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Editorial

Bio-geomorphology and resilience thinking: Common ground and challenges

Martin C. Thoms [a,*], Kimberly M. Meitzen [b], Jason P. Julian [b], David R. Butler [b]

Riverine Landscapes Laboratory, University of New England, NSW, Australia
Department of Geography, Texas State University, San Marcos, USA

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ABSTRACT

Geomorphology plays a fundamental role in shaping and maintaining landscapes, as well as influencing the social and ecological systems that occupy and utilize these landscapes. In turn, social-ecological systems can have a profound influence on geomorphic forms and processes. These interactions highlight the tightly coupled nature of geomorphic systems. Over the past decade, there has been a proliferation of research at the interface of geomorphology and resilience thinking, and the 2017 Binghamton Symposium brought together leading researchers from both communities to address mutual concerns and challenges of these two disciplines. This paper reviews some of the key intersections between the disciplines of bio-geomorphology and resilience thinking, and the papers presented at the symposium. The papers in this volume illustrate the current status of the disciplines, the difficulties in bridging the disciplines, and the issues that are emerging as research priorities.

1. Introduction

Geomorphology has a long history of intellectual exchange with many disciplines, including ecology (Renschler et al., 2007), engineering (Brierley and Hooke, 2015), geology (Morisawa and Hack, 1984), philosophy (Rhoads and Thorn, 1996), physics (James et al., 2012) and restoration science (Montgomery, 2006). Many of these interactions have been the focus of previous Binghamton Geomorphology Symposia (cf. Wohl et al., 2017), and have led to both conceptual and methodological advances in the field of geomorphology (Kondolf and Piegay, 2003). Integrating disparate disciplines, with different research paradigms, priorities, methods, approaches, and metrics of success is a fundamental challenge in many scientific disciplines (Dollar et al., 2007). This is particularly true in bridging the discipline of geomorphology and the concept of resilience thinking, despite the many intersections between the two (cf Thoms et al., this issue). Geomorphic processes occur in parallel with ecological (abiotic and biotic) and social systems, with all three operating at a range of spatial and temporal scales; collectively influencing, and being influenced by each other. The strong coupling between ecological and geomorphological systems frames the concept 'bio-geomorphic systems', and in the context of human and other environmental interactions, collectively the three can be linked through the emerging paradigm of social-ecological systems. These interactions should ensure, one would think, a high degree of mutual dependency between the study of bio-geomorphic systems and a resilience thinking approach to the natural environment, and social-ecological systems in particular.

* Corresponding author.
E-mail address: Martin.Thoms@une.edu.au (M.C. Thoms).

Societies have, and continue to evolve and adapt in the context of bio-geomorphic processes. Examples include, but are not restricted to, responses to extreme flood events (Meitzen et al. this issue), cultural adjustments to soils and land cover changes (Beach et al. this issue), and risk related responses to delta formation and sea-level rise (Tessler et al., this issue). Although societies have positively responded to bio-geomorphic events, it is not always the case (cf. Chafin and Scown, this issue). We contend that the sustainability of natural and human systems is reliant on an increased understanding of landscapes, and the processes that form them over multiple scales. Predicting future states of the Earth's landscapes and ecosystems, and developing effective management and restoration practices requires an understanding of complex social-ecological systems (cf. Kondolf and Piegay, 2011). This imperative has increasing emphasis especially in a period of rapid change and heightened uncertainty. Appreciation of how environmental forces drive biological and human systems, and how humans are increasingly driving the destabilization of geomorphic systems is gaining prevalence in the Anthropocene.

The 2017 Binghamton Geomorphology Symposium (BGS), held in San Marcos, Texas, USA, focused on the topic of Resilience and Bio-Geomorphic Systems, and the papers in this volume were presented and discussed at the symposium. The goal of the symposium was to review, synthesize, and discuss case studies and conceptual paradigms at the intersection between geomorphology, bio-geomorphology, and resilience, as well as to identify emerging issues in order to expand future research in geomorphology. In this paper, we briefly describe the scientific background and rationale for the 48th BGS on Resilience and Bio-Geomorphic Systems, summarize the contributions of the BGS, and examine emerging issues.

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2. Why bio-geomorphology and resilience thinking? A rationale for the symposium

Resilience is the amount of change a system can undergo (its capacity to absorb a disturbance or shock) and remain within the same regime that essentially retains the same function, structure, and set of feedbacks (Walker and Salt, 2006). Resilience thinking has rapidly emerged over the last 30 years in the environmental sciences as a concept that is being used to frame how we approach the study of biophysical systems, manage and set policy for their conservation, and sustainable development. It has been viewed as both an emergent property of systems, and a means by which to navigate coupled natural–human (social-ecological) systems. It seeks to determine how societies, economies, and biophysical systems can be managed to confer resilience; that is, how to maintain the capacity of a system to absorb, adapt or buffer disturbance. Resilience thinking promotes a focus on social-ecological systems; the examination of intrinsic system properties under different process occurring at multiple scales; and the importance of historical place contingencies in order to unravel systems complexities (e.g. Phillips, this issue; Segura, this issue; Rathburn et al. this issue).

