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Common Core Themes in Geomorphic, Ecological, and Social Systems

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Abstract Core themes of geomorphology include: open systems and connectivity; feedbacks and complexity; spatial differentiation of dominant physical processes within a landscape; and legacy effects of historical human use of resources. Core themes of ecology include: open systems and connectivity; hierarchical, heterogeneous, dynamic, and context-dependent characteristics of ecological patterns and processes; nonlinearity, thresholds, hysteresis, and resilience within ecosystems; and human effects. Core themes of environmental governance include: architecture of institutions and decision-making; agency, or ability of actors to prescribe behavior of people in relation to the environment; adaptiveness of social groups to environmental change; accountability and legitimacy of systems of governance; allocation of and access to resources; and thresholds and feedback loops within environmental policy. Core themes common to these disciplines include connectivity, feedbacks, tipping points or thresholds, and resiliency. Emphasizing these points of disciplinary overlap can facilitate interdisciplinary understanding of complex systems, as well as more effective management of landscapes and ecosystems by highlighting drivers of change within systems. We use a previously published conceptual framework to examine how these core themes can be integrated into interdisciplinary research for human–landscape systems via the example of a river.

Keywords Connectivity · Thresholds · Feedback · Nonlinear · Resiliency · Environmental governance

Introduction

Engaging in truly insightful interdisciplinary research that advances shared understanding can be difficult for many reasons. Among the difficulties are different ways of conceptualizing the world that underlie disparate scholarly disciplines. These different conceptual frameworks can translate into different priorities for the types of research questions asked, differences in research design, and even different vocabulary (Bracken and Oughton 2006) for describing similar features. Systematic examination of the conceptual frameworks underlying the way physical scientists, biological scientists, and social scientists approach research questions within their disciplines, however, reveals some key commonalities. We consider it useful to emphasize these similarities in conceptualization in order to facilitate communication among disciplines, collaborative research, and the ability to identify mutually compelling research themes. In this article, we first briefly summarize core themes of geomorphic, ecological, and social science (environmental governance) research, then discuss common themes among the disciplines and briefly

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explore the implications of these common themes for interdisciplinary research and understanding within an integrative framework.

Core Themes in Geomorphology

Geomorphology—the study of the processes that create and maintain landforms—inherently integrates many traditional academic disciplines. Although most geomorphologists are trained in geology, geography, or civil engineering, landscapes reflect tectonic forces, climate, chemical weathering, and interactions with plants and animals including humans, as well as the physics of interacting rock, sediment, ice, and water. The emphasis within geomorphology has shifted during the past decade from a focus on physical processes and largely conceptual models, toward a more explicit recognition of interactions among landforms, biota, and people (Bracken and Oughton 2009; Demeritt 2009b; Harden 2012) and increasingly numerical descriptions of process and form. Four core themes remain fundamental to geomorphology, however, and underpin much of contemporary geomorphic research.

Open Systems and Connectivity

Chorley (1962) borrowed the concept of a system from physics and applied the distinction between open and closed systems to landscapes. A system is a set of objects, along with the relationships among the objects and among their attributes. A closed system has clearly defined closed boundaries across which no import or export of materials or energy occurs. Entropy progressively increases in a closed system. Initial conditions are very important, and the operation of the system is irreversible. An open system has a constant supply and removal of matter and energy. An open system exhibits a tendency toward steady-state conditions, as a result of self-regulation among interacting components. Conceptualizing landscapes as open systems focuses attention on relationships between form and process, as well as characterizing inputs, outputs, storage, and fluxes of matter and energy within a system. This is exemplified by mathematical statements known as geomorphic transport laws (Dietrich and others 2003) that express mass flux or erosion caused by one or more processes in a manner that can be parameterized from field measurements and tested in physical models. The concept of open systems is also reflected in the attention given to characterizing various forms of connectivity, including hydrological connectivity (Bracken and Croke 2007), sediment connectivity (Fryirs and others 2007), and landscape connectivity (Brierley and others 2006). Emphasis on connectivity reflects a desire to move beyond small spatial and short temporal scales of investigation in order to focus on emergent properties that evolve from the self-organization inherent in landscapes (Phillips 2003; McDonnell and others 2007; Reid and others 2007; Ali and Roy 2009). Self-organization in this context describes order or coordination among Earth-surface processes arising out of local interactions, such as the formation of a channel and channel network as a result of precipitation and runoff processes.

Feedbacks and Complexity

Interactions among the multiple components of an open system can result in various forms of stability, known generically as equilibrium. Equilibrium is typically conceptualized as a condition of no net change, and is very dependent on time scale (Wohl 2010). Equilibrium implies that if the energy or material supplied to a system changes, the system will change as a result (Howard 1982). The simplest form of a change is an immediate, linear response proportional to the external change, but many landscapes are better characterized by delayed and nonlinear responses that involve lag times, or intervals between external change and system response. Lag times reflect the size and mass of natural systems, and larger, more complex systems tend to have greater lag times (Howard 1982).

Landscapes also tend to exhibit extrinsic and intrinsic thresholds at which operation of the system changes abruptly in response to progressive external or internal changes (Schumm 1979). The presence of intrinsic thresholds in small, semiarid channels illustrates what Schumm and Parker (1973) referred to as complex response. Semiarid regions commonly have sufficient runoff to move sediment from hill slopes into river channels, but not enough runoff to generate the stream flow necessary to move the sediment all the way through the channel network. Sediment accumulates over time in limited reaches of the network, causing specific channel segments to steepen until a headcut is formed and migrates upstream. Sediment released by headcut migration can cause sediment to accumulate in downstream channel segments, while upstream segments are eroding. Once headcut migration stops, the reduction in sediment supply to downstream channel segments can trigger another cycle of erosion and headcut migration, creating spatial and temporal differences in channel behavior within a single network.

