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Feedbacks in Human–Landscape Systems

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Abstract This article identifies key questions and challenges for geomorphologists in investigating coupled feedbacks in human–landscape systems. While feedbacks occur in the absence of human influences, they are also altered by human activity. Feedbacks are a key element to understanding human-influenced geomorphic systems in ways that extend our traditional approach of considering humans as unidirectional drivers of change. Feedbacks have been increasingly identified in Earth-environmental systems, with studies of coupled human–natural systems emphasizing ecological phenomena in producing emerging concepts for social–ecological systems. Enormous gaps or uncertainties in knowledge remain with respect to understanding impact-feedback loops within geomorphic systems with significant human alterations, where the impacted geomorphic systems in turn affect humans. Geomorphology should play an important role in public policy by identifying the many diffuse and subtle feedbacks of both local- and global-scale processes. This role is urgent, while time may still be available to mitigate the impacts that limit the sustainability of human societies. Challenges for geomorphology include identification of the often weak feedbacks that occur over varied time and space scales ranging from geologic time to single isolated events and very short time periods, the lack of available data linking impact with response, the identification of multiple thresholds that trigger feedback mechanisms, the varied tools and metrics needed to represent both physical and human processes, and the need to collaborate with social scientists with expertise in the human causes of geomorphic change, as well as the human responses to such change.

Keywords Feedbacks · Human impacts · Human–landscape systems · Coupled human and natural systems · Thresholds · Anthropocene

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Introduction

Humans have changed landscapes everywhere through activities such as agriculture, grazing, urban development, mining, and dam construction. These activities have promoted soil erosion, changed hydrologic and biologic processes, and caused loss of habitat and biodiversity. With a human population continuing to grow, the scale and magnitude of human impact on Earth have intensified to the extent that the term "Anthropocene" (Crutzen and Stoermer 2000) has entered the scientific literature to signify a new time-frame dominated by human activity. A proposal to formalize Anthropocene as a new geologic epoch within the Geological Time Scale (Zalasiewicz and others 2008; Williams and others 2011) is currently in development for the International Commission on Stratigraphy (Zalasiewicz and others 2011).

Awareness of the human impact on Earth's surface is not new. A century and a half ago, in *Man and Nature*, Marsh (1864) acknowledged the intricate relationship between humans and the environment and set forth the path for modern human–nature studies. After that, scholars convened at the International Symposium on "Man's role in changing the face of the Earth" and developed the foundational concepts for the reality of human impacts on Earth systems (Thomas 1956). In relation to river landscapes, for example, Strahler (1956) described system responses related to erosion and deposition caused by human activity. Leopold (1956) similarly identified changes in sediment yield and subsequent river-channel adjustments as responses to land-use modification. More recent work addressing global changes on sediment flux from rivers to oceans (Walling and Fang 2003; Syvitski and others 2005) also recognized human impacts on sediment yields due to dams and disturbances on hillslopes. Substantial progress has been made in the half century since the publication by Thomas (1956), with detailed studies producing a voluminous literature documenting the human impact on geomorphic systems in general (Goudie 2006), and on river channels in particular (Gregory 2006). James and Marcus (2006) provided a recent assessment and synthesis of the human role in changing fluvial systems.

While this body of knowledge has provided an invaluable foundation from which to draw for developing theories for landscape change and assisting environmental management, the magnitude and complexity of environmental challenges have grown to an extent that solutions now require new concepts and theories. Traditionally, Earth scientists have studied human impacts to the environment primarily from the perspective of humans as drivers of change (or as external disturbances to the system), and on adjustments within the natural system following disturbance. Yet, newer research emphasizes the need to go beyond the unidirectional focus of humans impacting landscapes (e.g., Grimm and others 2000; Pfirman and the AC-ERE 2003; NSF AC-ERE 2005; Head 2008) to capture two-way reciprocal interactions that characterize landscapes increasingly influenced by multiple human-caused stressors with, in turn, effects on human society. In this regard, while existing frameworks in social and natural sciences partially capture these interactions, new concepts for coupled natural and human systems have sprung up that explicitly integrate natural science and social science approaches (e.g., Liu and others 2007a, b), with focus on impact-response loops that return attention to modifications of the original human system causing landscape change; in other words, on "feedbacks" as defined below.

Although these emergent concepts offer potential for developing new ways of managing human-impacted landscapes, geomorphology as a discipline has not fully embraced them nor articulated their significance. The time is ripe, however, for the discipline to do so—and to draw upon the rich traditions of modeling human–natural systems in neighboring fields (e.g., Clark 2010) that have produced insights about feedbacks transferable to human–geomorphological systems. At the 2010 workshop "Landscapes in the Anthropocene: exploring the human connections," conducted in Eugene, Oregon and sponsored by the US National Science Foundation, 50 scholars identified feedback loops as one of four key integrative themes for interdisciplinary research. Thresholds, time scales and time lags, and spatial scales and boundaries were the other integrative themes to emerge (Harden and others 2013). These themes point the way to develop the next phase of research on human–landscape systems, beyond human "impacts" on landscapes, and are elaborated upon elsewhere (Jordan and others 2010; Wohl and others 2013).

In this article, we focus on feedback loops and explore their significance to advancing understanding of coupled human–landscape systems in which human actions affect the landscape, the modified landscape in turn affects humans—causing a modification in human actions that affect the landscape. First, we define feedbacks including positive and negative feedbacks that characterize open geomorphic systems, and trace the history and use of the concept in geomorphology and related sciences. Second, we outline a few select example studies of feedbacks in Earth systems that have been the subject of increasing attention in the interdisciplinary sciences. We focus on illustrative geomorphic interrelationships between deposition along coastal marshes and biological processes, and between land-surface erosion processes and the atmosphere, while recognizing that many example interactions are possible beyond those illustrated. Third, we provide examples that link landscapes to humans in particular. We discuss the extent to which general concepts from studies of feedbacks in Earth's systems and coupled human and natural systems may help advance research in human–geomorphic systems. In doing so, we also discuss the types of feedback linkages with potential to decelerate human impacts, and thereby highlight their significance to environmental management. Fourth, we identify key questions for geomorphology toward understanding feedbacks in human–landscape systems, and discuss future work needed and challenges for the discipline.