Resilience is a heuristic model—one way of viewing an entity in order to understand it. Key to resilience thinking are three concepts: 1) that humans are inextricably linked with the ecosystems in which they live; 2) social-ecological systems are complex adaptive systems; and 3) resilience, or the capacity for a system to absorb disturbance, is key to sustainability (Walker and Salt, 2006). From these concepts, a series of fundamental principles for understanding natural and human modified systems has been put forward (modified from Parsons et al., 2009):

1. Recognition of the potential for alternate stable states to exist within systems.
2. Recognition that system properties can vary significantly within a stable state.
3. System properties can display significant spatial and temporal variability at different scales within a stable state.
4. Thresholds exist within systems and act as tipping points between alternate stable states.
5. Thresholds exist at multiple scales, but not all result in a shift to an alternate state.
6. 'Slow' variables are important in driving regime shifts.
7. Systems cycle through adaptive loops and their position within the loop sets their form and function.
8. Natural systems are essentially social-ecological systems that integrate systems and human society.
9. Managing systems for resilience requires adaptability or the capacity to adapt to and influence change.

Geomorphology is primarily concerned with the formation of the surface of the Earth and how this may change over time and space. Studies of hillslope erosion, chemical denudation, aeolian sediment transport, coastal and fluvial processes, for example, have received much attention. Geomorphology, as a science, was dominated by physical geographers for much of the early 20th century, with the dominant paradigm being the description of landscape forms and their evolution. Geomorphology underwent substantial growth toward a more quantitative discipline in the mid-1900s in which landscape forms were quantified rather than just being described, and a new focus was placed on process. This period was dominated by extensive field campaigns by geographers, geologists, and engineers where insights into landscape patterns and processes were developed via intense observations (e.g., Leopold and Maddock, 1953; Wolman and Leopold, 1957). In particular, the accumulation of quantitative data from varying regions of the world allowed geomorphologists to synthesize landforms into classifications, and also note broad-scale systematic variability in landscape processes and forms and speculate on the probable mechanistic drivers of these patterns.

In the following decades, the discipline of engineering provided tools and methods for quantifying the dynamic processes associated with geomorphic forms, i.e., how landscape changes through time, and eventually numerical models for predicting these changes. Engineering also brought with it a paradigm of experimental modeling, particularly physical scale-modeling experiments (e.g., flumes, soil erosion). Thus, geomorphology incorporated a decidedly robust modeling perspective during the latter decades of the 20th century, leading to the development of a suite of sophisticated reach- and basin-scale models of landscape forms and processes. More recently, geomorphology has greatly expanded the spatial scale of research through remote sensing and Geographic Information Systems (GIS), and integrating insights from other disciplines to more fully understand broader scale external drivers of landscape forms and processes. Examples of this include climate-landscape coupling (Zeng et al., 2010).

The process-based understanding and the numerical models previously developed are now being applied to broad spatial scales allowing geomorphologists to explore landscape processes at the scale of entire continents, and even other planets (e.g. Claussen et al., 1999). Further, integrating insights from other disciplines, such as those from the atmospheric sciences, has promoted an expansion of geomorphology into exploring complexities and feedbacks in and among systems (Brovkin et al., 1998). Thus, geomorphology's development as a discipline provides a rich history of exploring spatial variability in landforms, the timescales over which these landforms adjust, and quantifying the biophysical processes that lead to these landforms. Further, geomorphology, particularly over the past few decades, has proven itself to be an extremely nimble and integrative discipline in terms of informing and being informed by insights from other disciplines (Rhoads and Thorn, 1996). The study of bio-geomorphology is a classic example of this integration. Bio-geomorphology emerged from the interdisciplinary overlaps among biology, ecology, and geomorphology as a means to study the bidirectional influences of geomorphic and biologic processes on each other (Viles, 1988).

The study of geomorphic systems has a long history (Phillips, 1999). Attempts to apply general systems theory to the study of geomorphology, with a view to examining the fundamental basis of the subject, its aims, methods, and implications date back to the 1950's (Chorley, 1962). Seminal works by Von Bertalanffy (1956) on entropy, Schumm and Lichty (1965) on time space and causality, and Schumm (1979) on complex response and thresholds, for example, continue to form some of the foundations of the study of geomorphic systems. This is seen in the more recent works of Phillips (2003, 2007) on the nonlinearity and complexity of geomorphic systems; Mayer (1992) and equilibrium concepts; Renwick (1992) and Tooth and Nanson (2000) with views on equilibrium, disequilibrium, and nonequilibrium; those on spatial variability in geomorphic systems (Magilligan, 1992); and the use of hierarchy theory to view geomorphic (and bio-geomorphic) systems (Parsons and Thoms, 2007). Bio-geomorphic focused approaches create a pathway to linking geomorphology and social-ecological systems by integrating a greater ecosystem framework of feedbacks, interactions, thresholds, and responses.

