



Geomorphology and ecology: Unifying themes for complex systems in biogeomorphology

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Abstract

The interaction of geomorphic and ecologic landscape components has been largely conceptualized as independent. In one direction, geomorphic processes and landforms shape the distribution of biota. Conversely, in the other direction, biota modify geomorphic processes and landforms. Increasingly, the interactions between geomorphic and ecological components are more circular and developmentally intertwined. In this paper, I integrate these two independent perspectives within the framework of complexity theory. I outline four themes that characterize complex systems in biogeomorphology: multiple causality and the concept of recursivity, the influence of organisms that function as ecosystem engineers, the expression of an ecological topology, and ecological memory. Implicit in all of these themes is the recognition that biogeomorphic systems are open and path dependent. They may exhibit a range of assembly states, from self-reinforcing stability domains to more transient configurations of organisms and environment.

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1. Introduction

The ecologist employs the methods of physiography, regarding the flora of a pond or swamp or hillside not as a changeless feature, but rather as a panorama, never twice alike. [Henry Chandler Cowles \(1899, p. 95\)](#).

One of the seminal studies of modern ecology was firmly rooted in a geomorphic framework. Through his field work in the sand dune vegetation of Lake Michigan, the geologist-turned-botanist Henry Cowles influenced a generation of plant ecologists with his ideas

about the dynamic nature of plant succession ([Sprugel, 1980](#)). Cowles was one of the first to articulate that plant communities change as the substrate changes, and they have an active role in changing the substrate. Ecological succession was ‘a variable approaching a variable’, a directional yet open-ended process. But how do geomorphology and ecology theory converse today? Perhaps because of the constraints of academic specialization, or the interdisciplinary nature of its subject matter, the theoretical overlap between geomorphology and ecology has a tentative, unfinished tone. Ample description exists as to how organisms influence geomorphic processes and landform development ([Butler, 1995](#)). Conversely, numerous examples exist of how geomorphic processes and landforms shape the distribution of biota ([Parker and Bendix, 1996](#)). What is

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needed is a theoretical synthesis of how these influences play out in both directions, one that retains a relevance for field-based research.

As the catalog of these unidirectional linkages has expanded, so have our conceptual frameworks to integrate them. Of late, the combined view of geomorphology and ecology (herein referred to as biogeomorphology) has taken a more prominent turn toward the reflexive and the dialogic. Organisms and their interaction can shape and are shaped by geomorphic processes and landforms (Swanson et al., 1988; Phillips, 1999a; Urban, 2002). We are recognizing that for some, but not all, systems on the surface of Earth, broad-scale properties can emerge from lower-level interactions between geomorphic and ecological components. These macroscopic properties may in turn feed back to constrain the subsequent development of biogeomorphic interactions. As an example, Bendix and Hupp (2000, p. 2987) suggested that ‘vegetation-induced sedimentation may change the nature of the vegetation which can be supported across a landform’, while these ‘successional changes in vegetation alter its contribution to sedimentation’. In this scenario, riparian vegetation mediates the effects of microscale sediment transport processes that scale up to shape landforms; these landforms in turn attenuate sediment transport processes and vegetation dynamics. In recognition of this multiple causality, the overarching question for biogeomorphologists becomes: *how* do vegetation dynamics and geomorphic flux interact with one another? Will any subset of these biogeomorphic feedbacks be reinforced and exhibit a degree of persistence? What types of landscape patterns emerge as a result (see Phillips, 1999b) and what is the geographic extent?

For biogeomorphology, the recognition of this multiple causality and its geographic signature can be viewed as part of the paradigmatic shift toward complexity and non-linear dynamical systems (Levin, 1998; Malanson, 1999; Harrison, 2001; Phillips, 2004; Rhoads, 2004). These two theoretical perspectives highlight the contextuality, openness, and organizational dynamism of systems on the surface of the earth (Chu et al., 2003). One of the operational entities of complexity theory is a complex adaptive system (Holland, 1995). In a complex adaptive system, a macroscale pattern can emerge that determines and is reinforced by the flows and interplay among a contingent assemblage of parts (Milne, 1998; Levin, 1999). In this paper, I review the overlap between geomorphology and ecology through four themes that characterize complex adaptive systems: multiple causality, ecological topolo-

gy, ecosystem engineers, and ecological memory. Other facets of complexity theory could be included, such as fractals, deterministic uncertainty, and self-organized criticality (see the review by Baas, 2002). But these additional topics are more common to remote-sensing studies and mathematical models. I wish to highlight the themes of complexity often woven (perhaps unknowingly by some authors) into the more speculative passages of discussion sections in field-based studies.