Feedbacks in Geomorphic Systems: Definitions

The concept of feedbacks in geomorphology can be traced to the application of systems theory to geomorphology

(Chorley 1962), where a system is viewed as elements and characteristics of a landscape and the dynamic forces and processes that influence it. Systems are structured sets of objects or attributes with interrelated components that operate together as a complex whole (Chorley and Kennedy 1971). Open systems tend to adjust to the throughput (transmission of mass and energy through the system) by modifying the interrelationships among the different elements or geomorphic variables of the system. The "fluvial system" is an example of an open system with boundaries that are defined by the watershed ridge tops. The fluvial system exchanges energy and materials constantly with its surrounding environment. From a geomorphic point of view, precipitation and solar energy enter as inputs to a watershed in which tectonic and isostatic processes create potential energy in the form of relief; water and sediment exit the system at the watershed outlet. The resulting morphodynamic processes condition the dynamic physical landscape response and interact with watershed ecosystems.

Change to any element within open systems may cause a variety of responses that operate over characteristic time and space scales. For example, following an externally imposed change (e.g., to water discharge, sediment input, or base level), short-term (days to years) responses typically include adjustment to the channel cross section, size of the channel's bed sediment, and form of the channel's bed; channel pattern (e.g., braided, meandering) adjusts generally over an intermediate time period (decades to centuries); and channel slope and longitudinal profile adjust over longer time scales (centuries to tens of centuries) (Knighton 1998). These system adjustments can exhibit a "complex response" in which responses of multiple components interact through time and space, and can involve abrupt change as extrinsic or intrinsic system thresholds are crossed (Schumm 1973).

Many system adjustments involve feedback. A "positive feedback" is an initial change to a system which in turn causes more change in the same direction (A causes B which in turn causes more of A). Positive feedbacks are self-enhancing mechanisms that tend to cause instability within systems. A "negative feedback" is an initial change that brings about an adjustment that counters or limits the initial change (A causes B which in turn causes less of A). A negative feedback is commonly referred to as a "self-regulating mechanism" that provides system stability. Feedbacks in geomorphic systems have been described for many environments, including glacial, coastal, fluvial, and hillslope, and at scales from sediment particles to continents (Murray and others 2008).

Fluvial travertine systems are an example where positive feedbacks govern morphology. Travertine precipitates from water when it is supersaturated with respect to calcium carbonate. Travertine precipitation is driven by degassing of carbon dioxide gas (CO_2) to the atmosphere. This may occur where river flow accelerates around irregularities in the travertine substrate, or where slope increases flow velocity and lowers the fluid pressure, thus enhancing CO_2 degassing (Chen and others 2004). As travertine deposits locally, the new bed morphology modifies flow hydrodynamics that favor further travertine deposition, in a positive feedback.

An example of a negative feedback is the channel response to an increase in water discharge during a storm event (Fig. 1). An increase in discharge (a change to "flow" in Fig. 1) leads to an increase in flow depth and boundary shear stress at a given location, which in turn erodes the channel margins, widening or deepening it. Several negative feedbacks operate to limit the magnitude of change to channel morphology, however, and thus to damp the erosive effect of increased discharge. For example, increased boundary shear stress (in the absence of an increase in sediment input or other change in system input) may induce preferential bed sediment transport and coarsen the channel bed. This coarsening limits further bed erosion and channel deepening; bed coarsening also increases flow resistance, which decreases the portion of the boundary shear stress available to erode the channel bed and banks. Increased discharge and boundary shear stress may also erode the banks and widen the channel; the increased channel width in turn decreases the channel depth, which increases flow resistance and decreases the erosive force of the flow (King 1970).

In the example above of a short-term change, channel slope functions as an independent variable, whereas over a longer time period it serves as a dependent variable (Schumm and Lichty 1965). Thus, over a long period of time, an increase in channel slope caused by tectonic uplift may set up a negative feedback: an increase in channel slope (change to "channel morphology" in Fig. 1) increases water slope and boundary shear stress, which causes

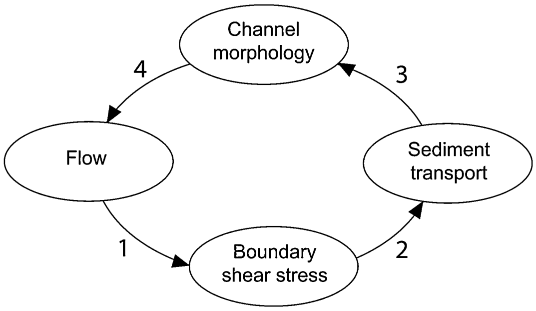


Fig. 1 Mutual adjustments among streamflow, boundary shear stress, sediment transport, and channel morphology in a river channel. See text for explanation. Figure is modified from Dietrich and Gallinatti (1991)

local channel incision and an eventual reduction of slope. These examples illustrate how fluvial systems have been viewed as process-response systems in which negative feedbacks that operate to counteract or reduce the effects of external change to the system (King 1970; Schumm 1973).

