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Invited review

Social-ecological resilience and geomorphic systems

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A B S T R A C T

Governance of coupled social-ecological systems (SESs) and the underlying geomorphic processes that structure and alter Earth's surface is a key challenge for global sustainability amid the increasing uncertainty and change that defines the Anthropocene. Social-ecological resilience as a concept of scientific inquiry has contributed to new understandings of the dynamics of change in SESs, increasing our ability to contextualize and implement governance in these systems. Often, however, the importance of geomorphic change and geomorphological knowledge is somewhat missing from processes employed to inform SES governance. In this contribution, we argue that geomorphology and social-ecological resilience research should be integrated to improve governance toward sustainability. We first provide definitions of engineering, ecological, community, and social-ecological resilience and then explore the use of these concepts within and alongside geomorphology in the literature. While ecological studies often consider geomorphology as an important factor influencing the resilience of ecosystems and geomorphological studies often consider the engineering resilience of geomorphic systems of interest, very few studies define and employ a social-ecological resilience framing and explicitly link the concept to geomorphic systems. We present five key concepts—scale, feedbacks, state or regime, thresholds and regime shifts, and humans as part of the system—which we believe can help explicitly link important aspects of social-ecological resilience inquiry and geomorphological inquiry in order to strengthen the impact of both lines of research. Finally, we discuss how these five concepts might be used to integrate social-ecological resilience and geomorphology to better understand change in, and inform governance of, SESs.

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1. Introduction

Resilience, as a concept of scientific inquiry, has grown tremendously in popularity and application over the past several decades as a useful, common entry point for embarking on interdisciplinary and transdisciplinary investigations aimed at achieving sustainability in coupled biophysical and social systems. Major themes in resilience research—including complexity, scale, systemic feedbacks, thresholds, and drivers of change—have received explicit disciplinary attention in geomorphology (e.g., Phillips, 2003; Marston, 2010), and the importance of geomorphology as a basis for managing coupled human-natural systems in the face of environmental change has recently been emphasized (Naylor et al., 2017). The study of resilience as a property of coupled social-ecological systems (SESs) and the underlying geomorphic processes that structure and alter Earth's surface are of utmost scientific importance in the Anthropocene, and geomorphologists alongside social and ecological scientists should be in the vanguard. As such, Parsons et al. (2016) have proposed a framework to coalesce resilience and river science for better management of river systems in the twenty-first century, and we further argue that integrating resilience science and geomorphology more generally will improve our ability to sustainably govern and manage society but also the Earth surface systems upon which they have developed.

Scientific inquiry on resilience shares foundations in basic and applied research: basic questions that attempt to explain dynamic interactions within and between complex biological, physical, and social processes, but also pursuit of similar questions under the assumption that consistent feedback of this knowledge to governance and management venues is necessary to ensure continued life on Earth amid human-driven environmental challenges. As a desirable outcome for governing SESs, sustainability—human use and conservation of environmental resources that provides adequately for future generations—can be significantly enhanced by a nuanced understanding of system resilience (Holling, 1986; Berkes et al., 2003; Gunderson et al., 1995; Anderies et al., 2013). The concept of governance, or more specifically environmental governance, can be best described as processes for mediating human values of the environment and for determining society's relationship with biophysical systems. Governance includes systems of rules, laws, and social norms, formal and informal, that dictate the use and conservation of resources (Lemos and Agrawal, 2006).

Knowledge of resilience as a property of complex systems—the nested and often nonlinear dynamics of biophysical and social interactions that determine the amount of disturbance a system can withstand before undergoing a regime shift fundamentally altering the structure and function of that system—can aid scientists and managers in illuminating paths of environmental governance that hedge against uncertainty by creating flexibility to adapt to rapid and unexpected change (Holling, 1973; Folke, 2006). In short, resilience-based governance is governance with a goal of planetary sustainability. Thus, resilience and sustainability are not equivalent; sustainability as a goal of governance is a desired state for SESs across the globe. Measuring and applying an understanding of the property of resilience in nested, complex systems is a means to more effectively achieve sustainability against a backdrop of increasing planetary-scale change and uncertainty associated with issues such as biodiversity loss, human population growth, and climatic change (Rockström et al., 2009; Steffen et al., 2015).

Given this orientation of resilience scholarship and combined with a widespread, global engagement of resilience frameworks beyond the academy into the realm of environment and development (e.g., Folke et al., 2002; Brown, 2016) and disaster risk reduction (e.g., Adger et al., 2005; Cutter et al., 2008; Alexander, 2013), much resilience research has initially unfolded in the environmental science and environmental social science disciplines as opposed to in more physical science disciplines such as geomorphology. Resilience research has followed the development of SESs as a scale of inquiry and the interdisciplinary investigation of coupled systems that include biological, physical, and social structures and processes as inextricably linked; any attempt to decouple those systems for research or management purposes runs counter to the inherent principles of complex systems (Berkes and Folke, 1998; Berkes et al., 2003). Further, social-ecological resilience explicitly recognizes humans as agents of change in environmental systems and introduces an emphasis on societal navigation of the complexity and uncertainty of coupled systems through managing resilience as a property of SESs to achieve sustainability goals (Gunderson and Holling, 2002; Berkes et al., 2003; Olsson et al., 2006).

