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Zoogeomorphology and resilience theory

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A B S T R A C T

Zoogeomorphology, the study of animals as geomorphic agents, has been largely overlooked in the context of resilience theory and biogeomorphic systems. In this paper, examples are provided of the interactions between external landscape disturbances and zoogeomorphological agents. We describe cases in which naturally occurring zoogeomorphological agents occupy a landscape, and examine whether those zoogeomorphic agents provide resilience to a landscape or instead serve as a landscape stress capable of inducing a phase-state shift. Several cases are described whereby the presence of exotic (introduced) zoogeomorphic agents overwhelms a landscape and induce collapse. The impact of climate change on species with zoogeomorphological importance is discussed in the context of resilience of a landscape. We conclude with a summary diagram illustrating the relationships existing between zoogeomorphic impacts and landscape resilience in the context of our case studies, and speculate about the future of the study of zoogeomorphology in the framework of resilience theory.

Contents

1. Introduction

The response of terrestrial systems to environmental disturbances is a primary aspect of the study of resilience in geomorphology. A disturbance is "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment" (Pickett and White, 1985, 4). The magnitude and the severity of the event influences the level of change to the landscape and the level of recovery it must go through to regain its intrinsic mechanisms, *i.e.*, to illustrate resilience.

To date, studies of geomorphic processes and systems examined in the context of resilience theory largely ignore the field of zoogeomorphology. Studies of biogeomorphic systems and resilience therein have almost exclusively focused on the subfield of phytogeomorphology rather than zoogeomorphology (*e.g.*, Thapa et al., 2016b; Thapa et al., 2016a, 2016b). One exception is the work of Eriksson (2011), described in a later section. It is precisely because of this lack of attention that in this paper, we discuss the application of the concept of resilience to the field of zoogeomorphology. We do so by first briefly considering the fundamentals of resilience theory. We then conceptually describe the environmental processes and factors that affect species that create zoogeomorphic impacts, as well as the zoogeomorphic processes and activities that feed back into the environmental processes and factors

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influencing the zoogeomorphic species. Our purpose is not, however, to develop a new conceptual model of resilience as it relates to zoogeomorphology; rather, we provide several examples of zoogeomorphological activities at a variety of spatial scales and describe the applicability of resilience theory in those examples. In addition, although the role of humans as geomorphic agents (*i.e.* anthropogeomorphology) has been widely recognized (*e.g.* Ehlen et al., 2005; Goudie and Viles, 2016), we do not address humans specifically as geomorphic agents in this paper. We do examine the interactions of human activities with animal species that are effective geomorphic agents, and describe how human actions may amplify or reduce those geomorphic impacts of animals within the context of resilience theory.

2. Resilience and zoogeomorphology

In recent years, researchers in ecology and geomorphology have explored and documented feedbacks between biotic and abiotic systems, but time and space have made the study of these a challenge because they do not share a simple, linear relationship. Viles et al. (2008), although not specifically using the terminology of resilience theory, suggested that geomorphological processes have stabilizing impacts that lead to negative feedback and destabilizing impacts that lead to positive feedback from biota. Holling (1973) first defined ecological resilience as the amount of disturbance an ecosystem could withstand without altering the self-organized structures and processes in that system (Gunderson, 2000). Climate changes, with attendant influences on the magnitude, frequency, and timing of ecosystem disturbances, can be considered the ultimate destabilizing (albeit non-geomorphic) impacts that are creating “historically novel disturbance events and disturbance interactions” (Johnstone et al., 2016, 369). Although land-use changes (*e.g.* deforestation) may have the same effect (Vitousek et al., 1997; Foley et al., 2005), they are not the primary focus of this paper. This fundamental change in disturbance event magnitude, frequency, and timing effectively violates concepts of resilience when ecosystems are viewed as existing in a single state of equilibrium, in which inputs and outputs remain relatively constant over time (Bone et al., 2016). Thus, resilience described by Holling (1996) as “engineering resilience”, is a measure of the speed with which an ecosystem recovers to the aforementioned single state of equilibrium (Folke et al., 2010; Bone et al., 2016), *i.e.* resilience is simply recovery potential (Johnstone et al., 2016). An alternative view of resilience acknowledges that systems have multiple potential states, and disturbances can cause a system to exceed a threshold or tipping point and enter a different state than that in which it began (Holling, 2001; Scheffer, 2010; Bone et al., 2016; Thapa et al., 2016a, 2016b). This view, identified as “ecological resilience” (Bone et al., 2016), is substantially more applicable to the field of zoogeomorphology, in which the geomorphic agents are themselves part of the ecosystem being changed by their own zoogeomorphic processes.

