic succession (Source: Stallins and Corenblit, 2018 building on the ideas of Corenblit et al., 2009).

Figure 7: Biogeomorphic niche construction pathways (Source: Phillips, 2016b).

Figure 8: Methodological bases of a sample of 50 biogeomorphological papers (1994-2018). Numbers sum to more than 50 as several papers use multiple methods.

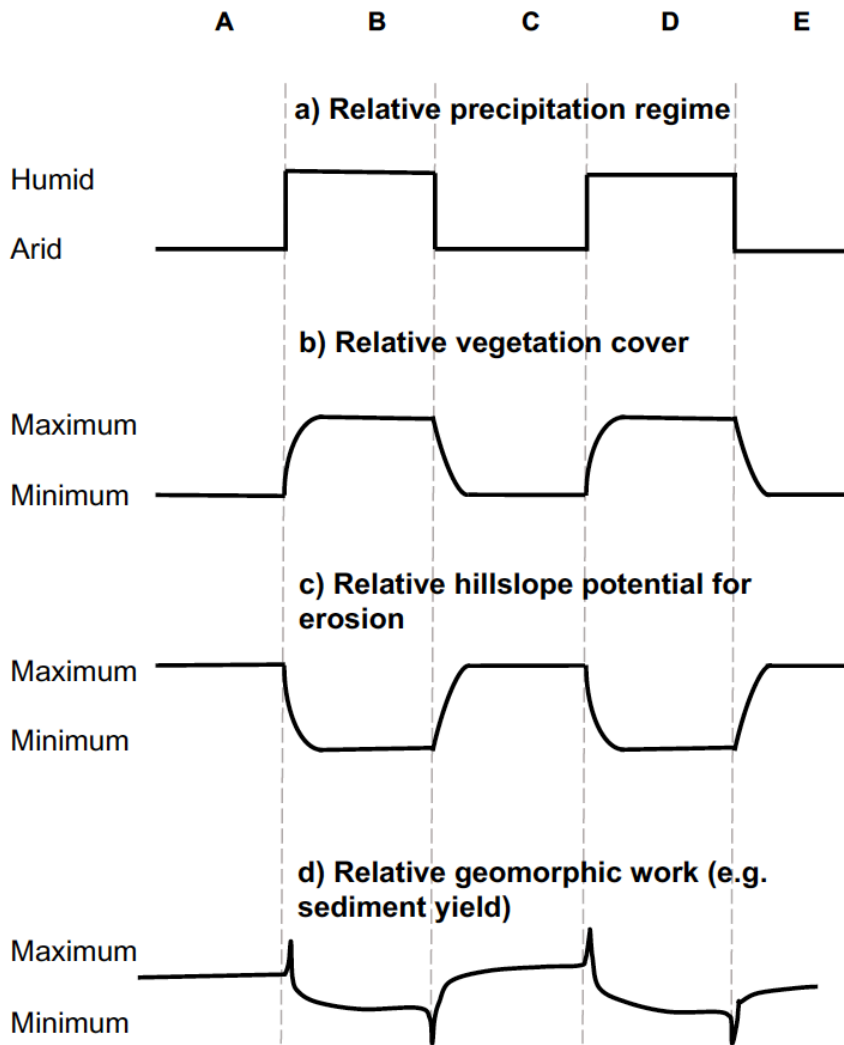


Figure 1

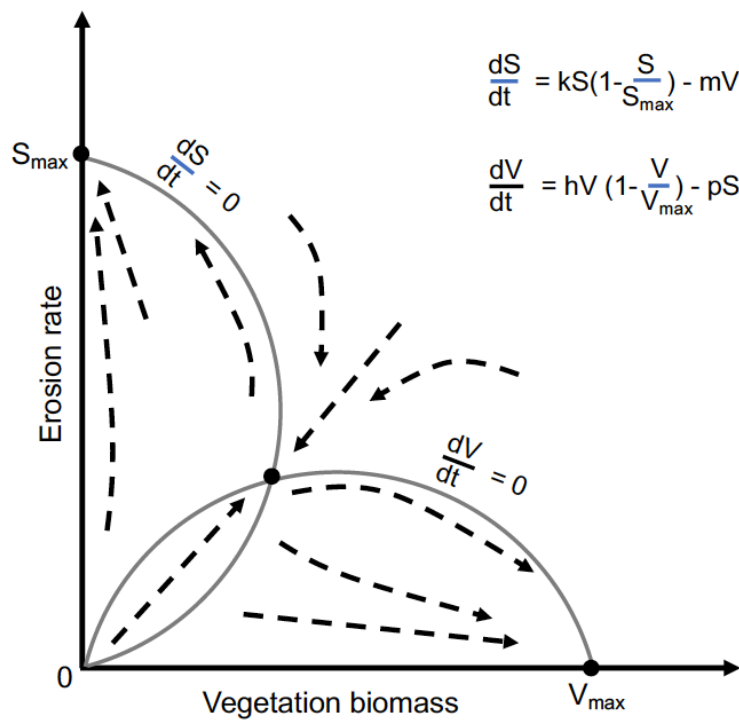


Figure 2

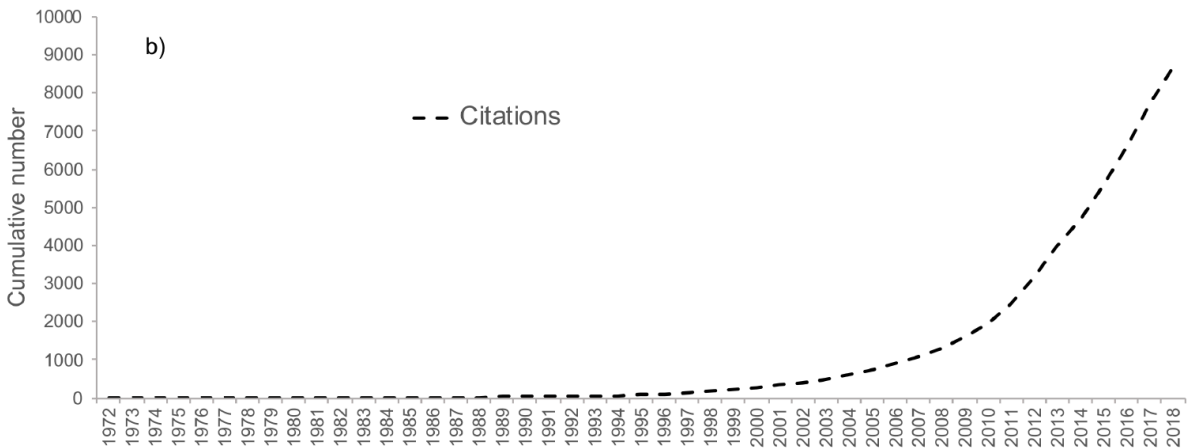
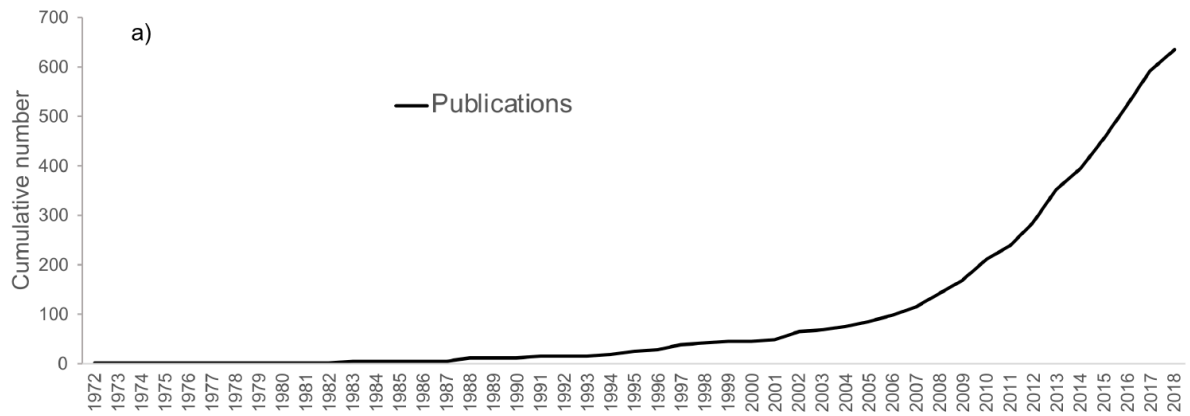