In this paper, we discuss the concept of social-ecological resilience and how it could complement and be complemented by geomorphology to enhance environmental governance toward sustainability. We first briefly survey the myriad definitions of resilience, focusing on those applied in biophysical and social environmental sciences. Next, we broadly locate resilience research in geomorphology within the context of these definitions. Third, we discuss key themes common to social-ecological resilience and geomorphology (Table 1); and building upon concepts of complexity in geomorphic systems (Phillips, 2003), sociogeomorphology (Ashmore, 2015), and human-landscape systems (Wilcock et al., 2013; Chin et al., 2014), we argue for a further integration of social-ecological resilience and geomorphology to improve Earth surface systems governance (Biermann, 2007; Murray et al., 2009). We then attempt to chart a path forward by proposing initial steps for achieving this integration through explicit research collaborations between geomorphologists and social-ecological scientists applying respective disciplinary tools to address core questions about social-ecological resilience.

2. Defining resilience

A multitude of definitions for the term resilience abound in popular and academic literature (cf. Brand and Jax, 2007; Baggio et al., 2015). We argue, however, that four main 'bins' or general definitions of resilience are important to explore if any progress is to be made toward a tighter, more explicit coupling between geomorphology and resilience research: (i) engineering resilience; (ii) ecological resilience; (iii) community resilience; and (iv) social-ecological resilience. Across these broad categories, resilience is generally applied as a *property of complex systems*, although specific definitions vary substantially.

2.1. Engineering and ecological resilience

Gunderson and Holling (2002, p. 27) argue that engineering and ecological resilience differ based on historically competing perspectives of ecosystems, 'draw[ing] attention to the tension created between efficiency on one hand and persistence on the other, or between constancy and change, or between predictability and unpredictability' (citing Holling, 1973). These contrasts illustrate differing perspectives between systems oscillating around an equilibrium or steady-state and systems as dynamic and able to move between 'regimes of behavior' given the combination of system instabilities and dynamic interactions of external or internal perturbations. The concept of engineering resilience emanates from the former perspective and is defined simply as resistance to disturbance from an equilibrium system-state (Gunderson and Holling, 2002). Quantifications of this distance from an equilibrium state as well as return time to this state often serve as empirical measurements or modeled predictions of the property of resilience in systems investigated under the assumptions of a stable-equilibrium paradigm (Pimm, 1984; Angeler and Allen, 2016).

In contrast, ecological resilience as posited by Holling (1973) describes the capacity of a system to absorb disturbance and still maintain similar structure, function, and feedbacks. Ecological resilience incorporates the idea that no single equilibrium state exists for any given system, but instead, systems exist across multiple regimes of structure and function at different times based on changing configurations of system controlling variables. Each of these regimes has an associated level

Table 1
Framing of key resilience concepts in social-ecological systems and geomorphology research.

Resilience concepts	Social-ecologial resilience definition	Geomorphology examples
Scale	Scale 'refers to the spatial extent and temporal frequency' of a specific configuration of social and ecological processes, structures, and function (Angeler and Allen, 2016). Generally, smaller spatial scales are the locus of faster processes, slower processes emanate from broader spatial scales, and both act upon nested SESs in different ways depending on the internal dynamics of the focal scale in SES research (Gunderson and Holling, 2002).	Scale in geomorphology generally refers to the spatial area and span of time over which process rates occur and influence pattern (cf. Schumm and Lichty, 1965; de Boer, 1992). Geomorphic systems are often considered hierarchically nested complex systems, which can have scale-dependent or scale-invariant properties (Church and Mark, 1980; Hallet, 1990). Depending upon scale, variables may be considered either dependent or independent; and the relative importance of time on geomorphic systems may vary (Schumm and Lichty, 1965), an idea that relates to the notion of fast and slow variables (Thorn and Welford, 1994).
Feedbacks	Feedbacks arise from interactions between social and ecological aspects of the system: biophysical processes, abiotic structure, species, human actors, and social or economic processes. Feedbacks further influence the system aspects that gave rise to the feedback; positive feedbacks amplify the interaction, negative feedbacks dampen (Walker and Salt, 2012).	Feedbacks between mass and energy underpin geomorphic systems. Concepts of dynamic equilibrium (Gilbert, 1877) and grade (Mackin, 1948) are based on feedbacks between stream power and denudation to which river channels adjust. Feedbacks between biota and geomorphic systems are also ubiquitous (Corenblit et al., 2011). Self-reinforcing (positive) feedbacks can create instabilities in geomorphic systems (cf. Phillips, 2003), while negative feedback is essential to maintain their dynamic equilibrium.
State or regime	A system *state* is a system configuration defined by a unique set of processes, structure, function, and feedbacks. Some authors differentiate between state and regime by describing a *regime* as 'processes and feedbacks that confer dynamic structure to a given state of a system' (Angeler and Allen, 2016); however, it is difficult in practice to disentangle an SES regime from its state, and often they are considered together for research purposes and data collection. A regime is a dynamic trajectory over time, but oscillates within what could be considered the *bounds* of a system state.	Clear definitions of the concepts of state or regime are difficult to find in geomorphology. Concepts including equilibrium, dynamic equilibrium, and steady state are more common and much debated (cf. Thorn and Welford, 1994). *Steady states* (sensu Ahnert, 1994) may persist at large spatial scales (e.g., that of mountain ranges) if boundary conditions (e.g., base level, weathering, uplift) remain constant. In this case, the *state* could be considered a dependent variable indicating the time-independent form of the whole system (e.g., average gradient or regolith depth), which remains constant at that scale (Ahnert, 1988). *Dynamic equilibrium* (sensu Gilbert, 1877), despite other uses, relates to negative feedbacks 'between the process components of the system' (Ahnert, 1994, p. 125). These feedbacks cause geomorphic systems to oscillate around a central tendency or mean value. In this case, the state could be defined by the *process components* (or system variables; e.g., stream power and denudation) that feedback and tend the system toward the mean value (i.e., the *attractor*). Geomorphic systems may exhibit multiple equilibria (attractors) between which they can alternate. These have been referred to as *multiple stable states* (e.g., Marani et al., 2010); however, depending on scale and the definition of *state*, these may represent multiple equilibria within a single system state or multiple fundamentally different system states.
Nonlinearity, thresholds, and regime shifts	Thresholds are essentially system tipping points at which the processes and feedbacks that keep a system in one regime alter fundamentally and the system shifts abruptly to a new regime defined by a new configuration of processes and feedbacks; the system takes on a new identity (Scheffer et al., 2001; Walker and Salt, 2012; Angeler and Allen, 2016).	Because geomorphic systems are underpinned by the laws of physics and the interaction between mass, energy, and force, it is difficult to imagine a threshold that fundamentally changes the processes and feedbacks as in SESs. However, geomorphic thresholds exist (Schumm, 1973). These have been defined as 'fundamental bifurcations in geomorphic systems' (Phillips, 1992, p. 223) that represent a transition from one equilibrium to another. For example, river channels in the same substrate, shift planform from straight, to meandering, to braided, at critical *threshold* slopes (Schumm, 1973). Thus, thresholds can exist in slow variables of geomorphic systems that, when crossed, fundamentally change the physical form of the system without changing the underlying processes and feedbacks that govern the system.
People as parts of the system	The idea that humans and human actions are inextricably linked to biophysical processes and outcomes (and vice versa) on this planet (Berkes and Folke, 1998). This is often coupled with the concept that isolating either human activity or biophysical processes for research purposes can negate critically important feedbacks necessary to understand system function and govern or manage systems for sustainability (Berkes et al., 2003). This idea is the basis for the SES concept—human activity influences biophysical processes and events, and biophysical processes and events influence human actions (reactions, decision making).	Geographers have long considered humans as agents of landscape change (Sauer, 1925) and, more recently, explicitly considering humans in geomorphological research has been advocated (Wilcock et al., 2013; Ashmore, 2015), a view that reflects people as coupled parts of geomorphic systems that have coevolved over time. Geomorphic systems can also exert great influence on humans living within them; for example, floodplains provide extremely fertile lands for cultivation (Verhoeven and Setter, 2009), whereas salinity and erosion can heavily impair agricultural production (Pitman and Läuchli, 2002; Montgomery, 2007). Thus, humans affect geomorphic change, and geomorphic change affects humans.