Bio-Geomorphic systems are fundamental to human wellbeing (Millennium Ecosystem Assessment, 2005). As anthropogenic pressures on these systems increase, the manner in which they are studied and managed is critical for maintaining and improving human wellbeing. The increase in research activities concerned with anthropogenic impacts highlight the extent and magnitude of human impact on landscapes and ecosystems; hence the introduction of the term Anthropocene - the current epoch in which humans and our societies have become a global geophysical force. However, many current practices of landscape and ecosystem management still rely on the assumption of an equilibrium state, where the focus has been on increasing or optimizing efficiency and performance in order to deliver defined benefits, including supply or sustainability (Hillman, 2006; Walker and Salt, 2006). New ideas are required to improve the management and sustainability of global geomorphic systems. Parsons and Thoms (2007) argue such ideas should consider emerging paradigms, like resilience, that move away from notions of optimal efficiency for delivering a defined benefit, and consider geomorphic systems as complex social-ecological systems characterized by variability, heterogeneity, adaptability, diversity, multi-scaled dynamics, change, and innovation in interacting social, economic, and ecological spheres. Problems facing the world's social-ecological systems cannot be solved with the same tools or approaches that partially created them. Although resilience thinking is considered to be a fresh approach to the sustainable management of social-ecological systems in general, we argue this can be substantially improved through an enhanced examination of the foundations of bio-geomorphology.

Strong overlaps exist between the scientific discipline of geomorphology and the concept of resilience, but there is a limited awareness of the foundations of the former in the emergence of resilience. This limits the application of resilience thinking to the study and management of bio-geomorphic systems. A collective examination of bio-geomorphic systems and resilience is an avenue to conceptually advance both areas of study as well as further cement the relevance and importance of understanding the complexities of geomorphic systems in an emerging world of interdisciplinary endeavors and the increasing influence of humans on geomorphic systems.

The 48th Binghamton Geomorphology Symposium focused on the intersections of bio-geomorphology and resilience. It was organized into six sessions, all within the context of resilience thinking: *Geomorphic Systems*; *Extreme Events and Thresholds*; *Eco-Geo Connections*; *Zoogeomorphology*; *Coastal Geomorphology*; *and Social-Ecological Systems*. The Symposium included participation from 90 attendees, including 17 invited speakers, 9 invited posters, 37 participant contributed posters, and was preceded by an all day field trip. Of the participants, 41 belonged to underrepresented groups in geomorphology and the sciences, and many were students, ranging from undergraduates to PhD. Attendees included geographers, geologists, engineers, ecologists, social scientists, and private consultants. Participants travelled to the conference from various locations in the United States, France, United Kingdom, Uganda, and Australia. During the Symposium, attendees participated in several discussions and surveys aimed to elicit what the main issues were in geomorphology and whether resilience thinking could assist in addressing these, and whether the symposium improved an understanding of resilience from a geomorphological perspective.

The field trip took place in the Texas Hill Country and included a variety of environmental and cultural sites that covered different aspects of how we interpret and apply the interacting concepts of thresholds and resilience in social-ecological bio-geomorphic systems. The field trip provided three main examples of these interactions, including (1) bio-geomorphic threshold responses to catastrophic flooding using examples from the Blanco River and community-facilitated recovery of the riparian corridor (see Meitzen et al., this issue); (2) the paradigm shift of social-ecological values transitioning from developing natural resources to restoring them using restoration examples from Spring Lake at Meadows Center for Water and the Environment and the Edwards Aquifer Habitat Conservation Plan for the San Marcos River; and (3) the highly contested removal of the more than 100 year old, hazardous, non-functioning Cape's Dam on the San Marcos River which some argue should be rebuilt for historic preservation and recreational value, whereas another contingent argues for its removal to improve river connectivity and provide habitat for endangered species. Specific details on the Symposium sessions including paper and poster abstracts, and digital field trip guide can be accessed from an archived website: http://www.geo.txstate.edu/about/news/binghamton2017.html.

3. Studies of the integration of resilience thinking and geomorphology

The three-day BGS and resulting Special Issue illustrate how the challenges of understanding the complexity of bio-geomorphic systems are substantial, and as soon as a societal component is introduced, the complexity and challenge escalates significantly. Thus, integrating geomorphology and society, and understanding the intricacies of coupling within social-ecological systems is no trivial exercise, but efforts to do so are all the more important in times of rapid and unpredictable environmental change. The 18 manuscripts presented in this Special Issue complement each other, providing the context for three integrative themes on resilience and geomorphology.