It is almost a truism to point out that ecological and geomorphological systems interact. But recognition of this coupling should now aim beyond the listing and one-way description of how ecological and geomorphic landscape components interact. Complexity theory is a constructive framework for this endeavor because, unlike general systems theory, it is more developmental in outlook (Spedding, 1997). Complexity theory encompasses the process–form interaction, the fundamental working unit of morphodynamics, but with much more explicit consideration of cross-scale interactions. Complexity theory can also accommodate the place-based uniqueness inherent in biogeomorphic interactions, while also acknowledging that a degree of generalization about these interactions can be applied at an aggregate or probabilistic level (Phillips, 2001a). Admittedly, my examples herein reflect some bias for fast biogeomorphic systems, specifically riparian corridors and sand dunes, in particular. Because of a responsive nature, these settings may facilitate the development of a baseline typology of how geomorphic and ecological components in the landscape interact and unfold. From there, more sophisticated models can be conceptualized.

2. Themes for a complex biogeomorphology

2.1. Multiple causality

Multiple causality is the first of four themes underlying complex systems in biogeomorphology. Multiple causality has long been acknowledged in ecology and geomorphology through the process–form interaction. Ecologists and geomorphologists have historically, however, relied on one or the other of these two causal positions rather than circularity to explain geographic observations. To an extent, this preference for a unidirectional interpretation is a compromise made in the interest of methodological tractability and clarity in language rather than any conceptual shortsightedness. Yet for ecologists, and for biogeographers in particular, the distribution of vegetation across a landscape is often singularly explained as an outcome of disturbance patch dynamics (Pickett and White, 1985) In this case,

process shapes vegetation patterns. Fire, floods, and gravity-induced slope failures create patches of vegetation of different age and composition. The distribution of vegetation is also a response to the underlying structure of environmental gradients of soil, water, and nutrients (Gleason, 1926; Whittaker, 1970). In this case, form is invoked as the causal agent. Like the division in geomorphology between form-based, historical narratives versus process-oriented explanations of geomorphic change, biogeographers are split between a process or form explanatory framework. Yet for some Earth surface systems, biogeographic patterns may better reflect the interaction of disturbance processes and recovery along environmental gradients (van Coller et al., 2000; Stallins and Parker, 2003).

For a longer period of history, and perhaps more openly, geomorphologists have understood that the relationship between landform and process is axiomatic. Geomorphic processes shape landforms, and these landforms shape geomorphic processes. Geomorphologists have also periodically over-relied on one of these two explanatory frameworks, process or form, each with its own underlying assumptions and favored methods (Smith et al., 2002). Process-based studies are reductionist and seek to apply mechanistic rules to explain landform patterns. In this perspective, deterministic interactions at the local scale are the causal factors of relevance to understanding Earth surface systems. Form-based interpretations of landscapes invoke larger time scales and more conceptual, less experimental modes of explanation. In this view, geomorphic landscapes can be explained by contingent geographic factors and particularistic historical narratives. The reductionist models of plant succession, proposed by Connell and Slatyer (1977), are ecological counterparts of the deterministic, process-oriented vein in geomorphological inquiry. Likewise, the ideas about succession initiated by Clements (1916), still resound as an example of narrative, form-based thought in ecology.

A complex systems biogeomorphology encompasses all the permutations of this process–form causal interplay. In this view, the process–form interaction becomes the central epistemological (and methodological) strand linking geomorphology and ecology. As an illustration, consider the disturbance by fire and mass wasting in steep forested terrain. Topographic variation can influence ecological processes, such as disturbance by fire, through slope aspect or shape. Conversely, disturbance by fire can exert an influence on surface erosion and slope stability via its impacts on vegetation. Ecological structure, specifically the type and patterning of vegetation, influences erosional processes and can

potentially modify downslope sediment transport. When of sufficient magnitude, slope failure can modify the spread and extent of disturbance by fire by creating fuel breaks and a patchy fuel mosaic.