Systems strongly affected by zoogeomorphic processes can be considered Complex Adaptive Systems (CAS) *sensu* Stallins (2006) and Eriksson (2011), and zoogeomorphic CAS are linked to resilience theory because they illustrate Holling's (2001) four distinct phases of: exploitation or growth (r); conservation (K); collapse or release (Ω); and reorganization (α). In a system strongly influenced by zoogeomorphic activity, that activity may be sufficiently quick and dramatic such that a phase shift is triggered from the conservation K phase to the collapse/release Ω phase. Reorganization (α) may characterize a system in which a strong zoogeomorphic impact has been removed or drastically reduced, or where it has been reintroduced.

In zoogeomorphology, external factors impact the geomorphic process (an animal engaged in one of the actions in box C, Fig. 1) and in turn the geomorphic process creates disturbances. External disturbances affect the zoogeomorphic process, but the zoogeomorphic process, whether in the form of bioerosion, bioprotection, or bioconstruction (*sensu* Naylor, 2005), is also a disturbance subsequently affecting the landscape that impacts the external factors and may trigger a phase shift if the disturbance is sufficiently powerful. In some cases external disturbances reduce the zoogeomorphic impact by negatively impacting the population of the species engaged in geomorphic activities or the habitat of that species; whereas in other cases, the external disturbances amplify the zoogeomorphic impact by enabling the species involved in the process, or by increasing the number of that zoogeomorphic species. In either case (see next section), a tipping point could be exceeded inducing a phase shift. The back-and-forth between environmental variables and the animal species conducting geomorphic work (C in Fig. 1) exists for all the environmental variables (A in Fig. 1) except for regional climate (B in Fig. 1).

Unlike the human agency, zoogeomorphic agents have not been shown to impact climate on a regional scale, although some zoogeomorphic species such as cattle can influence climate through production of methane. Additionally, beaver ponds have been shown to be a source of moderate to high methane fluxes in comparison to other wetland types (Butler, 1995; Weyhenmeyer, 1999). Nonetheless, zoogeomorphic impacts have local (micro)climatic influences *via* pathways such as changing the albedo of a surface as a result of trampling and over-grazing (*e.g.*, Li et al., 2000), or by creating a more mesic environment by expanding the amount of surface water impounded in beaver-dammed ponds (Butler, 1995; Gurnell, 1998).

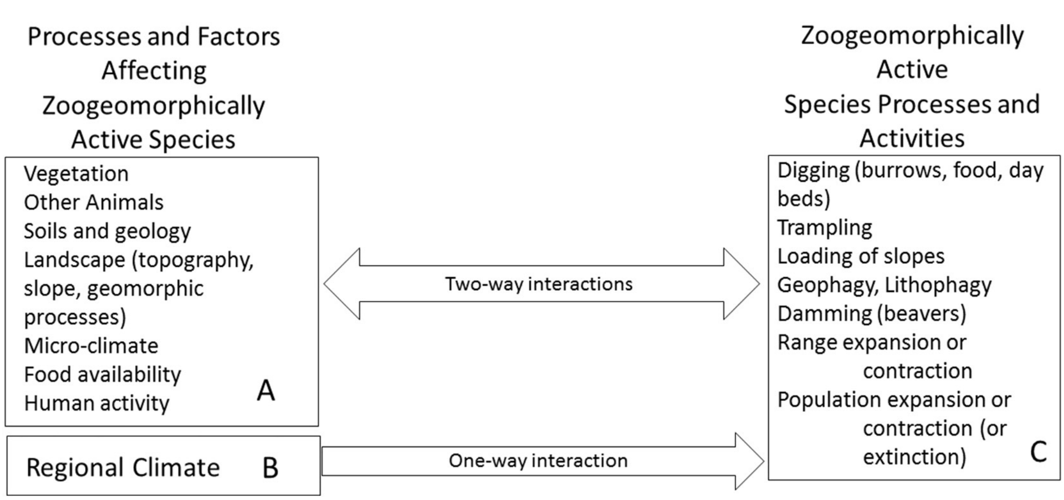

Fig. 1. The interactions between species with zoogeomorphic impacts and the environment.