Interactions among system components can result in a self-enhancing feedback, in which an initial perturbation triggers a system response that grows greater with time, as when a landslide deposit changes a bedrock slope into a site with greater infiltration capacity, allowing vegetation growth that enhances deposition of sediment moving downslope (Bull 1991). Alternatively, an initial perturbation can result in little change in a system if self-arresting feedbacks occur.

The stability of a landscape can be conceptualized via a transient form ratio in which the landscape is transient if the recurrence interval of events capable of producing change is shorter than the time necessary for the landscape to equilibrate, such that the landscape is constantly changing (Brunsden and Thornes 1979). A stable, persistent landscape remains fairly constant because the system reaches equilibrium long before the next event capable of producing change. Landscape resilience incorporates similar ideas; a resilient landscape recovers quickly following disturbance.

Differences in transience, persistence, and resilience among landscapes imply that large, infrequent events may be more important in some environments. Wolman and Miller (1960) first explored these ideas when they quantified the geomorphic work, defined in terms of sediment transport, performed by floods of differing magnitude.

The complexity of landscapes is also reflected in the concept of equifinality or convergence, when a similar end point in a system arises from the operation of similar processes, but from different initial conditions (Beven and Freer 2001). Replacement of native vegetation with crops, climatic changes that favor different vegetation, or progressive tectonic uplift that creates steeper slopes can each result in an increase in sediment yield to a stream, for example, and cause accumulation of sediment in valley bottoms.

Spatial Differentiation

Many landscapes have systematic spatial variations, as recognized in differentiation of production/source, transfer, and depositional/response zones in drainage basins (Schumm 1977; Montgomery and Buffington 1997) or in geomorphic process domains (Montgomery 1999). Explicitly designating zones across a landform or a landscape emphasizes potential differences in connectivity, fluxes, stability, persistence, and other characteristics within a larger system (Brierley and Fryirs 2005). Spatial differentiation can also recognize hierarchical structure within a landscape, as exemplified by progressively smaller spatial units from an entire watershed, to a stream segment of consistent channel geometry, to a channel unit such as a pool or riffle.

Legacy Effects

Legacy effects explicitly recognize the role of history and the sequence of events through time in shaping contemporary landscapes. Although geologists in particular are trained to emphasize effects of much greater duration than a human lifespan, it can be difficult to recognize the continuing influence of past events. Recent recognition that alluvial sediments deposited in what are now long-buried eighteenth and nineteenth century milldam ponds have dramatically altered the configuration of channels and floodplains throughout the eastern United States provides an example (Walter and Merritts 2008). Many of the field sites now considered to be highly altered by historical engineering were previously assumed to represent stable channels with little direct human influence. The changed interpretation has direct consequences for river restoration in the region and attempts to mediate excess sediment and nutrient yields to the Chesapeake Bay area.

In summary, geomorphologists tend to think of landscapes as highly complex systems with multiple interacting components. Adjustments among components continually occur, yet states of relative stability can persist. Different segments of a landscape, such as a mountain range or drainage basin, can behave quite differently through time, and events that occurred hundreds or even millions of years ago may continue to strongly influence the contemporary landscape.

Core Themes in Ecology

Ecology is a diverse scientific discipline that focuses broadly on questions of how organisms are distributed in space and time in relation to interactions among themselves and to their non-living environments. Ecology is defined by sub-areas that focus on level of biological organization, such as individual organisms (physiological ecology, behavioral ecology), populations of organisms (evolutionary ecology, population ecology), groups of interacting species (community ecology), or interactions of species with their non-living environment (ecosystem ecology), sometimes at large spatial scales (landscape ecology, macroecology). Ecological sub-disciplines are often partitioned by types of organisms studied (microbes, plants, insects, etc.), and/or defined by major system type (terrestrial, marine, freshwater, etc.), and specified by biotype (montane, grassland, tropical forest, intertidal, etc.). Ecologists employ a variety of research tools, ranging from the theoretical to the empirical and from site-specific experiments to regional scale correlative or synthetic studies. Increasingly, ecologists strive to integrate across traditional disciplines or levels of organization and to incorporate human dimensions into their research (e.g., human ecology, urban ecology).

Ecologists are challenged to develop specific, contextual understanding of their study systems, and then translate these into general principles that apply broadly across other ecological systems. In the domain of human–landscape interactions, several general guiding principles can be identified, and these can be more concretely illustrated with reference to a particular type of system: freshwater streams and rivers.

Open Systems with High Connectivity

Solar energy captured by photosynthetic organisms fuels ecosystems. The length of a food chain is a function of how much energy is available within an ecosystem to sustain viable populations given constraints on energy transfer across trophic levels. Ecosystem boundaries are generally permeable, with fluxes of matter, energy, and information occurring across boundaries. For example, stream ecosystems are strongly driven by external inputs of fixed carbon (e.g., dead plant material) from the terrestrial realm. This is especially true in small, forested watersheds (Vannote and others 1980). The exchange of organisms and energy can occur in a reciprocal fashion. Numerically abundant aquatic insects emerge from streams as flying adults, and can fuel terrestrial predators, including spiders and migratory song birds (Nakano and Murakami 2001).