Figure 3a

Figure 3b

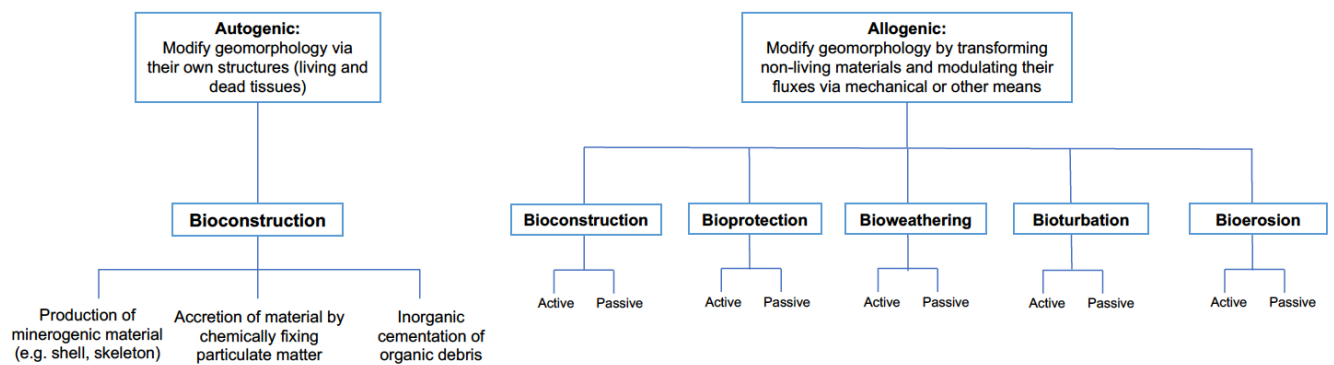
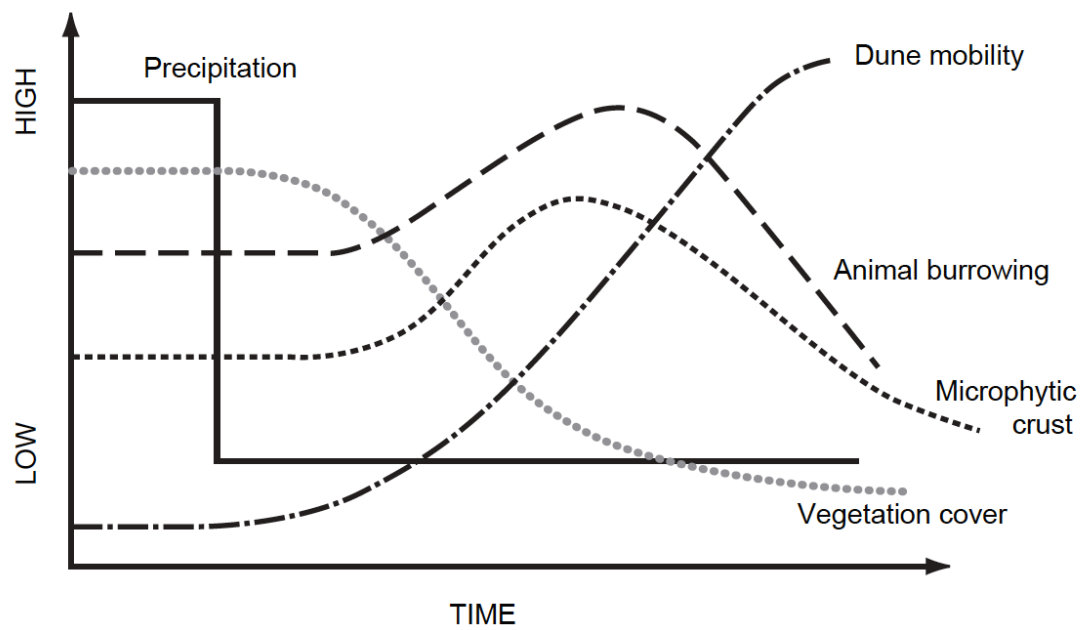
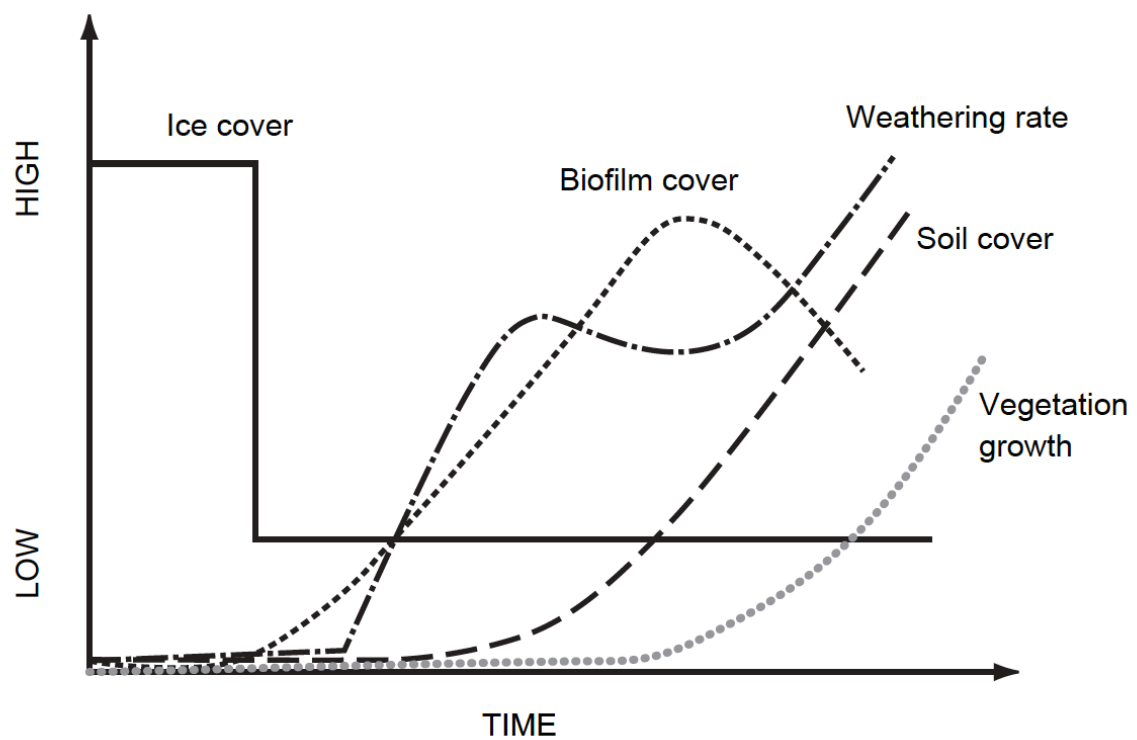