of resilience to shifting into an alternative regime. Disturbances, internal and external to the system in scale, can weaken or exceed system resilience causing a regime shift to a different, yet stable regime. In this context, ecological resilience as a property of complex systems is also highly influenced by the internal dynamics of a system, not just by perturbations. Further conceptualization of this phenomenon has been made accessible by Holling's (1986) adaptive cycle heuristic and has been described countless times in the resilience literature. Chaffin et al. (2016) described it as such:

[systems] go through sequential phases of growth, senescence, collapse, and renewal (Gunderson and Holling, 2002). The initial phase of rapid growth is characterized by increases in structure, connectivity, and complexity. Over time, systems mature and enter a conservation phase, when the system becomes overconnected, less flexible, and more vulnerable to disturbances, hence less resilient (Holling, 1986). External disturbances or minor variations can generate a sudden release of accumulated capital or structure. Following this collapse or release, the system reorganizes, and a new system

configuration emerges. The emergent trajectory can be similar to the prior system or quite different (e.g., undergone a regime shift). This pattern of rapid, then slowing growth, swift destruction, and reformation, has been observed in many systems… (p. 402).

To compound these dynamics of resilience, complex systems are nested and cross-scale interactions from smaller and larger scales relative to the system of interest can play formative roles during periods of collapse and reorganization. Large- and small-scale disturbances as well as large-scale system memory/capacity and small-scale innovation can have significant impacts on the trajectory of a reorganizing system (Gunderson and Holling, 2002; Chaffin and Gunderson, 2016). Attempts to measure the property of ecological resilience across complex systems amounts to attempts to measure the persistence of system-controlling variables, including processes, parameters, and important feedbacks, when the system is exposed to varying degrees of disturbance (Folke, 2016).

2.2. Community resilience

The term *resilience* has also enjoyed a robust home in the social sciences over the years, predominantly in the psychology and social psychology literature (e.g., Masten et al., 1990), although definitions of resilience more recently applied in environmental social science research have been strikingly contested (e.g., Brown, 2014). Several scholars cite Timmerman (1981) as among the first to integrate Holling's (1973) concept of ecological resilience (at least in part) in social science research to explore the resilience of human communities to the impacts of climate change (Klein et al., 2003; Eakin and Luers, 2006) and in so doing linked the term *vulnerability* to resilience. Adger (2000, p. 348) defined social vulnerability as the 'exposure of groups of people or individuals to stress as a result of the impacts of environmental change' and social resilience as the capacity of these individuals or communities to cope with that stress. This definition emphasizes the potential adaptability of groups of humans, and this type of resilience can be measured in terms of human ability (as opposed to systemwide capacity) to cope with changing social-ecological contexts and to mitigate uncertainty. Although highly dependent on social and institutional factors, social or *community resilience* is inherently linked with ecological resilience; resilience of communities to regime shift (often irreversible changes in livelihood, economics, settlement, etc.) may be enhanced by supporting resilience of ecosystem resources and processes depended upon by communities (Adger, 2000). Community resilience suggests, however, that strengthening social elements such as social networks, leadership capacity, knowledge, skills and learning, diversified economies, trust, and people-place relationships can enhance not only human resilience to disturbance, but also overall social-ecological system resilience in resource-dependent or resource-impacted communities (Berkes and Ross, 2013).