Human activity is a “wild card” in the context of Fig. 1 in that it may be so over-arching, so pervasive, that it trumps all other environmental variables. Human activity/disturbance has produced near-extinctions of several zoogeomorphic agent species, including North American bison (*Bison bison*), both Eurasian (*Castor fiber*) and North American beaver (*C. canadensis*), and prairie dogs (genus *Cynomys*) (Butler, 2006). In such cases, the zoogeomorphic agents were not able to adapt to human over-trapping/hunting. It is at first glance in such cases difficult to envision the “return” arrow influence (Fig. 1) whereby the zoogeomorphologic agent affects the landscape. In this situation, it is not the process itself that is involved in the return influence, but the expansion or contraction (or cessation, in the context of extinction; Fig. 1) of the range and/or the population of the species, and therefore the magnitude of the zoogeomorphic process on the system, in question. For example, range expansion of prairie dogs would impact virtually all the variables in box A of Fig. 1, including human activity. Until such times when extinctions occur, the interactions will always be two-way, although at distinctly different magnitudes.

3. Zoogeomorphology, resilient landscapes, and phase-state shifts

3.1. Phase-state shifts with anthropogeomorphic/zoogeomorphic interactions

Under what circumstances might a landscape with significant zoogeomorphological processes be considered resilient? Under what circumstances might phase-state shifts occur? Phase-state shifts occur in a landscape when a threshold is exceeded (when “the ball goes over the lip of the cup” in a ball-and-cup diagram; Gunderson, 2000; Scheffer, 2010; Eriksson, 2011), and the landscape is insufficiently resilient to recover to its initial state. Zoogeomorphological phase-state shifts will occur when the zoogeomorphic impact on a landscape either exceeds the ability of the landscape to recover from that impact; or when such an impact is dramatically reduced or removed from a landscape (a concept that incorporates population number as well as range of occupancy). With human influences extending into every environment around the globe, zoogeomorphic agents (*i.e.* individual animal species) are able to adapt to or even take advantage of the human presence and become part of affecting and altering the landscape. Such adaptations may assist in assuring continuity in the system phase (the K phase), but potentially could cause the landscape to cross a phase-shift boundary and collapse or release (Ω).

Predicting the direction of a phase-shift for a landscape on which zoogeomorphic impacts are widespread is difficult, particularly in anthropogenically disturbed landscapes. In an overgrazed landscape, where humans are the cause of overgrazing through overstocking of livestock, burrowing animals can mitigate soil compaction and offset the possible movement from the K phase to the collapse or release (Ω) phase of a landscape that overgrazing could induce. An early paper on the role of gophers as zoogeomorphic agents illustrated how gophers can mitigate the impact of grazing animals on the landscape (Grinnell, 1923; Anzah and Butler, 2017). On overused landscapes, landscape recovery time without grazing (or without camping, see following sub-section) can be aided by the presence of zoogeomorphic species that may help in shortening the recovery time; but given the complexity of landscapes, could equally possibly induce a phase-shift. This shift might transform the landscape to an even more over-used state than its two previous states (pre-grazing state and post-grazing state); or conversely, set the landscape on the stage to recovery. However, it is difficult to quantify and predict this type of resilience. In the following paragraphs we provide two examples, one of zoogeomorphological adaptation and landscape stability, and one with zoogeomorphological impacts that induce landscape instability and a phase-state shift. We follow this with discussions regarding several instances of impacts on landscapes associated with introduction of exotic species, removal of zoogeomorphic species, and the effects of climate change on species with distinct zoogeomorphic impacts on landscapes.

3.1.1. Kuwaiti campsite berms and burrowing jerboa

In the desert of Kuwait, humans establish and occupy widespread camping sites for winter recreation. These camping sites, located outside the cities, are typically square or rectangular in shape and frequently utilize anthropogeomorphically created berms (up to a meter wide and tall) to delineate boundaries. Large tents are placed within the boundaries of these berms. The berms are constructed from sand/surficial deposits from the area surrounding the campsite. Campsites abandoned during the intense heat of the summer months are typically unoccupied for several years in order to allow for site recovery from compaction and use as a toilet; thus, a mosaic of anthropogeomorphic campsite berms of differing ages appears across the floor of the desert (Fig. 2a).