Figure 4



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1260 Figure 5a



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1262 Figure 5b

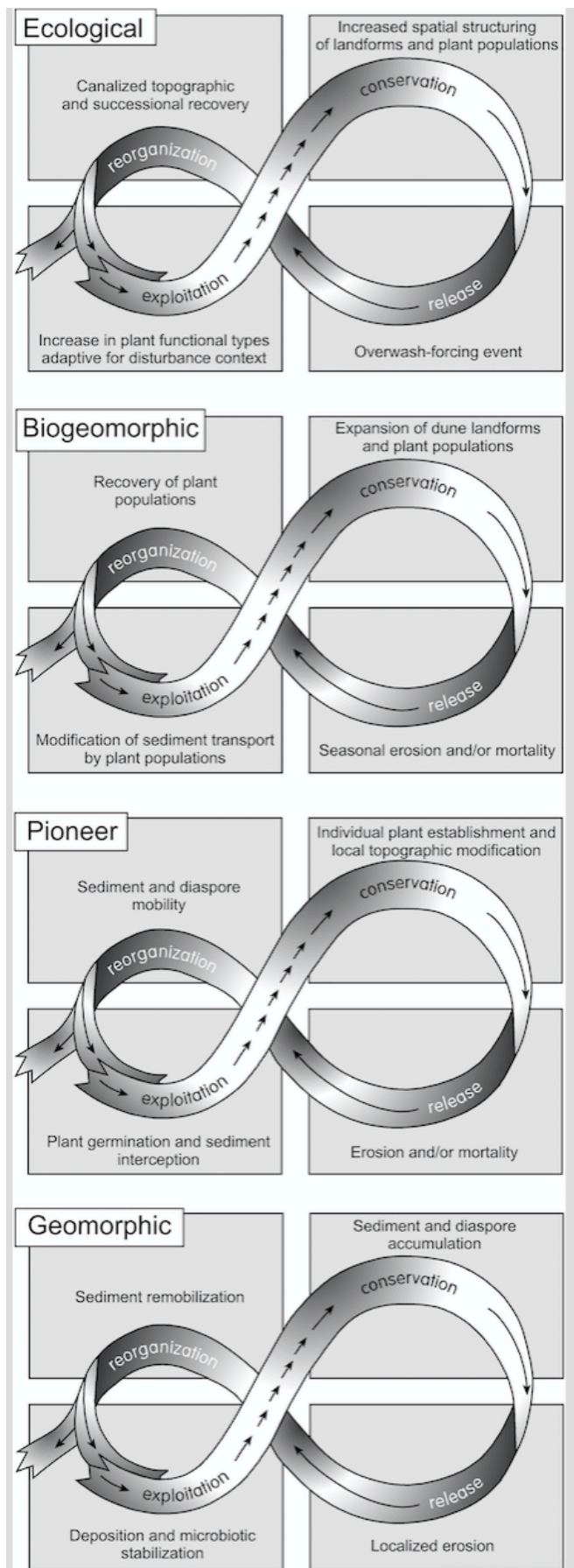