3.1. Theme one: convergent and divergent views in geomorphology and resilience thinking

Many of the principles of resilience thinking are implicit in the study of geomorphology. Geomorphic systems are dynamic, and may experience changes in state in response to multiple external and internal drivers over a range of spatial and temporal scales. Thus the concept of tipping points, system states, trajectories of change, and fast and slow drivers of change, which are common currency in resilience thinking are highly familiar in the study of geomorphic systems. Indeed, they are an essential components of the geomorphologists' tool kit (cf. Kondolf and Piegay, 2003). It is from this basis that Thoms et al. (this issue), argue that resilience thinking can provide additional avenues with which to assess non-linear trajectories of change and divergent responses in bio-geomorphic systems to external disturbances or shocks, and also to extend application of the science on geomorphic systems into the broader domain of social-ecological systems. Some of these concepts are examined by Stallins and Corenbilt (this issue). Using data of coastal dune topographies Stallins and Corenlit construct a model that illustrates how adaptive cycles and panarchies, important building blocks of ecological resilience, can be expressed as a set of hierarchically nested geomorphic and ecological metrics and in doing so advances our understanding of the complexity of bio-geomorphic systems. The concept of resilience explicitly acknowledges the ability of societies to adapt to dynamic environments. Given the recognition of the need to prepare for anticipated and unanticipated shocks, Parsons and Thoms (this issue) propose six elements that need to be considered in the design and implementation of resilience-based policy for river systems. These are (1) the recognition of rivers as social-ecological systems, (2) the science-policy interface, (3) principles, capacities, and characteristics of resilience, (4) cogeneration of knowledge, (5) adaptive management, and (6) the state of the science of resilience.

A key challenge for global sustainability, particularly with increasing uncertainty and rapid change that defines the Anthropocene, is the governance of coupled social-ecological systems. Chaffin and Scown (this issue) discuss social-ecological resilience as a concept of scientific inquiry, and argue it has contributed to new understandings of the dynamics of social-ecological systems by increasing our ability to contextualize and implement governance in these systems. However, they highlight that the importance of geomorphic change and geomorphological knowledge is missing from many processes employed to inform the governance of social-ecological systems. The primary reason for this, they hypothesize, is geomorphological studies tend to focus on the engineering resilience of geomorphic systems, and very few define and employ a social-ecological resilience framework that explicitly links the concept to geomorphic systems. Five key concepts are put forward to strengthen the impact of an integrated geomorphology-resilience based approach and therefore better understand change in, and inform governance of, social-ecological systems.

The emergence of many early civilizations occurred on the floodplains and coastal delta systems of large river ecosystems as a result of the abundant resources they provided. Tessler et al., (this issue) provide an example of the long-term sustainability of coastal deltas as social-ecological systems through the lenses of resilience thinking. In a study of 46 global deltas, they showed that changes to the flux of water, sediment and associated nutrients, over the Anthropocene, are having measureable effects on the biogeophysical functioning, and long-term sustainability of these landscapes for both human and natural systems. In addition, model scenarios of contemporary and future water resource management schemes were used to explore long-term delta sustainability. It is shown that local and regional strategies for sustainable delta management that focus on local and regional drivers of change, especially upstream dam construction and groundwater and hydrocarbon extraction, can be highly impactful in the context of climate change and sea-level rise. Surface water abundance and impairment has substantial repercussions for social-ecological systems, especially in urban settings. In a study that examined the abundance of streams, water bodies, and impaired stream length for 3520 cities in the United States with populations from 2500 to 18 million, Steele (this issue) showed surface water abundance to be a function of both city size and biophysical setting interacting with land cover intensity. These interactions can influence the resilience of urban streams to disturbance, and observations of distinct scaling domains indicate shifts in the organizing processes of cities and the development of resilient urban hydroscapes.

3.2. Theme two: geomorphic system behaviour indicators of resilience

Geomorphic system resilience has been perceived as an intrinsic property of system structure and function (Phillips and Van Dyke, 2016). It is also a system property bounded by geographic context, influenced by historical circumstances, and the scale of observation. This makes it difficult, at present, to generate definitive statements about geomorphic resilience. Seven manuscripts in this Special Issue tackle these issues directly. As a collective they add to the debate of resilience being an intrinsic propriety of systems and that bounded by geographical contexts.