2.3. Social-ecological resilience

The concept of social-ecological resilience follows the development of the concept of SESs—systems on Earth (at many, if not most scales) that include biological, physical, and social structures and processes are inextricably linked; and any attempt to decouple those systems for research or management purposes runs counter to the principles of complex systems, and thus may yield less useful results such as disparate knowledge and ineffective management strategies (Berkes and Folke, 1998; Berkes et al., 2003). Social-ecological resilience emphasizes the dynamics of SESs as complex and adaptive but explicitly layers a human element of environmental governance—collective human agency that increases (or decreases) system resilience, i.e., the potential that disturbances can be mitigated or adapted to or that systems can be forcibly transformed to new regimes of function (Chaffin et al., 2016). While still based on resilience as a valueless, emergent property of complex systems, social-ecological resilience additionally introduces an emphasis on navigating the complexity, uncertainty, and change in coupled systems—in other words, society's ability to manage system resilience in a human-dominated biosphere (Berkes et al., 2003; Olsson et al., 2006; Steffen et al., 2007; Cumming et al., 2013). Social-ecological resilience highlights that SESs can learn, self-organize, and adapt and that these processes are subject to human agency (Carpenter et al., 2001; Berkes and Ross, 2013). In terms of societal governance of biophysical processes, a social-ecological resilience perspective conflicts with the desire for stability in systems and instead embraces inherent uncertainty and the need for management flexibility (Folke, 2016).

Often in the definitions of engineering and community resilience, the property of resilience resonates normatively (i.e., a positive value judgment of resilience, being *resilient* is a good thing). The ability of a system (human and biophysical) to return to an equilibrium state or the ability of a society to persist through adaptation to disturbance and change can be labeled as a desirable quality. Ecological resilience and social-ecological resilience instead emphasize that resilience is a valueless, non-normative property of complex systems—resilience as the capacity of a system to withstand disturbance while still maintaining structure, function, feedbacks, and basic system identity. In this case, the property of resilience is not good or bad, but instead the regime of a given system may be labeled by humans as desirable or undesirable. The normative value here should be placed on the regime, not on resilience; through environmental governance, society aims to strengthen resilience of systems in desirable regimes and weaken resilience of systems in undesirable regimes, potentially causing a regime shift in a system that governance actors (hope to) direct toward a more desirable (e.g., sustainable) regime. This definition of resilience helps to remind us that the property of resilience is not what should be contested in scholarship, but instead the nature and contexts of the current regime, and to whom it provides benefits and of whom it marginalizes (Cutter, 2016).

3. Resilience and geomorphology in the literature

The various concepts that underscore resilience are not uncommon in the geomorphology literature, nor is geomorphology an uncommon concept in the resilience literature (Table 1). In the past two decades, the number of publications explicitly referring to resilience and geomorphology has increased (Fig. 1), likely reflecting the increase in popularity of resilience and related concepts such as SESs. A total of 101 publications were returned from an unfiltered *Web of Science* search for 'resilien* AND geomorphology' in the topic field (search date 14 March 2017), with the earliest published in 1995. We were able to obtain 90 of these publications, which were reviewed to determine the relative focus on resilience or geomorphology (using the frequency of occurrence of the terms 'resilience/resiliency/resilient' and 'geomorphic/geomorphology/geomorphologist' within each manuscript as proxies), as well as the definition under which resilience concepts were applied in each study.

Applications of engineering, ecological, community, and social-ecological resilience appeared in the 90 manuscripts reviewed. The most frequently used of these four definitions was that of ecological resilience, which was adopted in a total of 41 (46%) of the manuscripts. Most of these focused on change in the biology of an ecosystem, with geomorphology considered as a physical determinant of ecosystem resilience (e.g., Thapa et al., 2016). Few, however, applied the concept of ecological resilience to the geomorphology of a system; for example, identifying geomorphic phenomena that enable successful restoration (by increasing resilience) of coastal dunes (Walker et al., 2013) or through the creation of modular physical habitats that alleviate risk in river deltas (Kemp et al., 2016). The difference in the latter two examples is a focus on geomorphic change rather than biological or ecohydrological change. In contrast, when resilience is specifically applied to geomorphic changes within a system, engineering resilience

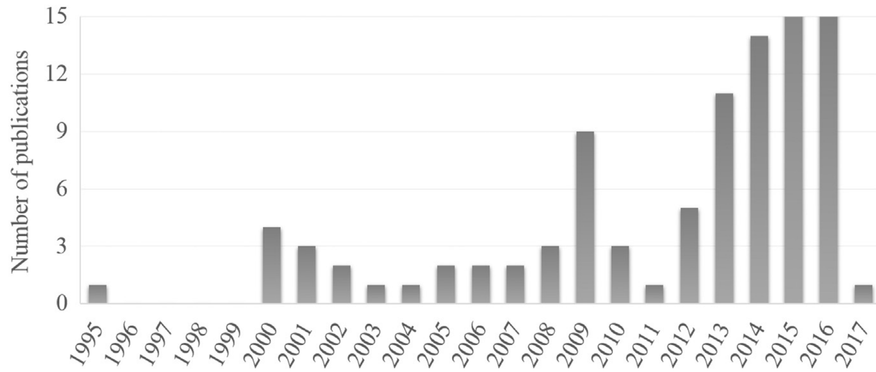

Fig. 1. Number of publications by year returned from an unfiltered *Web of Science* search for 'resilien* AND geomorphology' in topic on 14 March 2017 (total = 101).