Both positive and negative feedbacks operate within open systems, though often at different spatial and temporal scales. Within a meandering system, for example, a combination of secondary flow, flow inertia, and bed topography act to increase erosive forces on the outside of bends and to promote sediment deposition on the inside of bends. Thus, positive feedbacks among flow, sediment transport, and channel morphology cause the meander's progressive outward and downstream migration. Over the course of years or decades, however, negative feedbacks limit the rate of growth and migration of bends, when the radius of curvature becomes small (Hickin and Nanson 1975) or meanders are cut off by channel avulsion when slope or geometric thresholds are crossed. In this example, positive feedbacks operate over shorter time periods (high flow events) and the countervailing negative feedback operates over longer periods (years to decades). This example also illustrates how positive feedbacks may move a system toward a different state by crossing a threshold, which may then trigger negative feedbacks to limit or reverse a perturbation.

When positive feedbacks are counterbalanced by negative feedbacks, a steady-state condition can exist (Willett and Brandon 2002). For example, interactions among channel incision, landscape denudation, tectonics, topography, and climate create positive feedbacks that operate over very long time periods (thousands to millions of years) at regional scales. Channel incision causes landscape denudation by erosion processes, which in turn promote faster tectonic uplift (e.g., Burbank and others 1996; Willett 1999; Whipple 1999). Increased gravitational potential energy then concentrates precipitation due to orographic effects (Roe and others 2002), leading to more rapid channel incision and landscape erosion. Channel steepening, however, creates a negative feedback by increasing the rate of incision, and the net result can be a steady-state stream profile and topography.

Interacting Feedbacks Within Earth's Systems: Examples

Physical–Biological Feedbacks in Tidal Marshes

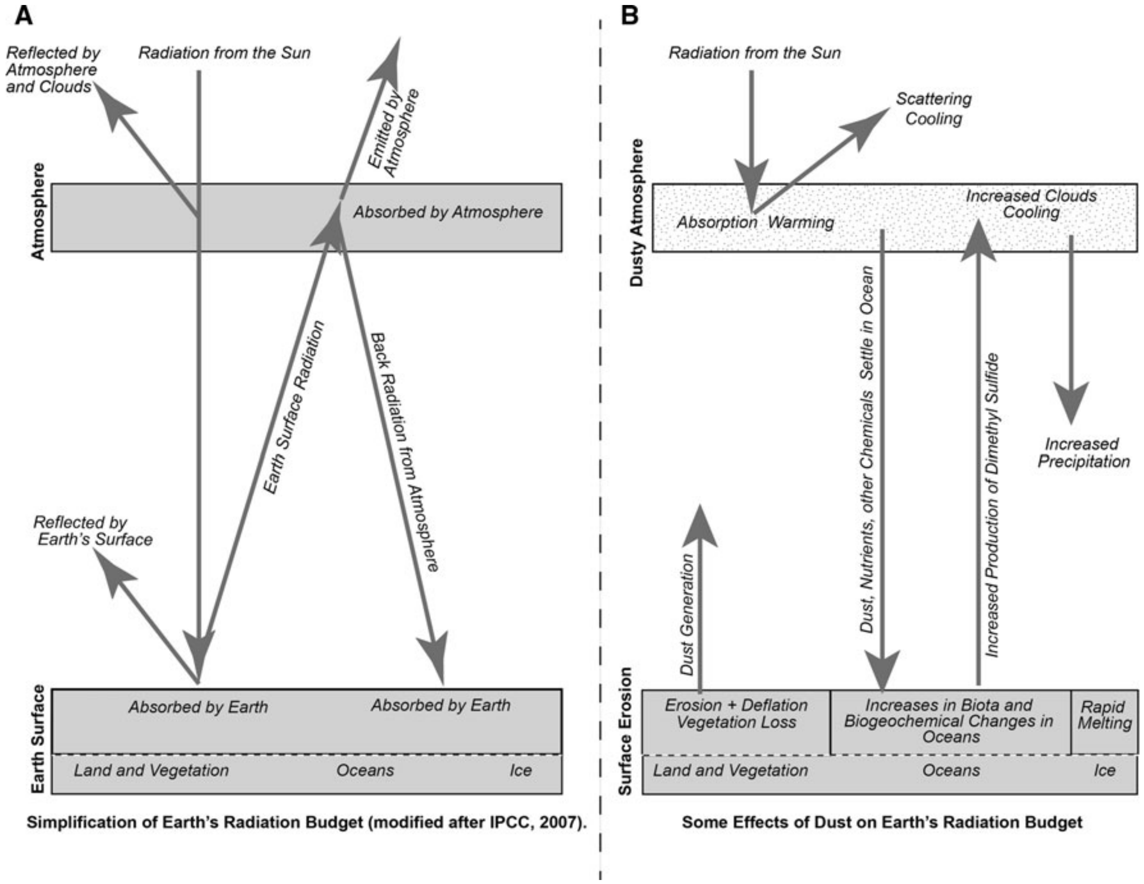
Coupled systems with tightly linked physical and biological interactions are increasingly described in the literature, with recent reviews found in Stallins (2006), Murray and others (2008), Corenblit and others (2007), Restrepo and others (2009), Marston (2010), Reinhardt and others (2010), Osterkamp and Hupp (2010), Wheaton and others (2011), and Corenblit and others (2011). Organisms are increasingly understood to have modulated or created landforms, and landforms and physical processes are understood to in turn have feedbacks not only on ecological communities, but also on the evolution of life (Corenblit and others 2011) since at least as early as terrestrial plant colonization about 450 million years ago (Gibling and Davies 2012).

The coastal marsh environment provides easily observable examples of physical–biological feedbacks. Traditionally, waves and sediment transport were considered to have unidirectional impacts on biota—in the sense that physical processes constrain organisms. Recently, however, biota has been recognized to have reciprocal impacts on geomorphological processes—so that feedback relationships exist, in which organisms respond to the environment, and in turn modify the physical coastal marsh environment (Gleason and others 1979; Morris and others 2002; Friedrichs and Perry 2001; Temmerman and others 2007; Kirwan and Murray 2007; Mudd and others 2010; Fagherazzi and others 2012).