How resilient are landscapes and individual landforms to natural and human disturbances was a common thread to the case studies presented in this theme. Focusing on wetlands in the South African drylands, Tooth (this issue) used geomorphological, sedimentological and geochronological datasets to provide the spatial (up to 50 km^2) and temporal (late Quaternary) framework for an assessment of geomorphological resilience. Findings demonstrate that some wetlands have been highly resilient to environmental change but others have not, with marked transformations in channel-floodplain structure and process connectivity having been driven by natural factors (e.g. local base level fall) or human activities (e.g. floodplain drainage). Key issues related to assessment of wetland resilience include channel-floodplain dynamics in relation to geomorphological thresholds, wetland geomorphological 'life cycles', and the relative roles of natural and human activities. In a similar multiple lines of evidence approach, Beach et al., (this issue) developed a soil landscape model to link accelerated erosion with ancient Maya history, 3000 to 1000 years ago. Using palaeoecological data obtained from sediment cores extracted from a depositional lake basin, and detailed *catena* sequences from across the landscape, Beach et al., were able to follow the sediment cascade through various forest catenas. High spatial variance in the character of catenas suggests areas of high ancient occupation and relatively high impact, and areas of scant ancient occupation and lower impact. Evidence of intense but rudimentary agriculture was found as were areas of ancient Maya forests reserves. The anthropogenically eroded, buried, and terraced slopes have influenced modern tree distributions, with many tree species having strong preferences for ancient Maya altered soil types and topographic situations.

Network-based analyses of system structure were used by Phillips (this issue) to determine the dynamical stability (~resilience) of coastal wetlands. General relationships between relative sea level, wetland surface elevation, hydroperiod, vegetation, and sedimentation were used to determine scenarios of stability or instability. Model results indicate system instability, hence the non-resilience of coastal wetlands. This instability is caused by complex gradients in environmental factors, microtopography, vegetation, and historical contingency. Coastal wetland landscapes can have extensive local variations in stability/resilience and in the key relationships that trigger instabilities. A case study of two coastal wetlands in North Carolina's Neuse River estuary show neither is keeping pace with relative sea level rise, and both show unstable state transitions within the wetland system; but locally stable relationships exist within the wetland systems.

The manuscripts of Abbott et al., (this issue), Rathburn et al., (this issue), and Meitzen, et al., (this issue), provide case studies of the behavior and response of geomorphic systems to various natural and human influences. The interaction of climate, geomorphology, land use, and land cover on catchment sediment production and associated river sediment loads in the Oroua and Pohangina catchments of New Zealand is reported by Abbott et al. (this issue). Using an impressive high-temporal resolution data set of suspended sediment transport, the study shows that large storms which generate extreme runoff and landsliding produce enough sediment to temporarily convert catchments from a supply-limited state to a transport-limited state. Sediment supply was disproportionately high in locations where livestock grazing occurred on steep hillslopes. Timing and intensity of previous storms was also shown to influence the response of the catchments. The methods and findings are suggested to be useful for assessing the resilience of catchments exposed to frequent disturbances such as land use changes and landslides. Keeping with a sediment focus, Rathburn et al., (this issue) determine sediment recovery following disturbances, resulting from wildfires, as a measure of the time required to attain pre-disturbance sediment fluxes, hypothesizing that knowledge of the controls on recovery processes builds understanding of geomorphic resilience. Post-disturbance sediment recovery in three small watersheds in the northern Colorado Rocky Mountains displayed a nonlinear pattern of: initial high sediment flux followed by decreasing sediment fluxes over time. From this study Rathburn et al., (this issue) developed an index of resilience, defined as the sediment recovery/disturbance recurrence interval and suggest sediment recovery and channel form resilience may be inversely related because of high or low physical complexity.

The bio-geomorphic response of the Blanco River (Texas, USA) to a large infrequent flood event is the focus of the study by Meitzen et al., (this issue). Using high-resolution aerial and satellite imagery from the pre- and post-flooding periods, their study mapped and quantified disturbance patterns for a 55-km reach of the Blanco River. Significant disturbance occurred along the entire study reach, and while complete floodplain stripping was greatest in the floodway, lesser forms of disturbance extended well beyond the 100- and 500-year floodplain. Disturbance patterns previously identified in the literature including meander scour, parallel chute scour, convex bank erosion, and macro-turbulent scour were all present following this event, as well as substantial disturbance proximal to tributary confluences. In the aftermath of this event, local community groups have begun a riparian corridor restoration program to supplement the natural passive recovery of the riparian corridor, enabling the system to recover more quickly and be resilient to future flood events.

3.3. Theme three: bio-geomorphic feedbacks and resilience

The interface between the disciplines of geomorphology and ecology has been a highly productive research area over the last decade. The emerging issues of coupled landscape ecology and geomorphic systems, and ecological restoration, identified at the 36th BGS (cf. Renschler et al., 2007) are now well researched areas. However, understanding bio-geomorphic processes through time, at a range of spatial scales, and predicting how these feedback to ecological and geomorphic systems is the key challenge for bridging these two disciplines (Julian et al., 2016). A key component of ecological resilience is to understand feedbacks among components of biophysical systems. Although physically-based explanations of ecological patterns and processes are common, examinations of ecological influences on geomorphic patterns and processes are not. Thus a collection of manuscripts at the 48th BGS considered abiotic-biotic interactions through the lens of resilience.