Within the campsite berms, a variety of small mammals including the lesser Egyptian jerboa (*Jaculus jaculus*) excavate numerous, but currently uncounted, burrows to unknown depths (Fig. 2b). Jerboa are widespread throughout the desert in the region (Anzah et al., 2017), excavating burrows that can be many meters long. Jerboa burrows run in an oblique and zigzag or spiral fashion, but are typically not more than half a meter below the surface (Anzah et al., 2017). The jerboa have adapted to the anthropogeomorphic campsite landscape, where they find the sediment in berms to be easily re-worked for burrow construction. Their zoogeomorphic presence has not been deterred by, and in fact seems to be fostered by, the presence of the camping berms. Their burrowing assists in the site recovery from the heavy human usage, *i.e.* they assist in sustaining re-usage of the camping sites and prevent them from approaching a tipping point that could lead to a phase shift. Work is currently underway to determine the number, volume of sediment moved, and spatial distribution of jerboa and other small mammal burrows in the Kuwaiti berms. This work will also provide a quantitative basis for comparison with jerboa burrow density in natural desert landscapes as described by Anzah et al. (2017).

3.1.2. Mountain goats at a bridge underpass

On the southern border of Glacier National Park, Montana, U.S.A., a major natural salt lick exposed in a cutbank of the Middle Fork of the Flathead River seasonally attracts large numbers of mountain goats (*Oreamnos americanus*) (Fig. 3a). U.S. Highway 2 cuts between the river and the surrounding peaks where the mountain goats reside. Prior to 1979, the goats had to negotiate a crossing of the highway in order to gain access to the exposed salt lick. Numerous goats were killed or injured as a result of collisions with vehicles on the highway, with many near misses as well (Butler, 1993). In February 1979, a major wet-snow avalanche there tore out the highway bridge spanning Snowslide Gulch. In re-building a new bridge across the aptly named avalanche path, the U.S. National Park Service, working with the Federal Highway Administration, created a new design whereby a “goat underpass” was built underneath Highway 2. Fencing was constructed to prevent goats from crossing the road, and instead directed the goats to travel to the salt lick by passing under the bridge (Fig. 3b). Completion of the bridge and the opening of the goat underpass occurred in 1981 (Butler, 1993).

Since completion of the goat underpass, the Park has recorded nearly 700 goat passages annually under the new highway bridge, compared to fewer than 20 such passages annually prior to 1981 (Pedevillano and Wright, 1987; Butler, 1993). This dramatic increase in the concentration of mountain goats passing under the bridge has altered the geomorphology of the south face of the avalanche path because of trampling and overgrazing by the hundreds of goats utilizing the bridge underpass each season (Fig. 4). The goats collectively are a zoogeomorphic disturbance that has amplified processes (surface wash, gully incision, and debris flows, in addition to the creation of numerous goat trails and excavated day beds at goat resting sites) that have apparently triggered collapse, a phase-state shift to an unstable and degraded erosional slope (because of the visibility of the site to tourists, on-location data collection is not permitted). The mountain a)

b)

Fig. 2. a) Aerial view of Kuwaiti campsite locations surrounded by sediment berms in which burrowing mammals take up residence. North is at top of figure, figure width represents approximately 1 km. Image credit to Google Earth. b) Typical anthropogeomorphic campsite berm with co-author Anzah for scale. Several burrows (arrows) are visible in the berm, most noteworthy near the right side of the photograph where a spoil mound beneath the burrow opening is also visible.

goats have adapted to the new bridge landscape, but the landscape has been unable to adapt to the increased concentration of mountain goats.

3.2. Phase-state shifts resulting from introduction of exotic species

Introductions of exotic zoogeomorphic species, such as the introduction of rabbits to Australia, can produce inherently unstable phase-state changes, *e.g.* collapse, resulting from an inability of a landscape to respond to and recover from the introduction and overload of zoogeomorphic activity. Rabbits in semi-arid portions of Australia have excavated tunnel-burrow systems, or warrens, over large geographic areas. The warrens intercept surface runoff and serve as "swallow-holes" into underground gypsum karst systems in some areas (Pickard, 1999), and warrens produce large areas of bare soil, mounds, and burrows with plant communities that are substantially different than the natural ecosystem (Eldridge and Myers, 2001; Eldridge et al., 2006). Even where "warren ripping" has been undertaken in an effort to exterminate the rabbits, the destructive effect of the rabbits on surface soils and vegetation in semiarid woodlands is of a sufficient magnitude such that "restoration of the original woodland vegetation after warren ripping is likely to be a slow and ongoing process" (Eldridge et al., 2006, 50).