Morris and others (2002) showed these interdependencies in relation to a smooth cordgrass (*Spartina alterniflora*) salt marsh along coastal South Carolina. This plant colonizes the intertidal zone, and is thus dependent on the interactions between sea level and sediment substrate elevation moderated by sediment concentration and tidal hydrodynamics. Tides also are the mechanism that provides nutrients, removes metabolic waste products, and carries away salts, so that the salinity of the substrate remains low enough for plant growth. In field studies within the salt marsh, primary production was measured as plant stem growth and elevation changes were quantified using a leveling device that did not disturb the surrounding marsh plain (Morris and others 2002). These field data parameterized a model and illustrated how plant establishment modifies local hydrodynamics to enhance sediment deposition, and in turn promote salt-marsh accretion. Ultimately, the plant controls the physical processes of flow, sediment transport, and morphological change within the tidal marsh system to keep the marsh-plain elevation in equilibrium with sea level rise. Thus, the biota and landscape function as a tightly coupled system, with feedbacks between them.

Feedbacks Between Atmosphere and Earth's Surface

Feedbacks between the atmosphere and Earth's surface have received growing attention in recent years. Geomorphology has traditionally emphasized climate controls on landforms (e.g., Cotton 1942; Wolman and Gerson 1978;



Simplification of Earth's Radiation Budget (modified after IPCC, 2007).

Some Effects of Dust on Earth's Radiation Budget

Fig. 2 **a** A simplified schematic of Earth's radiation budget. Although incoming radiation from the sun is partly reflected by clouds and the atmosphere or by Earth's surface, the majority is absorbed by the Earth's surface. In turn, some radiation reflected by Earth is absorbed by the atmosphere and reflected back to earth. **b** Direct and indirect effects of dust on Earth's radiation budget. Indirect effects may result from nutrients or other chemicals carried in dust that influence precipitation, temperature, and ocean biogeochemistry in general. Nutrients deposited in the ocean may cause an increase in ocean biota such as phytoplankton. In turn, phytoplankton utilizes carbon dioxide from the atmosphere and stimulates production of dimethyl sulfide, leading to increased cloud cover and cooling, with potential additional effects on temperature and precipitation

Bull 1991) through the field of climatic geomorphology (Büdel 1982) that addresses the influence of climate on rates and mechanics of Earth surface processes and landscape variability and change (Ritter and others 2002; Anderson and Anderson 2011). This tradition has continued in studies of how climate change affects Earth's surface processes, such as how melting glaciers and decreasing snow packs affect streamflow, erosion and deposition, and sea level rise (Rodriguez-Iturbe and others 1982; Knowles and Cayan 2002; Solomon and others 2007). However, scientists also recognize the reciprocal relationship between Earth's landscapes and climate—in that surface processes provide important feedbacks to the atmosphere in ways that may change climate on a global scale (Denman and others 2007).

In particular, complex feedbacks exist between land surfaces and the atmosphere through terrestrial wind erosion, dust, and climate. Wind erosion in dry landscapes generates fine sediment, or dust, that may be suspended in Earth's atmosphere until it settles. Atmospheric dust influences Earth's climate in multiple direct and indirect ways (Fig. 2) (Harrison and others 2001; Mahowald and others 2006; Denman and others 2007; Goudie and Viles 2010). Atmospheric dust may alter Earth's radiation budget by absorbing or scattering incoming shortwave and thermal radiation from the sun, which may cause warming or cooling, respectively. Changes in temperature may further alter precipitation and moisture regimes in ways that could influence vegetation characteristics. New vegetation characteristics could, in turn, lead to changes in wind erosion rates—a modification of the initial condition that is an example of a feedback. Dust in the atmosphere also provides nuclei for cloud condensation that may increase precipitation, similarly modifying the initial condition relevant to dust generation.

Recognizing its significance in altering climate on regional and global scales (Tegen and others 2000), climate models now include dust (Mahowald 2011). The spatial

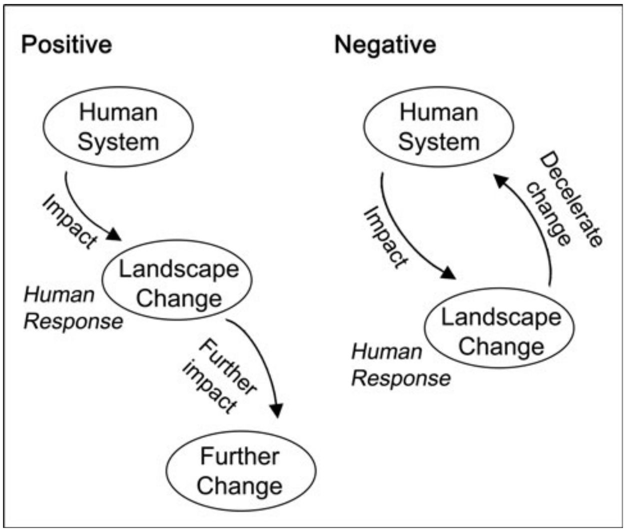


Fig. 3 Positive and negative feedbacks in human–landscape systems

distribution of sediment sources for wind erosion, therefore, also becomes important in the context of providing feedbacks to climate change (Goudie 1983; Goudie and Middleton 1992, 2001; Pye 1987; Claquin and others 2003). Sources include areas vulnerable to wind erosion such as glacial- or desert-derived loess deposits (Mahowald and others 2006), playas (Reheis and Kihl 1995), or salt flats such as the Salar de Uyuni in Bolivia (Washington and others 2003), and other large natural dry topographic depressions (Prospero and others 2002) such as the Bodele Depression at the southern edge of the Sahara Desert in Africa.