Animals and plants can significantly modify the structure and function of landscapes. This influence can be viewed as a hierarchy, in which the primary factors (fluxes of water, matter and energy) create a dynamic physical environment that become habitats for animals and plants. The habitat is further modified by animals and plants as they selectively burrow, establish, and build dams on streams, among other activities. Plants and microorganisms living and utilizing resources provided by the habitat influence the distribution and cycling rates of elements like nitrogen and phosphorus as basic population and community processes are carried out. The studies reported by Atkinson et al. (this issue), Corenblit et al., (this issue), Katz et al. (this issue), Stallins and Corenblit (this issue), Fremier (this issue), and Butler et al. (this issue) in this special issue highlight the complexity of abiotic-biotic relationships and how feedback mechanisms influence the resistance, and recovery trajectories of landscapes.

These interactions were illustrated within a riparian corridor through the studies of Corenbilt et al., (this issue), and Hortobagyi et al., (this issue). These studies, undertaken on the Allier River, France, show biotic-abiotic feedback mechanisms that occur between woody vegetation recruiting on alluvial bars are influenced by hydrogeomorphic processes (sediment transport and deposition, shear stress, hydrological variability), and initial fluvial landforms, which in turn are modulated by the establishing vegetation. The aim of their study was to empirically identify the preferential *establishment area (EA)* (local areas where species become established) and the preferential *biogeomorphic feedback window* (*BFW*) (where and to what extent the species and geomorphology interact) of three woody vegetation species on alluvial bars. Results show the EA and BFW of three species vary significantly longitudinally along the alluvial bars as well as transversally. This study highlights the role of functional trait diversity of riparian engineer species in controlling the extent of fluvial landform construction along geomorphic gradients within riparian corridors exposed to frequent hydrogeomorphic disturbances. These complex interactions are also illustrated by Butler et al., (this issue) who use examples of zoogeomorphology - the study of animals as geomorphic agents, to examine the resilience of landforms. Using examples of the interactions between external landscape disturbances and zoogeomorphological agents, Butler et al. (this issue) go on to examine whether zoogeomorphic agents provide resilience to a landscape or instead serve as a stressor capable of inducing a phase-state shift. The examples provided show that exotic zoogeomorphic agents can overwhelm a landscape and induce collapse.

The zoogeomorphic influence of aquatic animals on physical process and patterns within the riverine are shown by Fremier et al. (this issue) to be significant, especially when placed in a longer term context. In this modeling study, the physical influence of salmon spawning on the evolution of river channel long profiles is examined. Using a simple 2D model it was shown that spawning can profoundly influence the longitudinal profiles of stream beds and thereby the evolution of entire watersheds. Furthermore, this modeling study suggests that biological evolution can impact landscape evolution by increasing the sediment transport and erosion efficiency of mountain streams. Moreover, the physical effects of a species on its environment might be a complementary explanation for rapid adaptive radiation events in species, through the creation of new habitat types. This example provides an illustrative case for thinking about the long- and short-term coupling of biotic and abiotic systems.

Keeping with a river ecosystem focus, the manuscripts of Atkinson et al. (this issue) and Katz et al. (this issue) explore bio-geomorphic interactions at smaller scales. Atkinson reviews selected case studies highlighting the role organisms play in moderating geomorphic processes and how these interactions influence essential ecosystem process such as biogeochemical recycling. Information on biophysical interactions is essential for constructing models of system-scale river functions, specifically sediment transport, biogeochemical cycling, and system state shifts. The study of Katz et al., explores how spatial and temporal variability of flow and sediment regimes influence the biomass of benthic algae within a mountain stream. Resistance of benthic algal communities to river bed disturbance and its recovery following a flow event varied significantly throughout the study reach. Benthic algae communities in areas of river bed dominated by low shear stress were slower to recover following a major bed scouring event compared to those communities in high shear stress areas. The inverse relationship between recovery and the frequency of disturbance highlights the complexity of resistance and recovery of biotic communities to physical disturbances and its implications on the spatial organization of benthic communities.

4. Emerging issues of a resilience based approach to geomorphology

Manuscripts in this Special Issue convey a degree of familiarity of the principles of linking resilience and bio-geomorphic systems. Although the three-day symposia and resulting Special Issue reveal an emerging trend of integrative studies, co-informing each other, and developing truly integrative and over-arching theories, our understanding of how resilience, geomorphology, and social-ecological systems intersect is still evolving.