Another example of a profound phase-state shift occurred in the Tierra del Fuego region of southern South America. Westbrook et al. (2017) recently described the zoogeomorphic effects of exotic North American beavers (*Castor canadensis*), introduced in Tierra del Fuego in 1946 in an effort to improve the economy of the area by providing a new fur-bearing species available for trapping. With no natural enemies present, beavers have greatly expanded in number throughout the area; but, more significantly, Westbrook et al. (2017) describe several unexpected zoogeomorphic pathways whereby the beavers have in effect induced phase-state shifts in the *Nothofagus* forest ecosystem of Tierra del Fuego. Beavers there have, as elsewhere where they are natural components of the landscape, transformed some forested riparian areas to "beaver meadows" along low-order streams. However, in a greater number of areas, instead of building dams constructed of wood (as is typical), "beaver instead excavated large volumes of mineral sediment or peat soil and stockpiled it in dams" (Westbrook et al., 2017, 189), reshaping valleys in the process. This atypical form of beaver damming led to exotic grasses replacing native mosses in groundwater-fed peatlands. A new phase-state has emerged in Tierra del Fuego; the a)

b)

Fig. 3. a) Oblique aerial view of cutbank (arrow) left-center, on the Middle Fork of the Flathead River that mountain goats travel to in order to access a natural mineral lick exposed in the cutbank. The Snowslide Gulch bridge is at center of photo, with U.S. Highway 2 visible. b) From a helicopter window, mountain goat-induced erosion (arrows) on the south-facing slope of Snowslide Gulch is clearly visible. Both a) and b) photos taken in September 2002.

resilience of the pre-existing landscape has been overwhelmed by the introduction of an exotic zoogeomorphic species.

In northwestern Europe, reintroduction ("re-wilding") of Eurasian beaver (*Castor fiber*) has been proposed and undertaken in several countries. Although not an "exotic species" given that it was native to the area, the period of time (centuries) since extirpation in most locations makes the reintroduction functionally similar to introducing an exotic species. The time since reintroduction of Eurasian beaver ranges from the 1920s in Sweden (Hartman and Törnlöv, 2006), 1974 in Poland (Giriat et al., 2016), 1987/88 in the uplands of Germany (John and Klein, 2004), 1998 in Belgium (Nyssen et al., 2011), 2002 in Scotland (Law et al., 2016), and 2015 in England (Puttock et al., 2017). The number of beavers reintroduced varies, and in most cases has occurred over too little a time period to determine the direction(s) of change on the landscapes their presence may introduce and whether any phase-state shifts may occur, although the typical patterns of dam construction and pond environment establishment and expansion are occurring. It will be interesting to observe whether an out-of-control situation such as now characterizes Tierra del Fuego will occur at locations in Europe as populations of beavers expand.

An additional example of the zoogeomorphic impacts produced on a landscape by an introduced species was described by Eriksson (2011), from whom this description is taken. The house mouse (*Mus musculus*) has been introduced by humans to at least eight islands in the maritime sub-Antarctic. Mice were inadvertently brought to Marion Island in the early 1800s, probably by Scandinavian seal hunters (Eriksson, 2011). The mice have impacted the ecosystem of the island through their roles in seeking food *via* predation (insects), granivory, and herbivory, and *via* widespread sub-soil burrowing in solifluction terraces. The terrace burrowing has led to destruction of tundra plant cushions, leading to exacerbation of needle-ice activity in cushion centers (Eriksson, 2011, p. 52). Mice burrowing has produced an average of nearly 15 burrows/25 m^2, and nearly 5300 burrows/ha. Eriksson's calculations illustrated 5.61 m^3 ha^{-1} of sediment displacement by