Feedbacks in Human–Geomorphic Systems

Studies of feedbacks in Earth's interrelated systems have often emphasized process changes resulting from a specific forcing factor with a general goal toward quantification and predictive understanding of such interactions. In the terminology of Chorley and Kennedy (1971) and Bennett and Chorley (1978), these process-response systems link the structural or constituent parts (morphological system) with the throughputs of energy or mass (cascading system). Although these concepts and goals may apply generally to human–landscape systems, coupling human and geomorphic processes into the feedback loop is complicated because, in addition to the complex dynamics acting on geomorphic systems that themselves might exhibit feedbacks, human actions and behavior, decision making, political institutions, cultural issues, and economic circumstances are involved—thus studies to integrate these systems have been limited.

To fully articulate the coupled human–geomorphic system, one must address both the human and social factors driving the impact on Earth's surfaces, as well as the human response to landscape change. Because these factors are highly variable across space and over time, deciphering the causal linkages (i.e., the feedback loops), especially those that might mediate the original impact, becomes especially challenging. Advancing knowledge of coupled human–landscape systems requires adding a new set of social parameters to what may already be very complex series of interactions in the Earth-environmental system (e.g., Soares-Filho and others 2006). Coupled human–landscape systems may, in fact, be thought of as "control systems," (Chorley and Kennedy 1971; Bennett and Chorley 1978), whereby process-response systems are further controlled by some intelligence, such as a social body capable of decision making. A recent model coupling coastline change driven by wave- and sea level rise with the economics of coastal development and beach nourishment (the human control involving decision making) illustrates feedbacks and emergent physical and economic behaviors in this context (McNamara and others 2011).

Positive and Negative Feedbacks

Positive and negative feedbacks are key elements in coupled human and natural systems, in which people both influence and are affected by natural processes and patterns (Fig. 3). Analogous to the cases outlined above for Earth systems in general, positive feedbacks occur where human activities and responses in turn cause more change in the same direction. Positive feedbacks lead to system instability, which can bring about degradation in human–landscapes. Negative feedbacks involve human responses and behaviors that produce changes that counter or limit the initial impacts. These negative feedbacks, therefore, lead to system stability or landscape preservation. Both positive and negative feedbacks can operate in the same coupled human–natural system, leading to uncertainties regarding which feedbacks will dominate under different scenarios (e.g., Caers 2011). New data and analyses will be especially helpful to advance understanding in this regard.

Intense cultivation of land surfaces in the Embu District of Kenya illustrates a positive feedback in a coupled human–natural system (Liu and others 2007a). Without supply of nutrients, soils degraded and resulted in reductions in crop yield. The food insecurity subsequently prompted local residents to convert remaining forests to cropland, thereby accelerating the cycle of soil degradation (Imbernon 1999). Globally, positive feedbacks involving people, agriculture, and soils were acknowledged by Montgomery (2007), who noted that the capacity of a landscape to support people through agriculture depends on both the physical characteristics of the environment, e.g., climate and soil, and the farm technology utilized. Without soil conservation, the resource that people depend on, namely the soil, will be depleted—and the effort to feed society using non-conservative soil land-use practices will eventually fail.

Negative feedbacks in human–landscape systems often involve alterations in human behavior that potentially slow or reverse the original impact. A well-functioning market in economics, for example, provides negative feedbacks that may limit environmental impact without governance (Clayton 2009; Peterson and others 2013). When these markets fail to account for external impacts, however (e.g., on the environment and the associated negative impacts on humans), policies may be needed to slow or reverse impacts. Adaptive management and adaptive governance provide key instruments for effecting negative feedbacks in this regard (Dietz and others 2003; Walker and others 2004; Chapin and others 2006).

For example, construction of Ferrell's Bridge Dam on Cypress Creek in Texas eliminated the variability in flows, as dams typically do, and threatened the species that depend on periodic floods to deliver nutrients and disperse seeds. Eventually, when baldcypress (*Taxodium distichum* L. var. *distichum*) trees characteristic of the Caddo Lake region began dying (Klimas 1981), local stakeholders became concerned about losing a culturally and aesthetically valuable landmark, prompting efforts to re-evaluate and adjust release practices. Thus, the environmental degradation reached a threshold that prompted a human decision and action to slow or reverse the hydrologic impact—an example of a negative feedback—in contrast to the human response that accelerated degradation (positive feedback) in the example of the land cultivation in Kenya described above (Fig. 3). Presumably, in an adaptive process (Richter and others 2006), the adjustment in management response also includes finding new ways to meet the human needs for water supply and flood control that prompted the construction of the dam in the first place.

Coupling Management into Feedback Loops

Recognizing the role of management regimes in feedback loops is important to understanding and predicting landscape response. For example, management over the past 150 years on the Sacramento River in California through the progressive development of flood control infrastructure at the system level has conditioned the geomorphic responses to floods. Before this period, river floods maintained a dynamic multiple-channel system, inundated wide floodplain areas, and sediment erosion and deposition patterns supported a vibrant river-floodplain ecosystem. Even though management modified flow releases from dams on the river, and levee construction along channels was pervasive, climate variability still governs geomorphic responses to floods via erosion and deposition at levee breaks (Florsheim and Dettinger 2007). Now, in light of growing understanding of the role of atmospheric rivers in controlling historical mega-flooding in California, management decisions have become critical in minimizing future risks and damages from geomorphic responses to floods (Dettinger and Ingram 2013). A new and tightly coupled management regime is needed that could include reducing risk by modifying the levee system to restore portions of floodplains to accommodate floods.