appears the most appealing of the definitions to geomorphologists, being applied in 14 (16%) of the studies reviewed, perhaps because of the traditional core geomorphological notion of dynamic equilibrium (sensu Gilbert, 1877) and the time taken for a system to return to this balance of mass transfer following a disturbance (Phillips, 2009). An illustrative example of this is the time taken for river channels to stabilize following the construction or removal dams (Costigan et al., 2016). Community and social-ecological resilience definitions were applied in only 6 (7%) of the reviewed studies, each. These focused mainly on resilience to natural disasters in geomorphic systems; for example, beach-dune complexes and natural levees buffering coastal communities from cyclonic storm surges (Islam et al., 2016); or, although less tragic but often as socioeconomically disastrous, shifts in land surface states upon which societies have become dependent (Streeter and Dugmore, 2013). Although the remaining 27 (30%) of the manuscripts reviewed used the term *resilience* ambiguously, three of the publications reviewed clearly defined multiple types of resilience within a geomorphological context (Scopélitis et al., 2009; Wohl et al., 2014; Carle and Sasser, 2016). Such clear examples of resilience in geomorphology underpin our argument that integrating the two scientific avenues will greatly improve governance of Earth surface systems.

The frequency of the terms *resilience*/*resiliency*/*resilient* and *geomorphic*/*geomorphology*/*geomorphologist* in the reviewed literature ranged from 0 to 110 and 0 to 184 respectively (title and keywords not included in count). Although manuscript length varied greatly, patterns in the relative focus on resilience or geomorphology were evident. Most studies were clearly focused on either resilience *or* geomorphology (Fig. 2, indicated by the spread of points from the origin toward either the top left or bottom right), often with the other referred to seemingly as an afterthought. For example, several publications included the word *resilience* or *geomorphology* in the keywords or even the title, with no mention again throughout the manuscript. In such cases, the concept of resilience is likely being abused as a *buzz-word*, which is discouraging given our argument for its relevance to research on geomorphic systems. However, five publications in particular provided thorough reference to resilience (based on various definitions) *and* geomorphology (Fig. 2, top right), suggesting that value exists in integrating social-ecological resilience and geomorphology for improved governance of these systems.

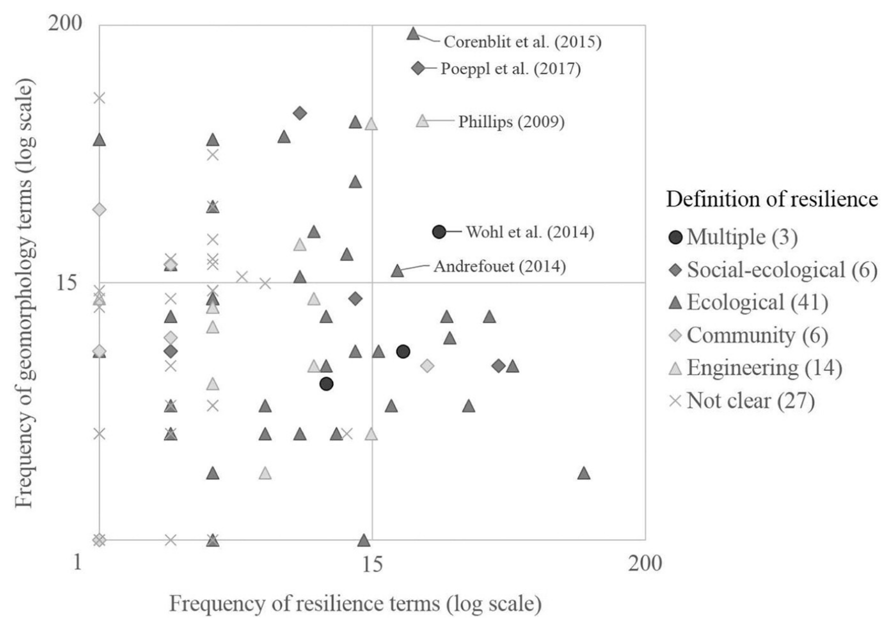

Fig. 2. Frequency of occurrence of 'resilien* and geomorph*' terms in the 90 manuscripts reviewed, shown on a logarithmic scale. Citations are provided for five papers that gave thorough reference to resilience and geomorphology (Andréfouët, 2014; Corenblit et al., 2015; Phillips, 2009; Poeppl et al., 2017; Wohl et al., 2014) (please see supplemental material for a complete list of references used in this analysis). Note: numbers of publications using each definition of resilience described above (shown in parentheses) do not sum to 90 because some used multiple definitions.

A deeper review of the literature reveals that applications of resilience in geomorphic systems are ubiquitous. As terms such as *hillslope*, *landslide*, *floodplain*, *river*, and *coast* are added to the search, along with *resilience*, thousands of publications appear (Table 2). Undoubtedly, even more studies that are not returned in such a search have considered aspects of social-ecological resilience in geomorphic systems, albeit unwittingly or inexplicitly. Although resilience is clearly an important concept in geomorphic systems (and thus in geomorphology research as well), it is overwhelmingly applied to individual case studies in isolation—often following a particular event in a particular geomorphic system—without recognition of its relevance to geomorphic systems in general. Thus, explicit integration of social-ecological resilience concepts in geomorphic systems remains limited. We posit that social-ecological resilience is relevant for much geomorphological research in the Anthropocene, particularly with the goal of sustainability. In the next section, we highlight key themes common between social-ecological resilience and geomorphology and discuss why and how these might be integrated in future research to guide environmental governance.