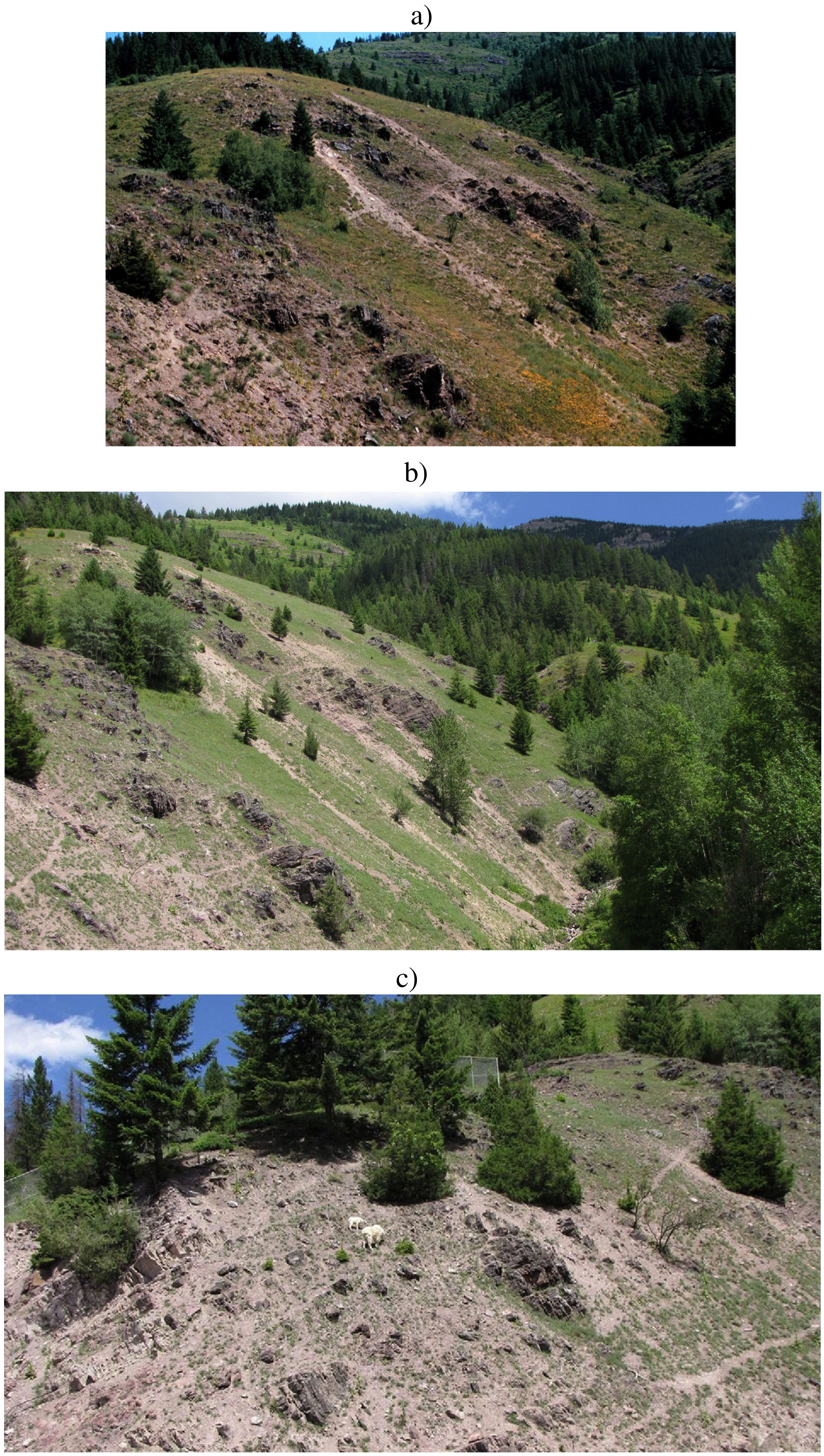

Fig. 4. a) Mountain goat-induced erosion in Snowslide Gulch, July 1994. b) Mountain goat-induced erosion in Snowslide Gulch, July 2012. c) Mountain goat adult female and young kid on goat paths, for scale.

mouse burrowing, and the burrowing additionally led to water passage through burrows acting as water conduits. Eriksson concluded that the actions of plant cover reduction and alteration of geomorphic processes attributable to the exotic mice made the resilience of the existing ecosystem very low, and asserted that the invasive mice could "be the factor that pushes the system over a tipping point causing a system transition into a new basin of attraction" (Eriksson, 2011, p. 71).

3.3. Phase-state shifts resulting from removal of zoogeomorphic species

When a powerful zoogeomorphic species is removed from a system, a phase-shift and collapse may occur. Numerous workers have noted how the removal of beaver in North America profoundly altered the fluvial system. Butler (1995) recounted how early colonial settlers in the eastern United States remarked upon the clarity and purity of streamflow in areas that now experience turbid, sediment-laden flow; a result of the removal of beaver and their ponds that acted as settling pools for sediment. Removal of beaver also led in many locations to a shift from multi-thread streams in alluvial meadows to deeply entrenched streams heavily laden with sediment (Marston, 1994; Butler, 1995; Pollock et al., 2007; Green and Westbrook, 2009). A change in state to a new system resulted from the removal of the zoogeomorphic agent that maintained stability. In many such locations, reintroduction of beavers has been able to reverse the erosional landscape back to a depositional landscape (Pollock et al., 2007; Polvi and Wohl, 2012).