A more complex suite of interactions coupling human and landscape systems can be illustrated with the feedback cycle described in the previous section, involving wind erosion, dust, climate, vegetation, and human activity (Fig. 4; Mahowald 2011). Human actions (such as livestock grazing) can clearly modify vegetation, sediment, and landform dynamics in ways that promote the generation of dust and thereby alter climate (Kohfeld and Harrison 2001; Prospero and others 2002; Bergametti and Gillette 2010). Despite a high degree of uncertainty, recent estimates suggest a significant increase in anthropogenic dust over the last century (Neff and others 2008; Mahowald 2011; Mulitza and others 2010). A climate modified by increased atmospheric dust will likely influence Earth's surface processes including the structure and function of terrestrial ecosystems. If the changes result in a reduction in the density of vegetation, for example, livestock grazing could be limited to an extent that economies are affected, prompting the need for new management solutions that also address the original causes of landscape change and the needs for livestock grazing. This scenario additionally illustrates a potential negative feedback loop that involves management in coupled human–landscape systems (Fig. 4).

Significance of Negative Feedback Loops

Understanding and effecting negative feedbacks is a key to managing complex environmental systems (Walker and others 2004; Chapin and others 2006), as illustrated above, because it offers potential to slow or minimize the negative effects of human activities while increasing resilience, or the ability of a landscape to absorb stress and recover from disturbance, in geomorphic and related environmental systems. It is also important in optimizing resources toward sustainability and improving human well-being. Yet, negative feedbacks are not easy to identify or manage because the causes of the impact may originate at faraway places and over different time and space scales.

In the case of the impacts of global climate change on Arctic residents (Chapin and others 2006), the bulk of the human activity-driving global climate change (e.g., emission of greenhouse gases) occurs outside the Arctic and is only indirectly coupled to changes occurring with the Arctic—in other words, the impact-feedback loop is weak.

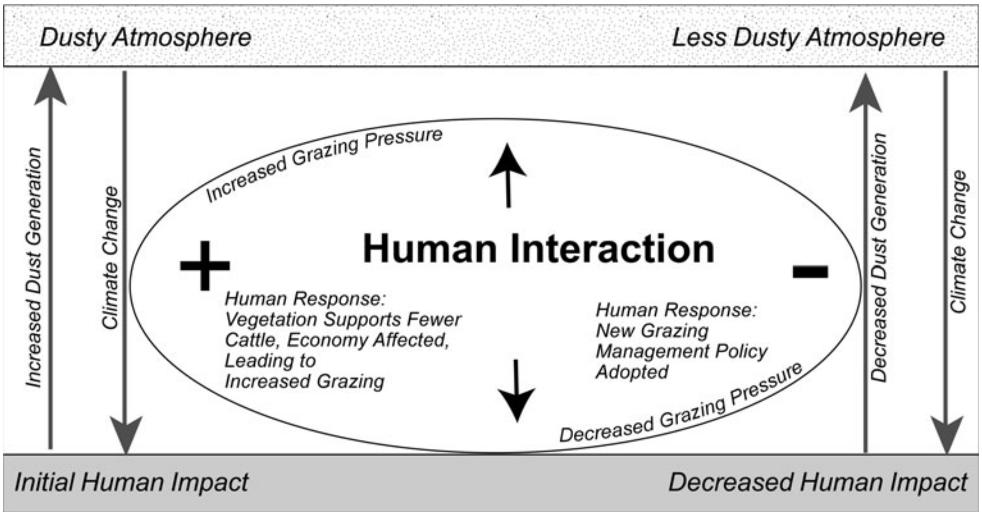


Fig. 4 A coupled human–geomorphic system involving grazing, wind erosion, and increasing atmospheric dust. *Plus* and *minus* signs indicate positive and negative feedbacks, respectively. The *left side* of the figure indicates positive feedbacks that increase grazing pressure. Grazing reduces vegetative cover initially, rendering Earth's surface vulnerable to dust generation. Interactions of dust in the atmosphere modifies climate in a way that further reduces vegetative cover and increases dust-producing surface erosion. Human are affected by the changing economics of a landscape that supports fewer cattle and respond by increased grazing. The human response shown in the *right side* of the figure represents a negative feedback with modification in human behavior due to the landscape change. Management efforts to reduce grazing pressure allow reestablishment of vegetative cover and less surface erosion. In turn, less dust is generated with decreased potential for climate change

Even though the effects of climate warming are strongly felt by local Arctic residents, addressing these impacts directly is difficult because it involves changing human behavior at the global scale. Currently, very little feedback exists to encourage people globally to change their behavior to slow the rates of Arctic change. Effecting a negative feedback loop to slow Arctic change would, therefore, involve larger scale efforts that include news media to inform the world about climate-change effects on Arctic residents, as well as policy and regulatory frameworks that are international in scope.

Geomorphology must play an important role in formulating relevant science and public policies in situations where interacting feedbacks operate over a range of scales, even though attempts toward global solutions in the specific case outlined above (e.g., United Nations Framework Convention on Climate Change resulting in the Kyoto Protocol, 1997; Copenhagen Accord, 2009) have met formidable political and economic challenges. Geomorphologists can recognize the many diffuse and subtle feedbacks, while time may still be available to mitigate the impacts on Earth's surface processes (NRC 2010). Understanding feedbacks and coupled human–landscape dynamics in general represents a grand challenge for the discipline.

Beyond Social–Ecological Systems

Study of coupled human and natural systems thus far has produced an emerging science for social–ecological systems that emphasizes ecological phenomena and feedbacks (e.g., Lew and others 1999; Walker and others 2004; Folke 2006) with associated case studies (e.g., Liu and others 2007a, b). In conjunction with feedback loops, coupled human and natural systems can be expected to exhibit nonlinear dynamics with thresholds, time lags and legacy effects, different degrees of resilience, heterogeneity varying across space, time, and organization units, and "surprises" when outcomes are not expected (Liu and others 2007a). Resilience, in particular, has been increasingly used as a concept to understand social–ecological systems (e.g., Folke 2006). It is also applicable to geomorphic (Phillips 2009) and eco-geomorphological (Collins and others 2012) systems, although specific application to human systems has been critiqued with "resourcefulness" proposed as an alternative framework in its place (MacKinnon and Derickson 2013). These concepts, as integrally related to feedbacks characteristic of open systems, provide valuable background for advancing research in coupled human–geomorphic systems.