When this full circularity of biogeomorphology is acknowledged, any ranking of the causal precedence of landform characteristics, the associated geomorphic processes, or vegetation, becomes tenuous. Parker and Bendix (1996) expressed this conundrum thus:

‘When a certain type of vegetation shows an affinity for a particular landform, it is often difficult to decipher whether the physical characteristics of the landform or the active geomorphic processes associated with it are the underlying cause.’

From the perspective of complexity theory, the distributional patterns we observe are an irreducible property of the dynamics of a system. Efforts to untangle the importance of one causal agent over another become scale dependent, as noted by Parker and Bendix. What becomes more relevant is how this interaction of process and form plays out across time and space. Specifically, to what extent does this multiple causality become self organizing, or recursive? When we say a system is recursive, the emergence of system properties can act as a constraint upon future development. Levin (1998) lists three conditions for the development of the recursive interactions that define a self-organizing complex system: 1) a sustained diversity and individuality of components; 2) localized interactions among these components; and 3) a selecting process that fosters a subset of these components for replication and enhancement.

In a study of how flood disturbance shapes the richness of patterns in riparian plant species and diversity within two watersheds in central California, Bendix (1997, p. 481) echoed the concept of recursivity when he speculated ‘how much is the pattern of diversity affected by the variation of species composition through a watershed, with its concomitant impact on disturbance vulnerability.’ Recursivity in this passage denotes how disturbance by floods and vegetation can potentially shape and be shaped by each other. This interaction can exert a sorting effect, a self-organizing regulation, such that disturbance exposure and vegetation responses cannot be decoupled from the patterns of diversity. Other biogeomorphic systems also exhibit recursivity. The variability of tree compositions on non-mountainous glacial landforms can be explained by substrate properties. These vegetation patterns reinforce soil contrasts among landforms by producing litter of different nutrient composition. This in turn reinforces the

vegetation contrasts and the differentiation of substrate properties (Parker and Bendix, 1996).

Such feedback scenarios are common in ecological and geomorphic systems (Wilson and Agnew, 1992), but the characteristics of the geographic signatures are less examined. To comprehend how recursivity has relevance for our understanding of biogeographic patterns, one must consider its effects upon environmental heterogeneity. Environmental heterogeneity is strongly associated with the distribution of species and the patterns of biodiversity. Heterogeneity can also emerge, however, from the recursive interactions of organisms and the geomorphic setting (Therriault and Kolasa, 2000; Phillips, 2001b). Although the positive correlation between geomorphic heterogeneity and species diversity has been recognized (Burnett et al., 1998), the degree to which heterogeneity is a cause and an effect of its relationship with biota, has not been well investigated. Usually only an external source of the heterogeneity, such as disturbance or physiography, is invoked. The multiple causality in fast biogeomorphic systems, such as riparian zones and dunes, may be productive settings to partition these sources of heterogeneity and delineate how they are intertwined with the patterns of species diversity (Stallins, 2003).

2.2. Ecosystem engineers

Some species exert a disproportionately stronger influence on overall ecosystem structure and function than others (Walker, 1995; Chapin et al., 1997). Most ecologists probably regard trophic links as the main mechanism by which these keystone species exert influence. From a geomorphological point of view, however, the material impacts of biota may be just as important. Through the construction of habitat or modulation of the movement of sediment and water, individual organisms and species can have large effects on entire communities. The beaver is probably the best-known example. Geomorphologists have long acknowledged the geomorphic agency of beavers as well as other organisms, from elephants and plants to invertebrates and cyanobacteria (Viles, 1988; Butler, 1995). But how these species, known in the ecology literature as ecosystem engineers (Lawton, 1994; Jones et al., 1997), are incorporated into biogeomorphic frameworks of complexity has not been broadly acknowledged.