Another case of near extirpation of a powerful zoogeomorphic agent from a broad landscape was the removal of bison (*Bison bison*) from the central plains of North America (Butler, 2006). The trampling and compaction of plains surfaces induced by the seasonal passage of millions of bison had notable but unmeasured impacts on the surface and subsurface hydrology of the region. In concert with the removal of another zoogeomorphic species typically found associated with bison, the black-tailed prairie dog (*Cynomys ludovicianus*), Butler (2006) asserted that the modern-day fluvial systems of the plains region are distinctly different than those that existed prior to European colonization and the subsequent bison and prairie dog near-extirpation; whether this difference triggered a phase-shift is problematic because of the absence of any meaningful pre-contact data on geomorphic conditions in the area.

3.4. Potential phase-state shifts resulting from climate change

Changing climate can "cause misalignment of legacies that erode resilience but are not apparent until after the system is disturbed" (Johnstone et al., 2016, 369). In Glacier National Park, Montana, glaciers are melting rapidly and it is projected that no glaciers will remain by 2030; the U.S. Geological Survey is studying the dynamics of glacial recession and the accompanying ecological effects in the Park (Butler, 2016; Goff and Butler, 2016). These ecological effects include impacts to the zoogeomorphological patterns and intensities of a number of zoogeomorphic species. Unfortunately, however, to our knowledge they are not examining shifts in the magnitude or distribution of the zoogeomorphological activity in the Park that is being affected by climate change. Butler (2012b) described how changing climate is affecting a number of species with strong zoogeomorphic impacts in Glacier National Park, including grizzly bears and beavers. Climate change may adversely affect food resources available to grizzly bears (*Ursus arctos horribilis*), with the potential for population decline and range contraction of the bears. Reducing or removing the zoogeomorphic influence of the bears, which is carried out by digging for food and through excavation of hibernation dens (Butler, 1992), would create a stress on the landscape in the context of resilience theory. Grizzlies affect forest, riparian, avalanche path, and tundra ecosystems in the Park; if their zoogeomorphic imprint is removed, the resilience of a wide number of sites across an elevational gradient in the Park will need to be monitored to determine whether these landscapes respond resiliently.

Beavers in Glacier National Park occupy most riparian habitats available there. They also occupy deltas on which the primary source of streamflow is glacial meltwater (Butler, 2012a) (Fig. 5). Hyporheic flow from the glacial meltwater filters through deltaic sediments to beaver ponds in swales with no discernible surface flow (Fig. 5). If the glaciers disappear as projected by the year 2030, the water supply for

Fig. 5. 1995 aerial helicopter view over the Red Eagle Creek delta. Three beaver ponds are visible (arrows), with no discernible surface flow feeding into the ponds. The ponds are sustained by hyporheic flow from Red Eagle Creek (out of sight above the top of the photograph), as described in Butler (2012a). Dimensions of farthest-right pond approximately 200 m by 40 m.

the beaver ponds will also disappear. The zoogeomorphic imprint of the beavers on the deltas will be removed, and the landscape will respond accordingly. In this instance, it is likely that the surrounding riparian and forest habitats will possess sufficient resilience to reclaim the beaver ponds and surrounding beaver meadows, but the beavers themselves will be reduced in number and may disappear from deltaic landscapes.

4. Discussion and conclusion

The preceding examples illustrate a variety of cases in which animals that have zoogeomorphic effects may initiate phase-state shifts, or where external disturbances initiate a phase-state shift by magnifying or removing the zoogeomorphic process(es) in a landscape (Fig. 6). In the cases associated with climate change, reductions in the animal population and therefore the zoogeomorphic impact are the likely outcome (upper left cell, Fig. 6), indicating landscapes whose resilience will need to be monitored to determine if the landscape undergoes a phase shift. In those cases where a new, intense zoogeomorphic impact overwhelms the landscape, whether at a localized scale such as in the case of the mountain goats at Snowslide Gulch or at a broader scale typified by the introduction of exotic rabbits, mice, and beavers in Australia, Marion Island, and South America, landscape phase-shifts occur. The landscape is insufficiently resilient to adapt to the high zoogeomorphic footprint (lower right cell, Fig. 6). Other landscapes (upper right cell, Fig. 6) may benefit from the reintroduction of species with distinct geomorphic impacts, recovering to a state similar to that which existed prior to the past removal of the species in question, although the question marks associated with the Eurasian beaver indicate that this conclusion remains to be proven over subsequent decades.