Due to hydrologic connectivity, small streams can export nutrients and terrestrially-derived energy downstream to larger streams and rivers (Vannote and others 1980). Similarly, species move up and down the river corridors, such as salmon or other species (Fausch and others 2002), and replenish nutrients after they die (Naiman and others 2002). The conditions present at one location may be influenced by subsidies or transfers of matter, energy, and organisms from distant, yet connected, localities, emphasizing that local ecosystems occur in a landscape context. Lateral connectivity between channels and floodplains allows for nutrient and sediment deposition on floodplains during high flows, and access to floodplain spawning and rearing habitats for many river fishes (Junk and others 1989; Poff and others 1997).

Hierarchical, Heterogeneous, Dynamic, and Context-Dependent

Ecological processes and patterns present at local scales are constrained or influenced by processes occurring at larger space–time scales in a hierarchical fashion (Allen and Starr 1982; Levin 1992). For example, the diversity and abundance of species at a locale in a stream will reflect the diversity of physical substrates or habitat types available (e.g., sand versus cobble), the habitat type that substrate is in (riffle vs. pool) and the channel type (steep canyon reach vs. low gradient alluvial valley). Further, the watershed-scale hydrologic regime—a function of climate, land cover, and soil infiltration capacity—will influence the stability of those local substrates to further dictate suitability of habitat for a range of species. Species abundance and ecosystem processes, such as nutrient retention, vary in response to this spatial heterogeneity, and the spatial configuration and connectivity of such patch types and the ability of species to move between them influences local and watershed-scale biodiversity (Townsend 1989; Brown and Swan 2010).

Temporal heterogeneity is equally important, and the process of natural disturbance acts to disrupt resources or induce mortality on organisms (Pickett and White 1985). Streams and rivers respond dynamically to variation in precipitation and runoff, so that the magnitude, frequency, and timing of high flows that disturb the streambed or inundate floodplains vary in response to regional climate (Poff and others 1997). Temporal patterns of hydrologic disturbance can promote local adaptation of species to the prevailing regime (Lytle and Poff 2004) or prevent non-native species from invading if they have traits that make them vulnerable to the prevailing regime (Fausch and others 2001). Frequency and magnitude of disturbance can also regulate energy flow through stream ecosystems by selectively disadvantaging keystone species or long-lived predators (Power and others 1996; Sabo and others 2010). Importantly, the “resilience” of a system reflects its ability to return to some pre-disturbance ecosystem state, and this is facilitated by high spatial heterogeneity in ecosystem structure such that organisms have “refuges” from mortality-inducing disturbances, and can then re-colonize disturbed patches (Townsend 1989).

Processes and patterns present in stream ecosystems, like most ecosystems, are strongly context-dependent. The particular local setting, watershed geology, regional climate, spatial connectivity of variable quality patches in the river network, and evolutionary history of the species that live in the region all interact to generate ecological complexity. By taking these hierarchical contexts into account, ecologists strive to generate more robust predictions about how system properties are organized and how resilient they might be as humans alter prevailing fluxes of water, sediment, and nutrients through river networks.

Non-linearity, Thresholds, Hysteresis, and Resilience

Ecological systems are characterized by complex interactions of multiple living and non-living processes occurring at different spatial and temporal scales. This complexity allows for threshold behavior—some small changes in environment lead to rapid, non-linear shifts in ecosystem state (Groffman and others 2006). Threshold changes can result in rapid transition from one ecological state to another, such as from a clear pond with macrophytes to a turbid pond with suspended algae (Scheffer and others

2001). Such changes may exhibit hysteresis: i.e., return to the pre-threshold state is not easily reversible by reinstating the pre-alteration environmental regime. Threshold state changes in streams have been identified for conversion of erosional riffles to shoreline wetlands, when cattle are denied access to the stream (Heffernan 2008). An alternate state may be maintained by feedbacks, such as when *Tamarix* establishes on small rivers, and then stabilizes the soil such that channel migration is reduced, thereby furthering the favorability of the habitat for *Tamarix* (Dent and others 2002). The prediction of when a threshold will occur is an important research area.

Threshold behavior and ecosystem state shifts are difficult to predict due to system complexity associated with high non linearity of process relationships and sensitivity to initial conditions, but research in this area is active (Scheffer and others 2009).

Human Dominated

The role of human agency in ecosystem structure and function in the "Anthropocene" is now part of mainstream academic ecology (Palmer and others 2004), as is incorporation of humans into ecological sustainability (Collins and others 2011). From increases in atmospheric carbon dioxide to elevated nutrient loading of the land and water on a global scale via agricultural activities (Vitousek and others 1997), virtually no ecosystems can be considered "pristine." Ecosystems also reflect the historical effects of human activities. In streams, historical land use has created legacies that confound explication of clear cause–effect organism–environment relationships. For example, historic land use can be a better predictor of contemporary distribution and abundance of stream species than current land cover (Harding and others 1998). Other past activities, such as extensive sediment storage behind milldams in clear-cut forests (Walter and Merritts 2008) or beaver removal from entire landscapes in the west (Wohl 2001), have created legacies to which contemporary ecosystems are likely still adjusting. A better understanding of the ecological adjustments to these legacies in their particular context-dependent hierarchical setting is a challenge to be met in gaining the perspective needed to forecast how current ecosystem states are likely to change in the future.

Core Themes in Environmental Governance

Environmental governance research can be seen as one subset of larger social science research around the environment and environmental processes. Environmental governance, or the "set of regulatory processes, mechanisms, and organizations through which political actors influence environmental actions and outcomes," occurs in a variety of forms including international accords, national policies and legislation, local decision-making structures, intergovernmental institutions, and NGOs (Lemos and Agrawal 2006, p. 298). Today, environmental governance is highly fragmented and internationalized, characterized by more decentralized, voluntary, market-oriented, networked interactions between public and private actors (Bäckstrand 2008, p. 74–75; Biermann and Pattberg 2008).