Evidence from a wide variety of ecosystems indicates that many organisms may stabilize habitat against erosion by wind or water (Naylor et al., 2002). Plant roots, biotic crusts, and biofilms can increase soil and sediment surface stability (Viles, 1988). Riparian vege-

tation affects the morphology of channel cross-sections and floodplains through its ability to bind sediments (Gregory and Gurnell, 1988; Hughes, 1997). Mosses stabilize potentially mobile sediments in coastal dune systems (Martínez and Maun, 1999). Aquatic invertebrates can modify the shear stresses of sediments (Statzner et al., 2003).

In addition, ecosystem engineers can facilitate species coexistence by providing habitat for themselves and other species (Stachowicz, 2001). Dune landforms, formed from positive feedbacks between vegetation growth and sediment entrapment, create protective microhabitats in the lee that increase the richness of local species (Odum et al., 1987). *Spartina alterniflora*, a common grass of salt marshes and beaches, facilitates the establishment and persistence of cobble beach plant communities by stabilizing the substrate and enabling seedlings of other species to emerge and survive (Bruno, 2000). By increasing the topographic complexity of benthic habitats, aquatic macroinvertebrates alter patterns of near-bed flow such that the feeding success of individuals is enhanced and species coexistence is augmented (Cardinale et al., 2002). Some invasive riparian species, such as *Ligustrum sinense* (Chinese privet) or *Tamarisk* spp. (salt cedar), may facilitate persistence by altering the patterns of sediment erosion and deposition along riparian landforms (Mack and D'Antonio, 1998; Ward, 2002).

By stabilizing substrates, enhancing weathering processes, providing habitat, and promoting facilitative relationships, ecosystem engineers introduce some of the requisite nonlinearity for dynamic activity in complex systems. Effects initiate time lags, legacies, and slowly appearing indirect effects that can ripple throughout a landscape. Even the nonliving products of organisms, beaver dams, coralline skeletons and woody debris, can influence a system long after the organism has died. These biotic imprints may communicate across temporal and spatial scales to entrench and shape community dynamics (Perry, 1995). Nonlinearity induced by ecosystem engineers can potentially lead to historical path dependency, whereby future interactions are constrained by initial effects. A corollary of path dependency is the potential for multiple stable states, a theme discussed in the next section.

Organism-mediated nonlinearity can also arise through the modification of geomorphic thresholds. During the intervals between external disturbances, ecosystem engineers can modify geomorphic thresholds and subsequent responses to extrinsic events. For example, with the plant-mediated formation of dune landforms, inland habitats in the short run are less likely to

be exposed to disturbance from overwash generated during passing storms (Odum et al., 1987; Rastetter, 1991). In wetlands, vegetation may alter sedimentation and fine-scale elevation, thereby modifying the patterns of inundation and disturbance exposure (Pollock et al., 1998). Following ideas from landscape sensitivity, biogeomorphic interactions modify the temporal and spatial distributions of resisting and disturbing forces (Brunsdon, 2001). These examples suggest that ecosystem engineers have the propensity to introduce a nonlinear relationship between disturbance forcing event frequency and subsequent exposure. In other words, because of biotic modifications of geomorphic thresholds, a simple tit-for-tat relationship between the event forcing disturbance and exposure cannot always be expected. This interaction is similar to Schumm's (1973) idea of complex responses in geomorphic systems, whereby different responses can develop from the same conditions of perturbation. In ecology, resonance and attenuation theory similarly posit that intrinsic processes may interact with periodic extrinsic fluctuations so as to reinforce or dampen effects (Orland, 2003). The extent of these nonlinear influences is dependent upon the durability of constructs, artifacts, and impacts in the absence of the original engineer (Lawton, 1994).

2.3. Ecological topology

Parker and Bendix (1996) stressed the need for a better understanding of how biogeomorphic interactions vary geographically. A major constraint to this task is how to visualize the multiple scales and cause–effect interactions that define complex biogeomorphic systems. Ecologists working in the area of complexity theory have developed conceptual and quantitative models for visualizing this complexity in space and in time (Peterson et al., 1998; Gunderson and Holling, 2002). These models work from the premise that natural and human-coupled systems may exhibit a range of assembly states depending upon the initial conditions and the extent of the recursive, nonlinear interactions. The shifts between these assembly states can exhibit threshold-like responses and be triggered by humans or by non-anthropogenic environmental or ecological change (Scheffer et al., 2001).