Researchers have begun to create models that couple human behavior with physical processes to understand emergent instabilities in human–coastal systems (Werner and McNamara 2007; McNamara and Werner 2008; McNamara and others 2011). Yet, enormous gaps in knowledge remain with respect to quantifying the full impact-feedback loops within geomorphic systems with significant human interactions. In this regard, the impact-feedback loop for human–landscape systems must account for the social processes that influence the original human impact, such as the need for livestock grazing that causes wind erosion in the example above. In addition, changes on Earth's surface need to be quantified explicitly in terms of how they affect humans directly or indirectly, such as through economic evaluation of changed landscapes (e.g., Clayton 2009; Doyle and Yates 2010).

For example, as a starting point, accelerated soil erosion can be quantified and predicted in terms of how it affects biological soil crusts and the water-holding capacity of soil profiles, and thus plant and crop production. These changes can then be translated into the language of ecosystem services and human perceptions and valuation to assess the extent to which predictable thresholds may exist that would trigger feedback responses (NRC 2010), such as to limit livestock grazing in the case above. Changes in vegetation densities resulting from increased anthropogenic atmospheric dust can be similarly evaluated in terms of how they may affect local economies and people's livelihoods (Fig. 4).

Studies involving the full range of interacting feedbacks in human–landscape systems are difficult to execute because it is likely not possible to quantify adequately the vast array of physical effects and human or ecosystem costs. Identifying and linking the relevant and important variables represents a major challenge. New, integrative tools for linking physical and human processes are also likely needed, including quantification of ecosystem services (Chapin and others 2006) in specific geographic contexts (Womble and Doyle 2012), agent-based and spatial simulation models (Dearing and others 2006; Galvin and others 2006; Soares-Filho and others 2006; McNamara and Werner 2008), and integrated assessments (Liu and others 2007b). These tools are reviewed in detail elsewhere including example applications to human–geomorphic systems (Zvoleff and An 2013). In addition, because policy and institutional processes are the key instruments that society has for effecting necessary feedbacks, as described above, a complete understanding of coupled human–geomorphic system necessitate inclusion of policy mechanisms and effective transmission of scientific information to policymakers. These challenges are discussed in the next section, in the context of key questions and research needs identified for geomorphology relevant to investigating feedbacks in human–landscape systems.

Key Questions, Challenges, and Research Needs for Addressing Feedbacks in Geomorphology

Key Questions

Key questions for advancing knowledge of feedbacks in human–landscape systems require that we also tackle the connections in the context of the integrative themes of thresholds, time scales and time lags, and spatial scales and boundaries identified in the 2010 NSF workshop on human–landscape systems (Chin and others 2010; Harden and others 2013), because of their highly interrelated nature. These themes provide the conceptual context or framework for pinpointing specific research questions addressing feedbacks in human–landscape systems. We propose the following key questions based on our current understanding of feedbacks in human–landscape systems:

- *In human–landscape systems, how can feedback loops be identified and altered to slow or reverse degradation, even where coupling is indirect, diffuse, or weak?*
- *How best can feedback loops be identified when they involve threshold response dynamics—within geomorphic and/or human systems?*
- *How, when, and where are feedback mechanisms triggered by interactions among geomorphologic, ecologic, climate, and human systems?*
- *What are the appropriate time and space scales and boundaries for investigating feedbacks that link across geomorphologic, ecologic, atmospheric, cultural, political, and economic systems?*

Challenges

In tackling key questions for coupled human–geomorphic systems, challenges for geomorphologists center on how to identify, quantify, and model the dynamics of the many diffuse and potentially weak feedbacks that occur through diverse systems, and varying across time and space scales ranging from geologic time to single isolated events. Key aspects of these challenges include:

Temporal and Spatial Scales

Time scales relevant to human processes and institutions are often short compared to the time frames of morphodynamic processes (Kondolf and Podolak 2013). Lag times may also exist between forcing factors and system responses; moreover, legacy effects of past disturbances often condition modern morphodynamics and alter system responses (Liu and others 2007a). A striking example comes from the recent recognition that gravel-bed streams in the mid-Atlantic piedmont region of the eastern US are actively incising into legacy sediment left when thousands of milldams were abandoned during the nineteenth century (Walter and Merritts 2008). Before recognition of the finer grained valley fill as milldam sediment, efforts to decrease sediment yields to downstream nearshore environments such as Chesapeake Bay had focused on erosion control in agricultural uplands. The focus of sediment-control efforts is now shifting toward river corridors and valley bottoms.

Feedbacks within legacy-influenced systems may operate over still longer time scales. A critical first challenge is, therefore, clarifying and linking appropriate time frames for the impact and response mechanisms, and identifying appropriate measures to represent the varying time scales of the processes involved. Similar considerations arise for spatial scales whereby human actions at a local scale, such as grazing, may initiate large-scale geomorphological responses (e.g., wind erosion at regional scale), with yet larger global implications, such as the generation of dust and resulting climate change (e.g., see Fig. 4). These considerations are further complicated by possible mismatches in spatial boundaries—e.g., cultural and political boundaries may not match physical spatial units, such as watersheds. Kondolf and Podolak (2013) further explore these challenges.

Linking Impact and Response

At present, much more data and knowledge exist pertaining to the human impacts on geomorphological processes and functions than to the human responses to those changes—in turn, less is known about how human responses alter the initial (reference) conditions of the system that existed prior to intensive human impact, or the landscape state within this spiral. This situation may reflect the fact that quantification of the cause and primary effects is in many cases limited, so trying to go beyond first-order response to subsequent second- or third-order responses is even more difficult and is not commonly done. The milldam example mentioned above is an exception. Efforts to reduce upland sediment yields are demonstrably succeeding, yet sediment yields remain high because of in-channel sources in the form of legacy milldam sediment.