Scholars of environmental governance come from a variety of disciplinary backgrounds, including political science, public administration, geography, law, and sociology. Just like social science more broadly, there is a great diversity in theoretical and methodological approach to studies of environmental governance. While matters of governance have always been at the heart of research by many international relations and public policy scholars interested in environmental affairs, more recently scholars working at the interface of ecology and management have paid greater attention to governance. This is reflected in the shift to treat social and ecological systems as integrated complex socio-ecological systems. New analytical frameworks around resiliency, adaptive governance, and adaptive co-management, all include governance elements.

One timely and relevant social science collaboration—the earth system governance project—highlights several core themes in environmental governance. Launched in 2009 by the International Human Dimensions Programme on Global Environmental Change as a 10-year research initiative, the earth system governance project outlines the concept of earth system governance as a challenge for the social sciences (Biermann and others 2010, 2012). We outline the five core themes outlined by the Project, along with two overarching themes emerging in environmental governance scholarship—thresholds/tipping points, and feedback loops.

Architecture

The notion of governance architecture "conceptualizes the overarching system of public or private institutions, principles, norms, regulations, decision-making procedures, and organizations" (Biermann and others 2010, p. 281). Research around this theme reflects a movement away from single institutions and toward studies of clusters, networks, and interactions and interlinkages between institutions and organizations. Some research suggests that a nesting of local institutions into a broader network of medium- to large-scale institutions is necessary to better address and tackle larger-scale problems (Anderies and others 2004). Others argue that the institutional solution or structures are not as important as their capacity to allow for self-organization, coordinated action at multiple levels and learning from changing circumstances (Folke and others 2011).

Agency

Agency "refers to the ability of actors to prescribe behavior and to substantively participate in and/or set their own rules related to the interactions between humans and their natural environment" (Schroeder 2010, p. 317). Today's research around agency moves us beyond a historic focus on governments and singular institutions to also address NGOs, scientific networks, and business organizations (Levy and Newell 2005; Betsill and Corell 2007; Andonova 2010; Pattberg 2008). We are beginning to understand the role of networks in cross-level interactions that rely on collaboration of stakeholders operating at different levels of governance (Folke and others 2005, p. 463–464), and how local knowledge can help inform decision-making and monitoring to improve effectiveness (Lebel and others 2006).

Adaptiveness

As an umbrella term for a set of related concepts, including vulnerability, resilience, adaptation, robustness, and adaptive capacity or social learning, adaptiveness aims to describe changes made by social groups in anticipation of or in response to environmental change (Biermann and others 2010, p. 284). Some research highlights how larger social and economic globalization trends impact adaptiveness in the social-ecological context (Young and others 2006). In another stream of research, scholars are exploring how social learning, or multiparty processes in which representatives from stakeholder groups interact on a regular basis to define the problems, and set and implement solutions, as potential mechanisms to enhance adaptive capacity (Mostert and others 2007; Pahl-Wostl and others 2007; Lebel and others 2010).

Accountability and Legitimacy

Questions of the accountability and legitimacy of systems of governance relate to the theory of democratic governance, and also serve as intervening variables that affect institutional effectiveness (Biermann and others 2010, p. 286). While these concepts were historically problems isolated to governments, today they pertain to all levels of governance, relate to both private and public arrangements, and offer a lens to examine emerging and novel governance arrangements (Biermann and Gupta 2011). Some research highlights the democracy-enhancing potential of culturally-sensitive and appropriate global administrative law to enhance accountability and legitimacy of governance (Spagnuolo 2011). Transparency may also be an important tool for furthering accountable and legitimate environmental governance (Mitchell 2011).

Allocation and Access

Allocation and access are defined differently in the social sciences: "Lawyers speak of equity, economists of distribution, resource analysts of access, political scientists of fairness, geographers of socio-spatial distributions and environmental justice, and sociologists of social justice" (Biermann and others 2010, p. 288). Although traditionally analysts have taken narrow disciplinary approaches to distributional problems around access and allocation, some recent research suggests the need for a more multi-disciplinary approach to these challenges (Gupta and Lebel 2010). Some research suggests that despite the widespread acknowledgment of the need for justice in the design of institutions for global environmental governance, attempts to introduce equity-based norms in institutions have yielded limited results thus far (Okereke 2008). Others highlight the uneven texture in allocation and access around resources, such as water (Gerlak and Wilder 2012).

Thresholds, Tipping Points, and Feedback Loops

Beyond the themes that underlie the earth system governance project, scholars of environmental governance are increasingly tackling issues around thresholds and tipping points (Gerlak 2013). Notably, researchers recognize the role of crises as exogenous events that can prompt environmental policy change at both domestic and international levels (Rosenbaum 2010; Young 2010). For Goldstein (2011), crises such as natural disaster, technological failure, or economic collapse can offer opportunities for collaboration, consensus building, and transformative social change. Further, Olsson and others (2006) argue that exogenous shocks can be used to help improve fit between biophysical and institutional systems.

In addition, research around adaptive governance calls for greater attention to flexibility and adaptability in governance to better allow for feedback to be incorporated and adjustments to be made in decisions and actions (Folke and others 2005; see also "The III Framework for Human–Landscape Change" below). The role of learning in the context of sustainability and environmental governance between groups and individuals is seen as a key factor in providing the necessary feedback in an institutional setting (Gerlak and Heikkila 2011; Henry 2009; Pahl-Wostl and others 2007).