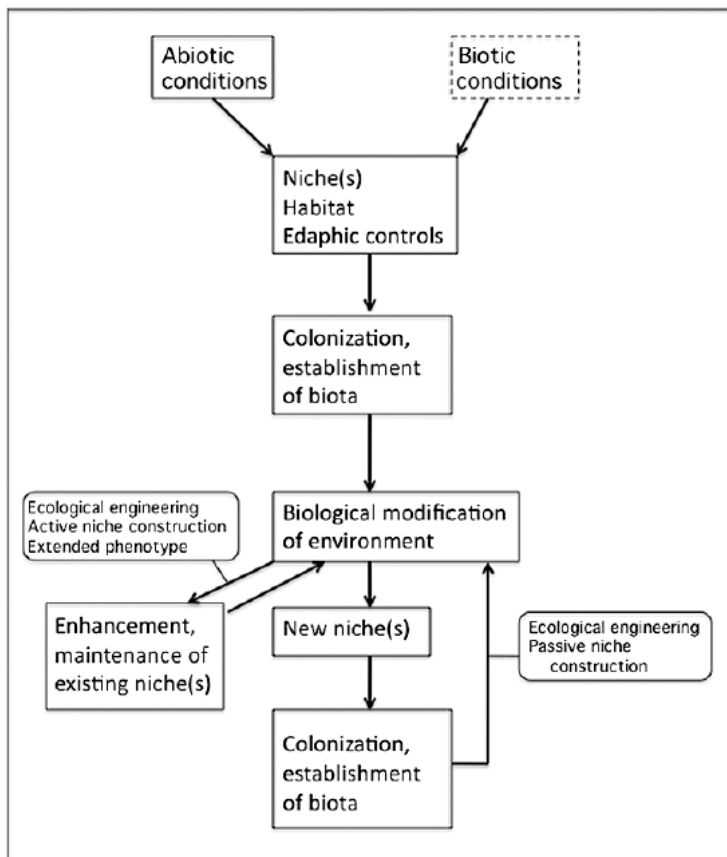
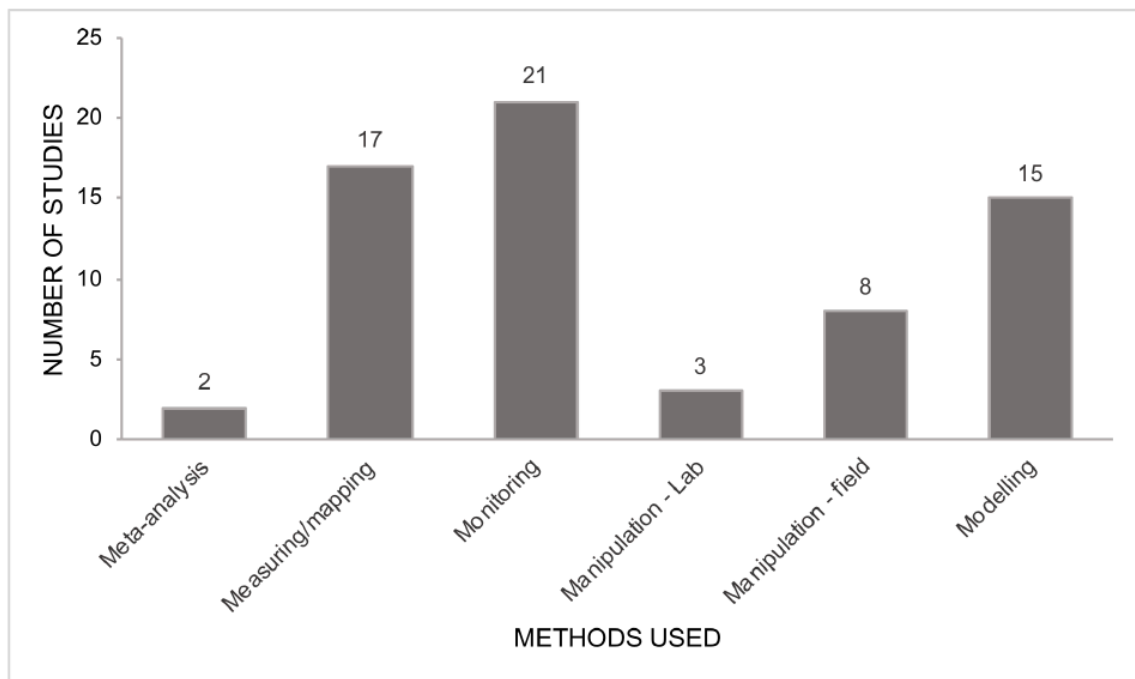


Figure 6



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1265 Figure 7



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1267 Figure 8