4. Guidance for integrating social-ecological resilience in geomorphic research

Although various applications of resilience and associated concepts appear often in published geomorphology research to date, we feel it important to draw explicit links between foundational aspects of *social-ecological resilience* inquiry and geomorphic inquiry in order to strengthen the impact of both lines of research, independently, and collectively as interdisciplinary endeavors. We aim here to build on calls such as Murray et al.'s (2009) argument for a new Earth-surface science discipline embracing complexity theory as an organizing concept, and calling for the substantive involvement of physical, biological, and social science disciplines in addressing grand challenges at the Earth-surface nexus. Arguably, however, the social science disciplines—although increasingly mentioned in contemporary calls for advancing interdisciplinary Earth science (e.g., Werner and McNamara, 2007; Ashmore, 2015)—are often only a footnote because of the inherent difficulties in reconciling disparate epistemologies and approaches to data collection, analysis, and interpretation. Embracing social-ecological resilience in geomorphology research, we argue, provides an explicit opportunity to further integrate qualitative and quantitative social science data and data analysis techniques, beyond the strictly quantitative techniques such as agent-based modeling that have been most appealing to biophysical scientists to date (Janssen et al., 2000; Hare and Deadman, 2004; Werner and McNamara, 2007). While quantitative datasets are more easily translated for interdisciplinary analysis across biophysical and social sciences, these approaches are often limited in their explanatory power; qualitative social science approaches can increase the meaning, context, and usefulness of quantitative data. In addition, social-ecological resilience provides more common ground between geomorphologists and social scientists than do other conceptualizations of resilience such as community resilience. Through our review of the above referenced literature, we selected five salient themes (see Table 1) that connect social-ecological resilience and geomorphological research, and below we employ these to highlight opportunities for geomorphologists to productively engage social-ecological scientists (and particularly social scientists) in social-ecological-*geomorphic* lines of inquiry.

Table 2
Results of a sequential literature search for resilience in different geomorphic systems on *Web of Science*, 14 March 2017.

Search order	Search parameters	Number of unique additional results	Cumulative number of publications
1	TS = (geomorphology AND resilien*)	101	101
2	TS = (hillslope* AND resilien*)	33	134
3	TS = (landslide* AND resilien*)	112	246
4	TS = (floodplain* AND resilien*)	233	479
5	TS = (river* AND resilien*)	1510	1989
6	TS = (coast* AND resilien*)	2037	4026

4.1. Scale

Issues of scale resonate strongly across social-ecological resilience and geomorphology research. Hierarchy theory is often applied in geomorphology as a mechanism for understanding scalar interactions within and across geomorphic, ecological (Dollar et al., 2007), and social systems (Werner and McNamara, 2007). Social-ecological resilience explicitly recognizes that these hierarchical scales are also nested; system function and identity at one scale is not possible without interactions from above and below. Application of this concept—panarchy (Gunderson and Holling, 2002)—to geomorphic systems is a fruitful area for further theoretical and empirical exploration of interacting system variables and processes across scales within geomorphology and social-ecological resilience scholarship (e.g., Thapa et al., 2016). In addition, identification of the role of key state variables and processes as they relate to scale across social, ecological, and geomorphic hierarchies helps to determine the influence of fast and slow variables to the resilience of a system or its governance; generally fast variables operate at small scales (e.g., stream reach, species, household) and slow variables at larger scales of organization (e.g., drainage basin, ecosystem, nation state).

For example, take the large investments that have been made by local, state, and national-scale agencies around the world in pursuit of river restoration goals. Despite the magnitude of investment, these efforts can fail to achieve biophysical and social goals when the importance of scale is not recognized. Matheson et al. (2017a, 2017b) recently demonstrated that government agency efforts to reintroduce large woody debris into the Barwon-Darling River, Australia, was ineffective at recreating 'reference' hydraulic habitat to improve native fish abundance and diversity at the reach scale. The authors hypothesize that limited cognizance of site-scale geomorphic and hydraulic characteristics of large wood, as well as catchment-scale conditions, contributed to the failure to achieve reach-scale restoration objectives. Increased awareness of scale during the planning and framing phases of these restoration efforts may have helped the agency to achieve more effective outcomes. On the other hand, a social-ecological resilience perspective suggests that the implementation of adaptive management—structured decision-making processes for implementing and adjusting *experiments as policy*—may have been a more appropriate approach to these restoration projects, and one that could have detected the importance of scale issues earlier on (Allen et al., 2011).

The challenge for interdisciplinary research between geomorphologists and social-ecological scientists is determining scales that align research questions and approaches between disciplines, but also scales that align research with relevant governance challenges. What is the appropriate, or *focal* scale for sociogeomorphic research questions with direct implications for building more sustainable systems? Huitema et al. (2009) discussed the *bioregional scale* as the best fit between an environmental issue of interest and the institutional system with the most capacity to affect change with respect to governing that issue or the interconnected social, political, and economic forces. In geomorphology, the bioregional scale for coupled research might correspond with the institutional scale most relevant for addressing the dominant geomorphic process driving socioeconomic vulnerability, which could be a basin scale in terms of flood risk, a municipal scale in terms of settlement patterns that incur landslide risk, or the scale of a regional authority (e.g., county in the U.S.) for coastal hazards. A good example of this institutional-environmental fit in the SES literature is the creation of institutions at an international scale to address illegal fishing in the south seas of the Pacific (Österblom and Folke, 2013).