Research around resilience and governance demonstrates the importance of these themes—namely, the ability to observe and interpret essential processes and variables in ecosystem dynamics to develop the social capacity to respond to environmental feedback and change (Walker and others 2004; Anderies and others 2004) as well as the ability of actors and decision-makers to detect and navigate hard-to-reverse thresholds in a timely manner to prevent ecosystems from crossing thresholds and ending up in undesirable states (Lebel and others 2006).

Common Core Themes: Toward Integrative Research

Natural sciences, as illustrated here using the disciplines of geomorphology and ecology, share numerous core themes, including the conceptualization of landscapes and ecosystems as open systems, and an emphasis on the importance of connectivity in controlling the traits of the system. Both disciplines emphasize adjustments through time in the context of feedbacks among multiple variables that result in complex, nonlinear behavior characterized by thresholds and hysteresis, and exhibiting varying levels of resilience. In addition, both disciplines emphasize the importance of temporal and spatial scales in studying system behavior, and both disciplines increasingly recognize the ubiquity of historical and contemporary human influences on landscapes and ecosystems. Formative articles in geomorphology explicitly recognize the influences of biota on landscapes (Corenblit and others 2011), and foundational articles in stream ecology explicitly recognize geomorphic influences on stream ecosystems (Hynes 1975). Although we can without doubt improve the integration of disciplines within the natural sciences, and particularly the integration of physically and biologically oriented disciplines, geomorphologists and ecologists increasingly work together on fundamental research questions and on applied issues, such as stream restoration.

Historically, integration of natural and social sciences has been less developed in large part due to greater differences in conceptual frameworks and methodological approaches. Nevertheless, just as ecologists and geomorphologists cannot ignore the influence of humans and environmental governance on most, if not all, ecosystems, so social scientists studying governance acknowledge the fundamental fact that all individuals and societies exist within an ecosystem and fundamentally rely on ecosystem services, such as surface and groundwater supplies, fertile soil, and fisheries. Using the core themes identified above, governance architecture relates to geomorphic and ecological ideas of connectivity in focusing on communication and flows of information. Agency relates to geomorphic and ecological ideas of feedback in recognizing decision-making processes that involve top-down and bottom-up components. Adaptiveness closely relates to geomorphic and ecological resiliency, and conceptualization of change and adjustment within systems occurring via thresholds and feedbacks is common to all three disciplines. Consequently, there are actually many common core themes among the three disciplines, but recognition of these commonalities has likely been hindered by use of different terms and slightly different contexts. As noted in previous articles, the manner in which environmental systems and problems of research and management are conceptualized strongly influences the extent to which multiple disciplines are involved and effectively integrated (Demeritt 2009a; Oughton and Bracken 2009; Wesselink 2009; Harden 2012; Tadaki and others 2012).

Social-ecological systems (SES) theory provides an example of bridging disciplinary boundaries and drawing on core themes. SES theory represents a shift toward treating social and ecological processes as integrated, complex systems. A social-ecological system in this context is an intentional, cooperative subset of a social system in which some of the interdependent relationships among humans are mediated through interactions with biophysical and non-human biological units (Anderies and others 2004; Olsson and others 2006). From this perspective, social and ecological systems are linked through feedback mechanisms and act as complex adaptive systems. Resiliency in SES has been addressed through interdisciplinary work between ecologists, economists, political scientists, mathematicians, archeologists, and social scientists, as part of the Resilience Alliance (Walker and others 2004). Researchers have engaged in multiple case study comparisons around a variety of systems, including lakes and wetlands, rangelands (Anderies and others 2004), coral reefs, and forest ecosystems (Weber and others 2012).

Other examples of bridging disciplinary boundaries include the concept of ecosystem services, which emphasizes how ecosystem functioning benefits human societies (Chan and others 2012). Environmental flow management, such as that in the ecological limits of hydrologic alteration (ELOHA; Arthington and others 2006) framework, inherently crosses disciplinary boundaries because it uses characteristics of the physical system—flow regime—to achieve ecological targets, such as aquatic community maintenance, within the context of human regulation of water resources. Specific examples of management and restoration that use interdisciplinary models of disturbance drivers and system responses also exist (e.g., Mika and others 2010).

One limitation of many existing approaches is that they do not explicitly identify physical, as opposed to ecological, landscape processes, and that they do not necessarily explicitly consider the longer-term, cumulative changes that commonly characterize the evolution of geomorphic

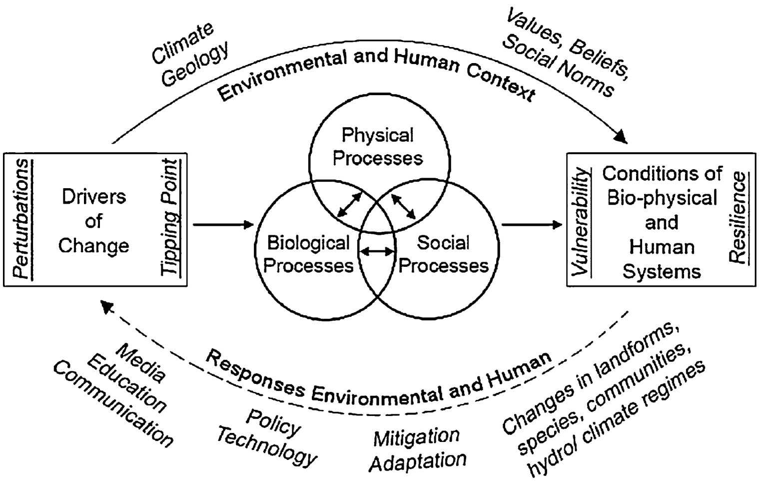

Fig. 1 The interactive, integrative, and iterative (III) framework for human–landscape change integrates impacts with feedbacks through bio-physical and human processes. Multiple interacting impact-feedback loops are likely at a range of scales. When applied iteratively (i.e., in succession), the framework is useful for articulating and understanding changing human–landscape-biota interactions