Discussions among the participants of the Symposium revealed several emerging issues to consider as we advance not only the study of bio-geomorphic systems but also the integration of resilience and bio-geomorphic systems. Participants identified 25 specific issues facing the study of bio-geomorphic systems (Table 1). These issues focused on the areas of rates and states of geomorphic systems, behavior of geomorphic systems, emergent properties, general laws of coupled systems, geomorphology as a social-ecological system; the future of geomorphology as a discipline, and bridging with others. Many of these issues were discussed at the symposium. However, three main areas that demand thought-provoking attention were recognized: (1) confusion over resilience terminology across social and physical sciences, (2) the role of humans as external drivers or internal components of geomorphic systems and what this means for system resilience, and (3) questions of scale in general, and which also include how to address cross-scale interactions in social-ecological systems.

4.1. Confusion over terminology

Resilience, like the terms complexity, heterogeneity, and sustainability, is a term that has multiple uses and interpretations. Holling (1973, 2001) summarises resilience in 'ecological' and 'engineering' terms. Engineering resilience focuses on resistance to disturbance and describes a system near an equilibrium steady state. By comparison, ecological resilience focuses on the magnitude of disturbance that can be absorbed before system structure and function change, and a new behaviour regime ensues. Different conceptualizations of terms can either help to advance a field or distract it (Strunz, 2012). Resilience has not yet been widely applied to geomorphic systems at a consistent scale. It is necessary to define the geomorphic conceptualizations of disturbance and perturbation as any process resulting in or having the potential to effect change or disruption in the structure and/or function of a system. Many of the traditional themes of geomorphology (e.g., equilibria, thresholds, stability) have stronger parallels to engineering resilience than to ecological resilience.

The concept of resilience thinking is implicit in the study of geomorphic systems, but with little qualification of its precise meaning. Principles of equilibria and recovery underpin our understanding of the way geomorphic systems function via inter alia, equilibrium theory,

Table 1
Issues facing the study of bio-geomorphic systems.

Research area	Research questions
Rates and states of geomorphic systems	- What are the natural rates and states of geomorphic systems? - What is the relative work of events shaping landforms – is there a dominant event? - What is the relative influence of humans on surface processes; both physical and biotic processes and do we separate natural and human influences at a range of scales? - What is the actual human footprint on bio-geomorphic systems and can we separate spatial change from the human footprint?
Behaviour of geomorphic systems	- What type of systems are we dealing with? - Equilibrium vs dynamic behavior - Linkages and coupling with biotic and humans systems and their influences on these and vice versa? - What happens to systems when we re-introduce natural geomorphic and biotic processes? - Are patterns and processes scale variant?
Emergent properties	- Rapid changing drivers and the mismatch of scales of study. - What are the emergence behaviours of systems? - Scale linkages between systems - Are there robust features of the landscape – those features and landforms that persist over time?
General laws of coupled systems	- Does history and geography matter to landscapes? - What is the persistence of spatial structure and where does maximum activity occur? - Do we have general laws for geomorphic systems and what happens in boundary systems?
Geomorphology as social–ecological systems	- Human element not integrated within geomorphic systems.
The future of geomorphology as a discipline	- How does geomorphology retain its own uniqueness within interdisciplinary research? - Training geomorphologist with enhanced field skills. - Issues of the analysis of repeat surveys. - Gender and race issue - other lines of evidence. Diversity
Bridging with others	- How to improve communication to managers and policy managers? - Connect our science and what we do with management. - Promoting interdisciplinary research - Increasing the scale of this interdisciplinary research.

first coined by Gilbert (1877) and discussed in some detail by Thorn and Welford (1994), as well as the role of extrinsic and intrinsic thresholds in governing the form and behaviour of landforms (cf. Coates and Vitek, 1980). Dynamic equilibrium is a normative concept in geomorphology and dynamic conditions are a point along a continuum of adjustment as systems respond and adjust to disturbance. The concept of equilibrium in geomorphic systems is the notion of balance between input variables (processes) and form, such that when disturbed, there follows a period defined as the relaxation time, during which the system will return to some relative state of balance when a balance exists between e.g. sediment production and transport (Graf, 1988).

Social-ecological resilience as a concept of scientific inquiry that has contributed to new understandings of the dynamics of social–ecological systems, increasing our ability to contextualize and implement governance in these systems (Chaffin and Scown this issue). Often, however, the importance of geomorphic change and geomorphological knowledge is somewhat missing from processes employed to inform social–ecological systems governance (Parsons and Thoms this issue).

4.2. Humans as external drivers or internal components of geomorphic systems

Resilience thinking advocates an approach in which landscapes, ecosystems, economies, and societies are managed as linked social-ecological systems. It effectively facilitates knowledge exchange and adoption at the often turbulent boundary of science, management, and policy. While human impacts on landscapes has long been a component of geomorphic research, this has been from the viewpoint of humans as external drivers of geomorphic systems. This contrasts to ecological resilience (and social–ecological systems more broadly), where the intrinsic coupling of human and natural systems is central to the discipline (Thoms et al. this issue).