4.2. Feedbacks

A better understanding of feedbacks in human-geomorphic systems is essential given the nature of uncertainty brought on by global patterns of change that define the Anthropocene. Specifically, however, we see an opportunity to better identify and articulate the coupled, two-way, human-geomorphic interactions that are the most pronounced, widespread, and impactful to humans (socially, culturally, economically) and to geomorphic processes worldwide. Social-ecological resilience framing helps researchers ask questions about potential traps in these interactions (i.e., feedbacks that reinforce degradation of geomorphic or social processes toward potential regime shift) (Gunderson and Holling, 2002). Werner and McNamara (2007, p. 399) stated that these 'types of dynamics [interactions, feedbacks] for which the effects of human-landscape coupling could spread and become pervasive… have not been extensively studied.' They suggested that strong coupling will be pervasive at scales (SESs) where the system is dominated by geomorphic processes (e.g., fluvial, oceanic, or atmospheric) that make the landscape vulnerable to change on human timescales; and at the same time social and market forces assign value to these landscapes, often driving up land prices, and instead of deterring vulnerable development, incentivize investment in societal protections such as engineered infrastructure or financial insurance from inevitable geomorphic events (e.g., developed coastlines). On the other hand, social and market forces could also serve to decrease the value of lands dominated by acti geomorphic processes, but these same forces may push marginalized populations to occupy these lands as the only affordable option, increasing human vulnerability, social injustice, and proliferating unsustainable settlement patterns and structuralized poverty (Werner and McNamara, 2007). This last example is a typical problem in highly populated mountain communities (e.g., South American Andes) where landslides pose serious natural hazards to human settlements (Alcántara-Ayala, 2002). The balance of shear strength and stress that determines hillslope stability can be disturbed by biophysical and anthropogenic factors such as groundwater use, fire, earthquakes, vegetation (or removal of vegetation), road construction, and development such as construction or mining (Sidle et al., 1985).

Investigation of these human-geomorphic feedbacks presents an opportunity for geomorphologists to contribute to the governance of complex SESs. Understanding geomorphic processes is an essential aspect of measuring or estimating the resilience of an SES regime (see Angeler and Allen, 2016). Facilitating a better understanding of the explicit role of geomorphic processes in either strengthening or eroding the resilience of an SES regime (by altering dynamic interactions and feedbacks) can provide opportunities for governance to support processes that strengthen resilience of desirable regimes or to undermine these processes when a regime shift is societally desirable. Geomorphologists can and should play a leading role as actors in this paradigm shifting approach to environmental governance.

4.3. State or regime

Despite the contested definitions of state (or regime) in geomorphology, defining the parameters, bounds, or relative identity of a geomorphic system is useful for distinguishing trajectories of potential change. Defining equilibrium, or the oscillation around an attractor, is one method of beginning to parameterize a state or regime in geomorphology. Definitions of equilibrium—or more specifically, dynamic equilibrium—are likely as debatable as those of resilience (cf. Thorn and Welford, 1994). The distinction between multiple equilibria within a single system state versus multiple equilibria as fundamentally different states in geomorphology is an important ongoing debate and should be explored further, theoretically and empirically.

A clear definition, however, may not matter in the context of SES governance. The state or regime of an SES is defined by a particular combination of variables, processes, their interactions, and associated outcomes. Geomorphic processes play a role in these regimes and perhaps even a dominant one in some cases. But in terms of governance of SESs toward sustainability, processes that mediate competing human values (social, political, and economic processes) often determine pathways or trajectories toward desirable states or regimes. From this point, one could simply (or perhaps lazily) conclude that social processes alone, not geomorphic process, dictate the important structures, functions, and feedbacks that society chooses to maintain or undermine in SESs (for human benefit e.g., resource extraction, flood control, land stabilization). Instead, we argue that society needs to be more cognizant of geomorphic processes when determining desired future states or regimes for SESs because geomorphic processes can negatively feedback on society (i.e., destruction of infrastructure, loss of human life, disaster) if critically undermined. Alignment of the concepts of states or regimes across social-ecological resilience and geomorphology is not so much about a synergistic explanatory framework, but instead about recognizing the spatial and temporal influence (and often dominance) of geomorphic system variables and how they align or conflict with societally desirable trajectories. A good example of this is the importance of free-flowing river networks for buffering flood disturbances at the catchment scale (Moore et al., 2015); alterations at any subscale within the river network have the potential to alter the overall flood regime at the catchment scale.

4.4. Nonlinearity, thresholds, and regime shifts

Geomorphologists and SES scholars seem to agree that thresholds exist in systems and are associated with regime shifts that result in changes to system form or identity. Examples include river channel form change from straight to meandering; the transformation of a forest- to a grassland-dominated watershed; or the urbanization of historically rural agricultural or pastoral watersheds. While we recognize that geomorphic thresholds and regime shifts—expressed as a sudden change in form or identity—do not necessarily include a change in physical process and function, we also recognize that when interactions between geomorphic systems, biota, and humans are considered, social-ecological thresholds at the scale of a focal system (e.g., a system scale most important or relevant for governance and management interventions) are likely to exist and be critical to achieving sustainability (e.g., Streeter and Dugmore, 2013). Reconciling the definitions of thresholds between geomorphology and SES scholarship ultimately depends on the scale of the system under investigation; in some cases this reconciliation may be impossible but, in most cases, is likely unnecessary. Geomorphic thresholds may be one of just a few key drivers of overall system resilience and, if crossed, may dynamically interact with other critical biological, physical, and social processes on the landscape, yielding a systemic regime shift to a socially undesirable state. Thus, we highlight that in SES scholarship (and specifically in the context of SES governance), thresholds may take on a more value-laden meaning than do thresholds in geomorphology. For example, social-ecological resilience perspectives may emphasize the importance of *not* crossing specific thresholds in the pursuit of global sustainability (Rockström et al., 2009).