systems. The eighteenth and nineteenth century milldams mentioned previously provide an example. River restoration based on the understanding that contemporary human actions, such as upland farming, were the primary driver of enhanced sediment and nutrient delivery to rivers and the Chesapeake Bay identified incomplete feedback loops and thresholds (Wohl and Merritts 2007). Recognition of the legacy effects of past human landscape manipulation led to more appropriate and effective river restoration strategies by identifying that (i) enhanced sediments and nutrients were in fact coming from erosion along river corridors, rather than uplands, and (ii) restoration designed to recreate meandering gravel-bed rivers would not mimic channel form and process present before historical, intensive human landscape manipulation, as previously believed (Wohl and Merritts 2007). Therefore, in the remainder of this paper we explore interdisciplinary research using a recently developed conceptual model of interactions among physical processes, ecosystems, and human communities: the integrative, interactive, and iterative (III) framework for human–landscape change (Chin and others 2010). This framework emphasizes the iterative sequences of change produced by interacting impacts and feedbacks in the evolution of human–landscape systems. We draw on this model to illustrate how the key themes discussed in this article can be integrated into interdisciplinary research for human–landscape systems. We then examine how these themes might look through the specific lens of a river.

The III Framework for Human–Landscape Change

The III framework for human–landscape change focuses on the core interactions among physical, biological, and social processes resulting from perturbations in the landscape (box at left in Fig. 1). Examples of perturbations include installing or removing dams, human-induced soil erosion, or deforestation. These perturbations may be substantial enough to drive the system across a tipping point or threshold. Installing a dam, for example, blocks fish migration and eliminates a fish population and associated commercial or recreational fishery. The particular environmental and human context in which the perturbation occurs (top arc in Fig. 1) determines the initial vulnerability and resilience of human communities and bio-physical systems to the perturbation. It also contributes the background processes (e.g., the geology or culture of a particular place) that determine the resulting vulnerability and resilience of bio-physical systems following adjustments to the perturbation (box at right in Fig. 1). The three intersecting circles at the center of the diagram provide a visual representation of the interacting systems that adjust to the specific perturbation, such as installing a dam (see below for specific illustration). The resulting conditions of vulnerability and resilience in human communities and bio-physical systems in turn elicit environmental responses and possible changes in human actions that potentially feed back to the original causes (the bottom arc of Fig. 1). Feedback responses at the micro level include mitigation and adaptation strategies to environmental stress as well as behavioral changes. Macro responses occur through policy along with technology, media, education, and communication.

The III framework includes the concepts of feedback mechanisms, resilience, and cross-scale analysis that characterize SES research; yet, a main feature of the framework is adjustments through time in response to perturbations in the system—emphases shared by the geomorphological and ecological disciplines—resulting in iterative changes in system states in the evolution of the landscape (Fig. 2). For example, the initial construction of a dam changes the interactions among physical, biological, and social processes, such as interrupting sediment movement, decreasing habitats, and increasing recreational

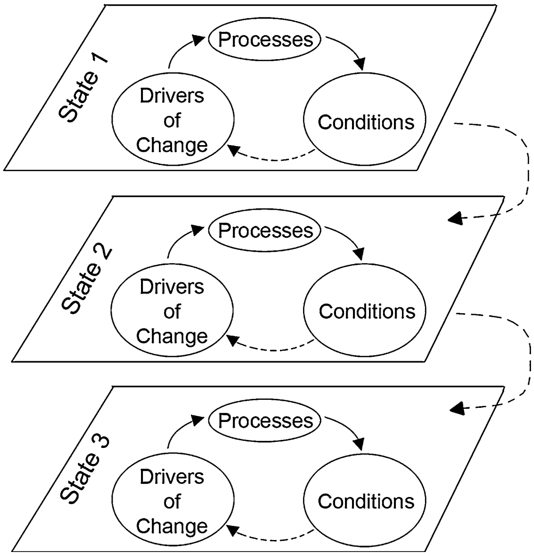

Fig. 2 A schematic illustration of iterative application of the III framework. Interactions among drivers, processes, and conditions in state 1 result in a different system configuration (analogous to an alternate stable state in ecology) and a different set of interactions in state 2, and so on to state 3

opportunities (Fig. 3). These interactions result in disconnected stream and riparian ecosystems with muted responses (state 1), setting up adjustments including changes in hydrologic and sediment regimes, channel morphology, and species. As scientific knowledge advances regarding the environmental effects of dams, feedback responses include mitigation (e.g., planning alternative ways to acquire water and recreate) and adaptation strategies (e.g., adapting to changed regimes with diminished sediment supply), and changes in policy (e.g., new funding for restoration programs).

In state 2, scientific advances prompt the removal of dams in river management. A non-regulated stream increases the variability of flow and improves habitats, although some recreational opportunities may be reduced (Fig. 3). Over time, these interactions ultimately enable the stream system to improve connectivity and re-gain some of the lost functions, resulting in further feedback responses. Such iterative states could continue until a new equilibrium is reached. Chin and others (2012) provides another application of the III model to illustrate the historical management of wood in changing river systems.