The self-reinforcing, assembly states that can emerge from these nonlinear interactions go by a variety of synonyms: attractors (Harrison, 2001; Thompson et al., 2001; Baas, 2002), stability domains (Gunderson, 2000), domains of scale (Wiens, 1989), or process domains (Thornes, 1985). These entities demarcate the boundaries in time and/or space over which process and

form reinforce another. Within each stability domain, a small set of species and abiotic processes mediate structure and function, and exert some control over reproduction (Holling, 1992). The regions bridging stability domains are described as transient states or phase transitions (Wiens, 1989; Milne, 1998). These locations exhibit weaker recursive properties, and a higher turnover in the arrangement of feedbacks among components (Savage et al., 2000). This geometry of stability domains and phase transitions is often abstracted as a fitness landscape of hills and valley, giving rise to a 'lumpy' (Holling, 1992) or 'granular' (Ulanowicz, 1997) ecological fabric, or topology. One might consider the parameters of this topology an extension of phase space, a concept originating more directly from complexity theory (Malanson et al., 1990).

This ecological topology has been used to conceptualize the spatiotemporal domains of causality in biogeomorphic systems. Feedbacks between regular, predictable forcings of high flows of water and organisms in riparian zones may become a mechanism for defining distinctive domains of recursive, biogeomorphic cause and effect (Reice, 1994; Bendix, 1997). Shallow lakes can flip through time between a nutrient-rich and a nutrient-poor stability domain in response to changes in sediment and nutrient inputs (Scheffer et al., 1993). Barrier island stability domains can be defined by biogeomorphic propensity to reinforce or damp overwash exposure (Godfrey et al., 1979; Stallins and Parker, 2003). The concept of stability domain has also been invoked for rivers (Montgomery, 1999; Dent et al., 2002), coral reefs (Knowlton, 1992; Nystrom et al., 2000), and rangelands (Walker, 2002). In each of these examples, ecosystem engineers directly or indirectly mediate flows of matter, energy, and disturbance, setting up recursive, nonlinear feedbacks that confer a degree of persistence to a particular organizational state or domain.

A lumpy ecological topology can emerge when a few key recursive structuring processes establish a temporal frequency that entrains, or captures, other processes and forms (Holling, 1992; Allen and Holling, 2002). This process is similar to slaving, a concept with geomorphological leanings (Werner, 1999). In slaving, variables with disparate time scales, when nonlinearly coupled, can develop an asymmetric relationship. Fast variables become entrained or slaved to slow variables and lose status as independent dynamical variables. For example, along sandy coastlines, the fast motion of sand grains can become slaved to the slower motion of sand dunes. In turn, sand dunes can be slaved to the migrations of the shoreline. Dune plants are slaved to these

motions, but they also exert a degree of control on the process. The extent of this control could be expected to vary as a consequence of dispersal processes, the magnitude or intensity of sediment transport, as well as the degree to which the temporal scaling of vegetation dynamics and geomorphic processes overlap (Phillips, 1995). Hierarchy theory in ecology similarly recognizes that the coupling among processes operating at different scales can vary from strong to weak (Turner et al., 2001).

Stability domains may be more apparent in some biogeomorphic environments than others. Where geomorphic processes operate very slowly, biogeomorphic interactions driven by vegetation may be less visible. Steep gravitational gradients may complicate domain structure (Nakamura et al., 2000). Because of linear geometry, rivers may require a combination of continuum and lumpy approaches (Montgomery, 1999). Where disturbances are large and return times frequent, domain structure may not develop (Turner et al., 1993). Topology for many biogeomorphic systems may ultimately be constrained by sediment budgets. Lastly, the distribution of domains across a landscape should reflect deterministic and contingent conditions. In other words, topology should be a function of the contingent underlying variation in physical variables, as well as the propensity for species and the related environments to self organize.