The implications of these ideas for governance is also at the heart of linking geomorphologists and social-ecological scientists studying SES dynamics. Geomorphic dynamics are likely one of a few critical driving variables that determine the identity of SESs. Geomorphic thresholds, when crossed, have a high likelihood of altering the internal dynamics of an SES—described above as an SES's position in the adaptive cycle—potentially making that system more vulnerable to external (or additional internal) disturbances. For example, the change in channel form from meandering to straight may signal an increase in flood risk, erosion, and/or downstream sedimentation negatively affecting human activities such as agriculture or disrupting the provision of other ecosystem services provided by the geomorphic form prior to the shift (e.g., water quality, flood control, certain species habitat).

Identifying potential geomorphic thresholds and the subsequent impacts on human communities is inherently an interdisciplinary effort that would benefit from teams of geomorphologists, ecologists, sociologists, political scientists, and economists, among others. Contemporary governance does a poor job at integrating the impact of slow variables and slow onset change. Thus, a better understanding of potential geomorphic thresholds (through historical analysis and modeling) and their coupled impacts on society is an essential first step in defining early warning signals for regime shift at the SES scale through the integration of geomorphic data into human management and planning frameworks (e.g., forest plans, county zoning, city resilience plans) that aim to maintain a desired state in coupled systems.

4.5. People as parts of the system

Recent ideas of zoo-, bio-, eco-, ethno-, and socio-geomorphology—which have been advocated to provide a more complete perspective of the integrated components of geomorphic systems (Butler, 1995; Hughes, 1997; Thoms and Parsons, 2002; Wilcock et al., 2013; Ashmore, 2015)—emphasize the importance of considering living things that impact and are impacted by geomorphic change. A social-ecological resilience perspective recognizes that humans are inextricably linked to biophysical processes and outcomes, but additionally, this perspective offers a structured way of relating geomorphic change to interrelated components (e.g., ecological and social dynamics) of systems at a focal scale that intersects more directly with governance—*societal* governance of systems. This concept cannot be overstated. Although geomorphic processes will continue independent of human interventions, the reality of current (and rapidly growing) population levels and distribution is that human actions will continue to influence how geomorphic processes act on the landscape, and geomorphic processes will continue to influence the societal enterprise. Without recognition of this, the most visible impact of geomorphic processes on society may likely continue to be in the form of loss and damage.

We encourage geomorphologists to collaborate with SES scholars, particularly social scientists, as a means of explicitly recognizing this interconnection between people and geomorphic change. Social scientists such as sociologists, anthropologists, and human geographers employ robust methods of data collection and analysis that can reach into the written and unwritten records of the human experience to reveal past geomorphic conditions and associated but long-forgotten methods of societal adaptation. Contemporary geomorphology research coupled with the present needs of vulnerable human communities can potentially create pathways for valuing geomorphic information in more real-time governance decisions in arenas such as river management, zoning, and disaster preparedness and response. Employing social-ecological resilience concepts as a unifying frame for working together on different disciplinary research questions, but within the bounds of a common geography or system, would be a nontrivial step toward integration of social science and geomorphology for finding sustainability outcomes. We are certain that much of this work is already underway at various scales across the globe; we hope that geomorphologists will begin to explore these applications more actively in the literature. An additional step in this direction could include the identification and description of adaptive cycles of geomorphic and human systems as a means to guide coupled research and governance of linked systems.

5. Conclusion

The foundations for applying social-ecological resilience concepts to geomorphic systems largely exist (see Table 1). Our goals for encouraging the further exploration of this integration are twofold. First, we hope to encourage interdisciplinary approaches to geomorphology research that recognize and incorporate (i) the complex, often nonlinear processes of individual and collective human agency that can drive regime shifts and threshold dynamics in SESs, and (ii) the understanding that SESs can be significantly impacted by unforeseen and often powerful feedbacks from geomorphic systems and processes. A major question for geomorphologists, social scientists, and hybrid, social-ecological scientists to continue to wrestle with is, *at what scale or scales should research be focused to best explore human-driven and geomorphic-driven regime shifts*? This will depend greatly on the nature and degree of coupling in these systems, for example: how dependent is society on particular resource uses within a system (including ecosystem services); how resilient are human and geomorphic components to sudden disturbances and the interaction of slow drivers of change; and what are the current governance trajectories of the system? Additionally, are governance actors actively pursuing desired regimes of sustainability that include a recognition of abrupt and gradual geomorphic changes?

Second, we hope to leverage this type of inquiry to enhance science-to-policy pathways for socio-geomorphic information. By actively promoting geomorphology research questions and results in interdisciplinary venues as a critical aspect of understanding dynamic SES regimes, we foresee an opportunity to better understand how geomorphic processes contribute to or detract from systemic resilience, alone and through dynamic, variable interactions. While scientific knowledge by itself does not always result in desirable policy or policy change, embedding geomorphologists familiar with social-ecological resilience into positions of potential influence at multiple scales of governance (e.g., government agencies, scientific advisory committees, land use planning entities, as well as international academic and development-oriented sustainability initiatives) will undoubtedly lead to a more strategic integration of geomorphic information as both (i) part of critical calculations for limiting or expanding resource use or protection, and (ii) as indicators of threshold dynamics and potential regime shifts in SESs. Geomorphology research and information can and should play a more central role for determining biophysical intervention points for either strengthening or weakening resilience of an SES in the societal search for sustainability.

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Appendix A. Supplementary data

Complete list of manuscripts analyzed for a frequency of occurrence of 'resilien* and geomorph*' terms (analysis performed March 2017).

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