Although a wealth of information is also available relating to the human dimensions of hazards, disasters, and global change, a challenge remains to link these bodies of work and identify relevant and usable data for connecting impact and response for single and multiple events. Real estate market and insurance market data, for example, potentially provide new ways to connect multiple events and states of the geomorphological system with human activities (Smith and others 2009; Lazarus and others 2011; Gopalakrishnan and others 2011). Despite increasing emphasis on identifying and characterizing feedbacks, however, standard protocols for interdisciplinary efforts do not exist, and identification of appropriate data is not straightforward. This situation likely reflects the combined effects of different languages among disciplines, different approaches to gathering information (e.g., hypothesis testing and mathematical simulations vs. anecdotal knowledge), and differing emphases on relevant and important questions among disciplines (Benda and others 2002).

Further complications arise when multiple thresholds trigger feedback responses. During the 1930s, Dust Bowl in the US prairie, drought and agricultural practices pushed prairie soils across a threshold that triggered widespread soil erosion and eolian transport (Egan 2006; Cook and others 2009). This situation pushed some farmers across a psychological and economic threshold and they abandoned their farms and left the region, even as other farmers continued the same agricultural practices. Localized eolian deposition crossed another threshold, and some parts of the prairie became covered in wind-blown sand that prevented agriculture and interfered with human habitations and transportation corridors. Other regions continued to be primarily erosional. Governmental responses to the Dust Bowl included establishment of the national grasslands to take marginal land out of agricultural production (Wohl 2009). As drought conditions lessened, however, the time required for vegetation cover and human communities to recover varied and was not easy to predict.

The magnitudes of impact and response also may not be symmetrical—in other words, a small impact may produce a large response and vice versa, with further complications arising when cumulative impacts are involved. Cumulative impacts describe the combined and interactive effects of numerous human resource uses that occur through time. Although each individual action may have a relatively minor effect, the cumulative effect can be substantial, as demonstrated by case studies of successive limited scale logging projects within the Caspar Creek watershed in California, USA and the progressive effects of continued and expanding areas of sheep grazing in New Zealand (Reid 2001).

Integrative Tools: Analysis and Modeling

Clearly, quantifying and linking processes that span geomorphological and human systems over diverse space and time scales require both development and application of new tools, and more effective use of existing tools such as geomorphic principles and theoretical frameworks that can be used to hypothesize potential feedbacks. Examples of relevant geomorphic principles include complex response, equilibrium, and thresholds, all of which are discussed by Wohl and others (2013). Fundamental to the challenge of integrating is the need to develop metrics that are capable of representing both physical and human processes within a common conceptual framework for human–landscape systems, similar to the call for common metrics for studying instream wood at a smaller scale (Wohl and others 2010). As well, recent advances in modeling have enabled incorporation of human behavior and decision making in Earth's surface processes, such as in the use of agent-based models to understand human interactions with coastal change (McNamara and Werner 2008). Bayesian data fusion (Bogaert and Fasbender 2007) also offers potential to integrate diverse datasets. Yet, challenges remain to develop and incorporate these new tools into investigations of feedbacks in human–geomorphic systems, as well as to advance human-interaction models in general (see Zvoleff and An 2013 for full discussion). Particular difficulties arise when quantitative models are capable of representing realistically only portions of human–landscape interactions—such as biomorphodynamics or atmospheric-surface processes—necessitating the potential use of mixed methods to fully capture human interactions with these processes.

Interdisciplinary Collaboration

The topic of feedbacks in human–landscape systems is interdisciplinary and requires collaboration across a range of physical and social sciences. In particular, tackling the key questions outlined above requires collaboration with social scientists with expertise in the human causes of geomorphic change and especially with the human responses to such change. Challenges of interdisciplinary research have been discussed elsewhere (e.g., NRC 2004) and include institutional as well as thematic issues. A particular difficult step, however, is collaborating across the social and physical-scientific divide. Challenges include the need to learn the languages, perspectives, and methodological approaches of each other's disciplines, and to develop ways to communicate and integrate them.

Research Needs

To meet some of the challenges and tackle key questions, we call attention to the following specific research needs:

- Developing response curves (plots of how a system or parameter changes through time—e.g., changes in channel width/depth ratio through time as discharge increases in response to upstream urbanization) for human and geomorphic components of landscapes that can be used to conceptualize and numerically simulate feedback loops and associated thresholds—this would be based on specific examples/environments/scenarios relevant to coupled human–geomorphic systems and integrated with the other themes elucidated in this volume;
- Examining recent historical episodes of coupled human–landscape change for which abundant social and physical data are available (e.g., 1930s Dust Bowl in central US; current effects of natural processes influenced by global warming) within the context or conceptual framework of the key questions above (Pastore and others 2010);
- Exploring potential for coupled human-geomorphic feedback loops to be influenced by rational decision making, management, and policy; modifying positive feedbacks that degrade geomorphological and ecological resources to negative feedbacks that conserve resources and ecology (e.g., in the example illustrated in Fig. 4). Such human interventions that modify feedbacks might create alternative "control systems" (Chorley and Kennedy 1971; Bennett and Chorley 1978);
- Developing, testing, and incorporating new techniques with potential to link physical and social data for investigating integrated human–geomorphic systems, including agent-based and spatial simulation models and mixed methods (see Zvoleff and An 2013).

All of the points above relate to the need for more specific, detailed case studies from which we can start to synthesize, generalize, and identify the key gaps in understanding. Future research requires intensified interdisciplinary interactions and collaboration across a range of physical and social sciences, necessitating the need for increased opportunities for such collaborations. Advancing this challenging research agenda will help geomorphologists, together with other physical and social scientists, develop the new integrated theories needed for the "Anthropocene." The time has never been more urgent and opportune.

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