2.4. Ecological memory

Ecological memory (Phillips, 1999a; Thompson et al., 2001) is another prominent theme that ties geomorphology and ecology together under the framework of complexity. Ecological memory encompasses how a subset of abiotic and biotic components are selected and reproduced by recursive constraints on each other. This recursiveness has the potential to become canalized through time, whereby it is encoded in organisms, and to an extent the immediate environment (Dawkins, 1999; Lewontin, 2000).

Disturbance can become encoded and reinforced in the abundance and spatial pattern of vegetation and topography across a landscape. In the longleaf pines forests of the southeastern U.S., fire can become a replicable process encoded in the structure of a biological community as a result of past environmental conditions, the distribution of topographic and soil variables, and subsequent selection on populations (Peterson, 2002). In mountainous forested terrain, slope failures form fire breaks that interrupt fuel connectivity and limit the size of fires. In turn, the vegeta-

tion and landform characteristics that emerge following these disturbances (such as the abundance of fire-enhancing or slope-stabilizing plant species, the density and composition of seed bank, slope angle and stability, soil permeability and nutrient content) may or may not reinforce the replication of these landscape processes. Memory can also occur on smaller, more discrete scales. The location of trees may be influenced by the past location of trees, via the effects upon soil properties (Phillips and Marion, 2004).

This concept of ecological memory is strikingly visible in vegetated coastal dunes, systems in which history is often perceived to be constantly erased (Hansom, 2001). In barrier island dune systems, the frequency and spatial extent of overwash exposure initiated by passing extratropical storms are dynamically encoded in the interactions among this disturbance agent, species abundances and topography (Stallins and Parker, 2003). Species abundances reflect the local disturbance regime not through passive adaptation, but by constructing and reinforcing topographic niches in light of the historic frequency at which disturbance forcings have occurred. In other words, by modifying topography in the periods between storm-forced overwash disturbance, dune species interdependently facilitate the historically prevailing patterns of mobility of the surface sediments and species abundances in a positive feedback. At locations where storm forcings of overwash disturbance are more historically frequent, plant species well adapted to sediment burial but lacking growth forms that enhance dune-building may promote abundance and persistence by contributing to a low-profile topography that lowers the resistance to future overwash exposure. Where disturbance is infrequent, dune-building plant species reinforce presence in the landscape by contributing to a high topographic roughness that damps overwash exposure. At both locations, the historic interaction of dune plant species and the local patterns of sediment mobility ‘remembers’ or perpetuates the topographic habitats and disturbance processes for these species.

Ecological memory does not denote the organismal idea of a preordained final successional structure. Biotic and geomorphic components of a landscape can exert some control over reproduction, but memory in this sense is contingent and open-ended (Egler, 1954; Malanson, 1993, p. 206). Sequential species replacement can occur, but superimposed upon this may be the effects of ecosystem engineers. Their subsequent responses to and effect upon environmental variability, whether novel or historically prevalent, have the propensity to influence how biogeomorphic interactions play out and create geographic patterns. More

abstractly, the conceptualization of biogeomorphic memory can be pared down to questions of what patterns and processes get remembered and which do not, and what is the geographic patterning of this remembering?

3. Summary

Four overlapping themes link geomorphology and ecology within the framework of complexity theory: multiple causality, ecosystem engineers, ecological topology, and ecological memory. Feedbacks between geomorphic and ecological components are developmentally intertwined. As these biogeomorphic interactions play out, the feedbacks can demarcate persistent (but not perpetual) domains in time and space, giving rise to a 'lumpy' ecological topology. Nonlinearity, a foundation for the complex interactions that promote this lumpiness, can be woven into biogeomorphic systems by ecosystem engineers. Sometimes these species attenuate processes of sediment transport, and through time may direct a sorting and reproduction of pattern and process that resembles memory. By doing so, ecosystem engineers link microscale process–form interactions to landscape scales of pattern development, an unresolved and longstanding tension among geomorphologists (Schumm and Lichty, 1965; Spedding, 1997) as well as biogeographers and ecologists (Brown, 1995; Maurer, 1999). Implicit in all of these themes is the recognition that biogeomorphic systems are open and path dependent. They may exhibit a range of assembly states, from self-reinforcing stability domains to more transient configurations of organisms and environment. Determinism exists in biogeomorphic systems only as a synonym for probability, a propensity for one of these assembly states over the other at a particular point in time, rather than any Clementsian–Davisian notions of organismal development.