4.3. Questions of scale

An important issue that arises frequently in coupled research of geomorphology and resilience thinking is that of scale, and problems associated with selecting an appropriate scale for research and analysis emerged frequently during the symposium. Scale is a critical issue in designing a study and collecting data, but also in less recognized issues such as model development and selection and data availability and quality. Discussion during the symposium indicated that the issue of hierarchical processes and theory was a conceptual strength in geomorphology, and thus is one that merits further research on both sides as an interface topic. Based on the discussions and the papers here, we suggest that exploring the coupling of geomorphic processes across a wide variety of scales is a potentially fruitful area of research. Some scales of interaction are well researched, e.g., the effect of vegetation on erosion or river migration over annual to decadal timescales (Julian et al., 2016). However, others are less well understood, and could pose conceptual and logistical challenges. These scales are likely to be the extremely fine scales (sub-meter) and extremely broad scales (continental) and how (or if) geomorphic and ecosystem processes are linked at these scales; and where there may be potential causality shifts.

4.4. The value of BGS and this Special Issue

The Binghamton Geomorphology Symposia is one of the foremost annual geoscience meetings worldwide. For 48 years it has addressed a range of scientific and socially relevant topics in geomorphology (Wohl et al., 2017). Its value to the global geoscience community, and beyond can be measured by the number of highly cited publications that have emerged from the different symposia. However, this is only one metric of the status of the BGS; another is the longer lasting influence these symposia have on the attitudes and views of both geomorphologists and non-geomorphologists. To this end a 'before and after' survey of participants who attended the 48th BGS clearly show the positive benefits on their level of understanding of bio-geomorphic systems and resilience thinking (Fig. 1). To paraphrase Burroughs (1886) with respect to the discipline of geomorphology '…one views landscapes only for hints and half-truths … their facts are often crude until you have observed them in many different ways and then absorbed and translated these'. It is not so much what we see in landscapes, rather what we see suggests. The discipline of geomorphology allows those engaged with it to observe landscapes, associated landforms, and the ecosystems they contain through a multitude of lenses. Thus, it encourages a continuum of ideas, concepts and approaches, from those having a purely physical focus to those with a bio-geomorphic focus to those who seek a greater social-ecological focus. We hope this Special Issue has the same, lasting effect.

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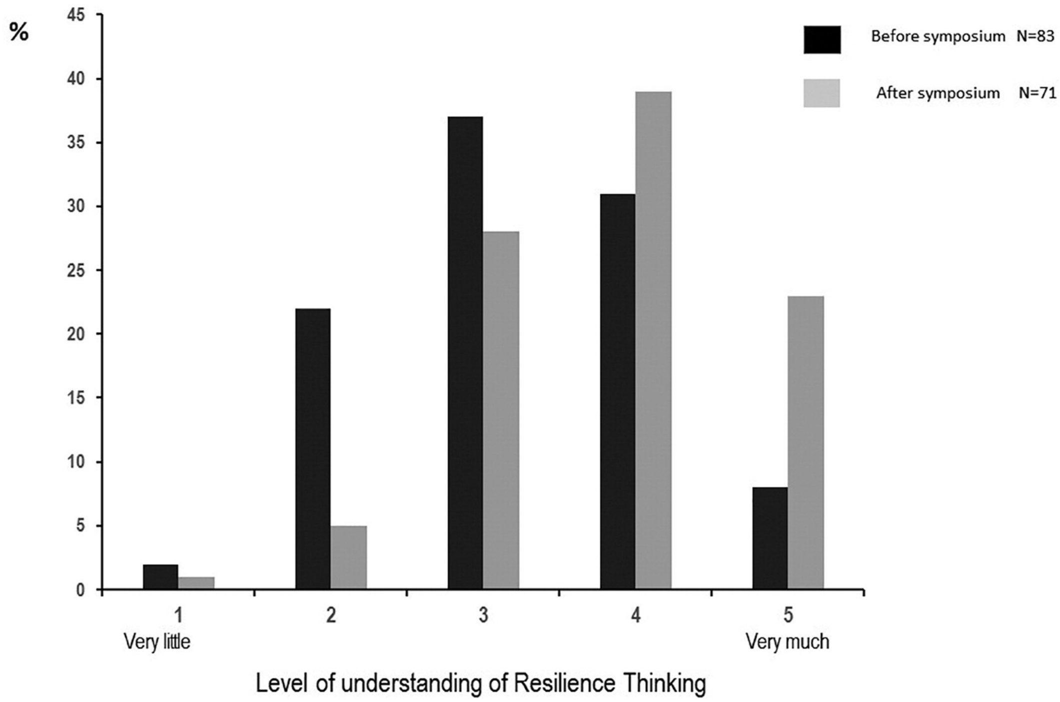

Fig. 1. Changes in the level of understanding of Resilience Thinking through a geomorphological lens, before and after the 48th Binghamton Geomorphology Symposium.

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