Through the Lens of a River

By examining a common object, such as a regulated river flowing through a human community, it is easy to see how numerous relevant issues pertaining to physical, biological, and social processes are intertwined (Fig. 4). Questions from disciplinary viewpoints could be explored and ultimately linked to tackle more complex, integrative problems, such as

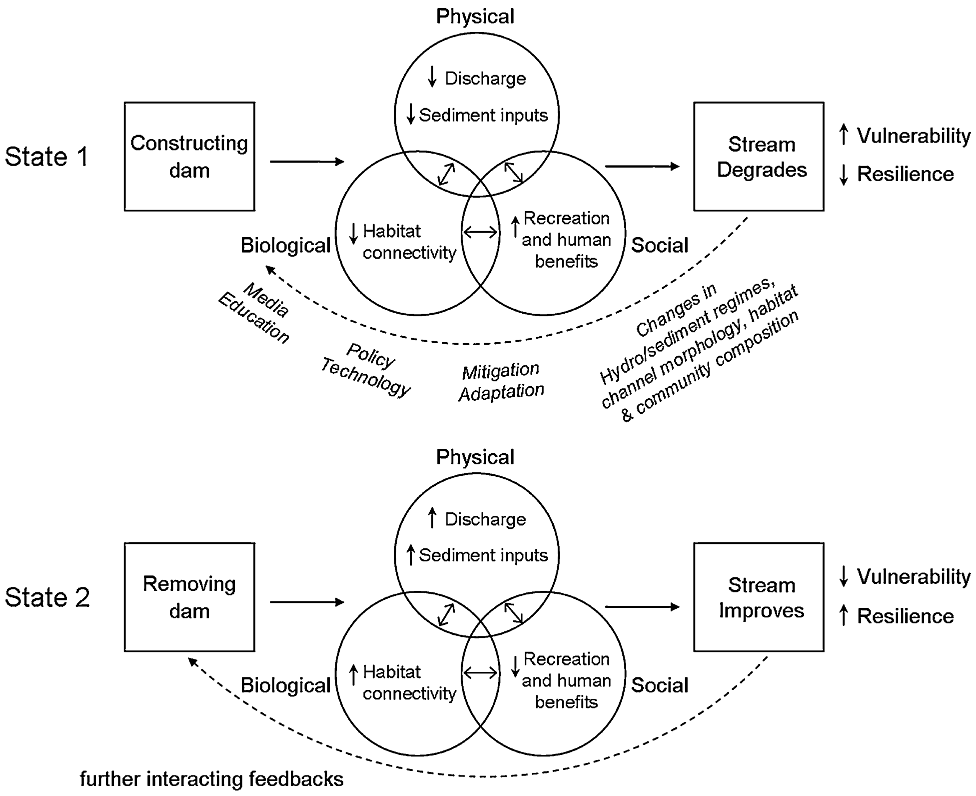

Fig. 3 Iterative states within human–landscape systems for constructing dams (state 1) and removing dams (state 2) and subsequent interacting impact and feedback loops. *Up* and *down arrows* indicate increasing and decreasing, respectively

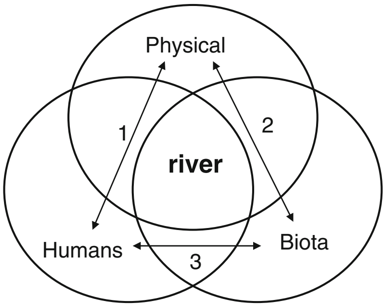

Fig. 4 Simple conceptual diagram of the relations among physical processes, biota, and humans. Dividing a river into these three systems is arbitrary, but reflects the disciplinary approaches of geomorphology (physical), ecology (biota), and environmental governance (humans) discussed in this article

1
Humans use river for water supply, navigation, waste disposal, food source, recreation, property boundaries
Humans alter yield of materials (water, sediment, nutrients, contaminants) to river, flux of materials along river, river geometry & boundary composition
River creates hazards (floods, bank & bed erosion, channel movement)

2
River processes create habitat & disturbance regime for biota, provide nutrients
Biota alter flux of materials along river, river geometry & boundary composition

3
Humans alter habitat, disturbance regime & resources for biota
Humans remove or alter species & biotic communities
Biota provide resources for humans
Biota create hazards (disease vectors, predation, resource competition)

maintaining physical and ecological integrity of the river, as well as potable water supply, while limiting hazards to the human community that are associated with natural disturbances, such as floods and channel change, which are in turn critical to maintaining physical and ecological integrity. Questions could also include how the institutional structure promotes development and development interests along the river, drawing from the earth system governance project described above.