This complexity-based view of biogeomorphology is an attempt to prompt reflective questions about conceptual models, methodologies to examine them, and the ontological tensions that link geomorphologists, ecologists, and biogeographers. Admittedly, reliance on a singular causal framework, be it process or form, streamlines research, and makes the language clearer. This may be particularly true for reductionist studies that look only at deterministic, 'timeless' processes, or seek to understand land form via process alone. In addition, a reluctance to explicitly consider multiple causality and recursivity may obscure a richer tableau of interactions, and may even limit theoretical insights. As an example, the activity of ecosystem engineers may

have important implications for evolutionary theory (Odling-Smee et al., 2003). Standard evolutionary theory underplays the full set of interactions that occur between biotic and abiotic components and ignores diverse forms of feedback that contribute to evolutionary scenarios and ecosystem dynamics. Through the modification of geomorphic processes and forms, ecosystem engineers transform the environment to generate a form of feedback that may have important evolutionary consequences for themselves and for other species. Collaboration among geomorphologists and evolutionary biologists may even seem plausible in this light.

A synergistic coupling of new conceptual models, field observations, and computer simulation maybe the most productive route to develop complexity-based typologies of biogeomorphic systems (see Fonstad and Marcus, 2003 for a recent example). Because complex systems operate over multiple scales, a need still remains for broad, qualitative, landscape narratives (Spedding, 1997; Phillips, 1999c). These narratives, when linked to more recent reductionist, process-oriented studies, can be used to develop new conceptual models and hypotheses that can subsequently be verified with field observations. One barrier for biogeomorphic inquiry resides in extrapolating results among landscapes where contingency and determinism are so variably intertwined. A more synoptic approach, as employed in meteorology, is advocated by Phillips (2001a) to address this issue. Another angle is to rely on replicated observational units in nature (Diamond, 2001). These might include barrier islands, periodically flooded lake islands, specific riparian landforms, and slope faces. Even relictual, anthropogenic habitats (Johnson, 2002) could offer insights into underlying biogeomorphic structure and function. Because of the time and space-restricted snapshot quality of field observations, it will be necessary to unfold biogeomorphic interactions across a broader spectrum of scales. This can be accomplished through the use of cellular automata and agent-based modeling. These tools can be configured to simulate how differences in initial conditions and recursiveness between organisms and the geomorphic environment can play out through time and space and shape the underlying ecological topology (see Savage et al., 2000). Breaks in the scaling relations underlying power laws can also be used to infer breaks in the ecological topology of landscapes (Milne, 1998; Allen and Holling, 2002). But power laws, especially when obtained from simulations built around abstracted data, are just proxies, summaries of underlying interactions and structure. More detailed biogeomorphic field studies are needed to develop

real-world data sets that contain physiographic metrics and species cover data for use in complexity-based simulations.

4. Conclusion

Biogeomorphology needs to move beyond list-bound descriptions of unidirectional interactions of geomorphic and ecological components. Future research will be productive insofar as it explores the extent that relationships between geomorphic and ecological spatial patterns and processes are encoded, reproduced, and distributed. Through this complex systems approach, we will better comprehend how to combine processes observed over limited spatial and temporal scales to longer-term landscape change. The four themes discussed in this paper also have pragmatic applications. Understanding the recursive nature of biogeomorphic systems is necessary for restoration and resource management (Hughes et al., 2001). Maintenance of the heterogeneity of geomorphic and ecological processes and forms enable system adjustments to perturbations (Levin, 1998). Even the feedbacks of restored systems may be as important as the outward appearance (Nordstrom, 1990). By broadening, and by necessity, complicating ideas about the interaction of ecological and geomorphological components on the surface of Earth, we aim toward ends that are more theoretically and pragmatically relevant.

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