Two specific examples can help to illuminate the general interactions illustrated in Fig. 4. The first comes from the Danube River, which drains 816,000 km^2 and flows through 18 countries in Europe. Eighty million people currently live within the Danube drainage. Human societies have relied on the Danube for water supplies, waste disposal, transport, and fisheries for many centuries, and have heavily modified river form and function through dams and channelization (arrow 1 in Fig. 4) (Wohl 2011). The Danube begins in mountainous headwaters of the Alps and alternately flows through broad lowlands and mountains as the river continues downstream to the Black Sea. Diverse riverine habitats support more than a hundred species of fish, thirty of which are commercially important, and sediment and nutrient fluxes exert an important influence on the Black Sea ecosystem (arrow 2 in Fig. 4). Construction of dams from the massive Djerdap Dam in Romania along the lower Danube, to hundreds of smaller hydroelectric facilities along the upper Danube in Germany and Austria, have severely limited fish migration and strongly altered natural flow patterns on which fish rely for feeding, reproduction and migration (arrow 3 in Fig. 4). Channelization of the formerly anastomosing or braided alluvial reaches of the Danube into single channels of uniform width have further reduced riverine habitat (Aarts and others 2004). Drastic reductions in fish populations (as much as 95 % in abundance of river organisms downstream from hydroelectric dams) have triggered efforts to restore river habitat and fish populations along the Danube and its tributaries (arrows 1 and 3 in Fig. 4) (Bloesch 2003). River restoration is strongly influenced by social conditions, including differences in the economies and societal priorities of diverse countries along the Danube's course, reliance on existing riverine alterations, such as electricity supplied by dams and transport supplied by barges able to operate year-round because of channelization and flow regulation, and ability to coordinate activities between countries (Wohl 2011). Restoration of the Danube River drainage as a resilient, sustainable source of ecosystem services is likely to be most effective if focused on (i) tipping points for water quality, habitat abundance and connectivity, and species populations, (ii) feedbacks between human manipulations and river process and form and aquatic and riparian communities, (iii) resilience of human communities to alterations of water quality, hydroelectric supply, fisheries, and hazards, such as flooding or stream bank erosion, and resilience of river physical and biological systems to human alteration, and (iv) connectivity of physical and biological fluxes throughout the drainage basin, as well as connectivity among diverse decision-making entities, from local communities to the European Union (Fitzmaurice 1996; Nachtnebel 2000).

The second example comes from a small drainage in northern Colorado, USA (Wohl and Dust 2012). La Poudre Pass Creek drains 61 km^2 from the continental divide east into the Poudre River, and ultimately into the Mississippi River and Atlantic Ocean. A transbasin diversion completed in 1974 brings water from the upper reaches of the Colorado River system (which flows westward to the Pacific Ocean) into Long Draw Reservoir at the head of La Poudre Pass Creek. Releases from the reservoir increase peak flows in the creek by 150 %, but flow to the creek is effectively turned off during autumn and winter. La Poudre Pass Creek flows through the Roosevelt National Forest and historically supported native salmonid fish. Excessive peak flows and associated channel erosion, combined with dewatering of the creek during certain periods of the year, have eliminated resident fish populations. Restoration of physical and biological function on La Poudre Pass Creek requires modification of the altered flow regime, but enhanced flow on the creek is part of a regional water-supply system that maintains more than three million people living in a semiarid region at the base of the mountains who rely solely on surface-water supplies for municipal, agricultural, and industrial consumption. La Poudre Pass Creek is thus much smaller and ostensibly simpler than the example of the Danube River drainage, yet effective management of the river ecosystem requires analogous focus on tipping points for fish habitat and consumptive water supply, feedbacks between human manipulations and river process and form and aquatic communities, resilience of human communities to alterations of water supply, and resilience of river physical and biological systems to altered flow, and connectivity of aquatic organism movement between the creek and more stable river segments, as well as connectivity among water engineers, fish biologists, recreational fishers and other users of public lands, and state and federal decision-making entities.

Conceptualizations such as Figs. 3 and 4 could be used to identify tipping points at which variations within one component of a river system, such as wastewater discharged by the human community, drive another component such as water quality across a threshold that then creates feedbacks that limit sustainability or integrity of the other components, such as fish biomass and then fish catch by humans. Integrative research might ask: do particular thresholds arise from interactions among hydro-geomorphologic, ecologic, and human systems? Given multiple and cumulative drivers of change, how can we infer the exact cause and effect relationships? Are thresholds predictable—i.e., are signals of irreversible change identifiable, especially where the path of response differs from the trajectory of impact?

The object of a regulated river in human–landscape systems can also provide insights into feedbacks. For example, integrative research might ask: how can feedback loops be identified and tightened to slow or reverse degradation, especially when coupling is weak, or when coupling is driven by a threshold response? Much of La Poudre Pass Creek is a steep channel with a boulder-bed and a high threshold for erosion of the channel boundaries, for example, so peak flows can be increased beyond natural levels without necessarily causing extensive channel change. Increasing peak flows without causing channel erosion requires identifying thresholds for channel erosion and for minimum habitat required to sustain fish populations. Sustaining fish populations also requires identifying thresholds for minimum instream flows, and quantifying feedback loops between flow levels, habitat abundance and quality, and fish populations, as well as feedback loops between water supply and fish populations. How can coupling be managed to promote greater resilience in desired system states toward sustainable ecosystems and human communities? In the case of La Poudre Pass Creek, where hydroelectric power generation is not involved, mechanisms could be developed to spread flow releases from the reservoir over greater periods of the year in order to continue downstream water supply without creating such an extreme “boom-and-bust” flow regime on the creek. Do the governance structure and processes feature the learning necessary to support social and institutional resilience? Differences over flow regulation led to a case at the Colorado State Supreme Court between the U.S. Forest Service and water-supply entities (Gordon 1995). Research and management could explore mechanisms to make decisions about water distribution more collaborative, and less confrontational, within the highly regulated legal framework of water management in Colorado.

For most terrestrial environments, the landscape, ecosystem, and human community are integrated by a river. Scholarly disciplines must be similarly integrated in order to effectively address contemporary challenges to the sustainability of ecosystems and human societies. We suggests that such integration can be effectively achieved by using common core themes of thresholds or tipping points, connectivity, feedbacks, and resiliency to focus on identifying, predicting, and manipulating systems of interest, such as a regulated river.

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