Fig. 6 does not easily suggest placement of the Kuwaiti example or the case of the near extirpation of bison. We have placed the Kuwaiti example in the lower left cell, because the harsh desert environment of Kuwait is one which allows little in the way of resilience in a landscape, and because the overall zoogeomorphic impact of burrowing animals is not profoundly impactful to the non-anthropogenic landscape. Nonetheless, the burrowing does assist in the refreshing of the camping berms *via* bioturbation such that the campsites can be reoccupied again perhaps more quickly than if burrows did not exist; this hypothesis is currently being examined by co-author Anzah in a study in progress. As for the case of the North American bison, the removal to the point of near extinction of a significant zoogeomorphic agent did not cause a catastrophic decline in the ecosystem of the plains region; but it did result in a strong geomorphic

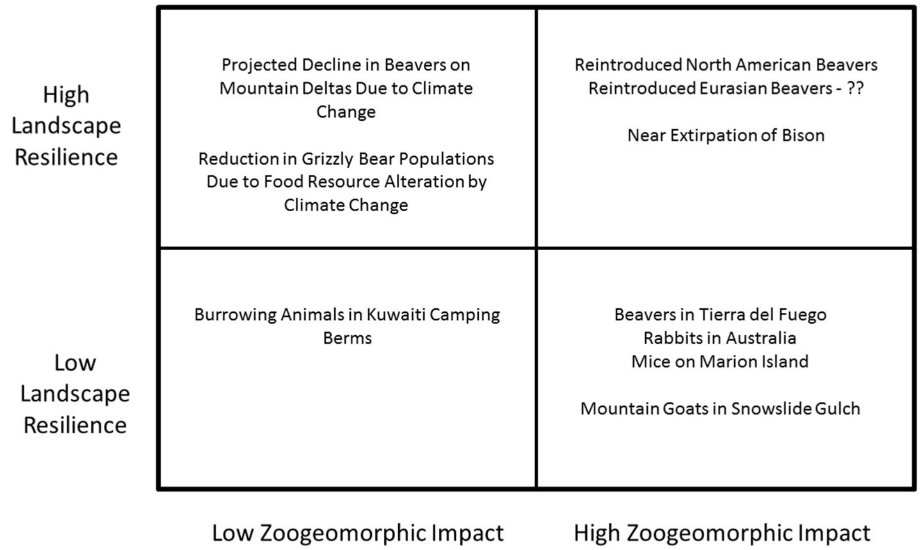

Fig. 6. The hypothesized relationships between levels of zoogeomorphic impact and levels of landscape resilience. Each case presented in the text is categorized in one of the four cells.

response of a change in the nature of plains stream systems and hydrology. Because of that high geomorphic impact, we have placed the action of bison removal in the upper right cell of Fig. 6, indicating that the plains are resilient in spite of the altered state of the streams of the region.

In those landscapes where a phase-shift occurs (*e.g.* mountain goats in Snowslide Gulch, mice on Marion Island, beavers in Tierra del Fuego), questions arise – how long will it take the landscape to stabilize? And will the landscape stabilize? It is difficult at present to answer these questions, because the disruptions caused by the excessive zoogeomorphic impacts have not been in play for more than a few (Snowslide Gulch) to several (Tierra del Fuego) decades. Monitoring the sites will need to continue for the foreseeable future to discern whether the landscape reverts to a more stable (previous?) state, or if a new and different state endures (and if so, at what level of stability?). The Marion Island exotic mice case illustrates a landscape that has not returned to its previous state after two centuries, but we cannot assume that all cases will follow this example. The extreme maritime tundra climate of that location makes recovery or adjustment to a new state a distinctly slower process than might occur in a location with a milder climate.

Another question that arises from these examples refers to the terminology of resilience and its applicability in zoogeomorphology – what do resilience theory and its terminology add to an understanding of zoogeomorphological landscapes? It could be argued that the terminology of geomorphology state transitions and state-and-transition models, as described by Phillips and Van Dyke (2017), would be equally appropriate. Yet, we believe it is important to consider zoogeomorphology within the conceptual framework of resilience theory. Although we did not explicitly address anthropogeomorphology in this paper, most of the zoogeomorphological impact cases we described herein illustrate interactions with the human agency (*e.g.* introductions, reintroductions, alterations of landscapes by humans inducing zoogeomorphic responses, reductions or near extirpations, human-induced climate change impacts), and the human agency is an important component in modern resilience theory studies. It is, therefore, appropriate to address zoogeomorphological impacts to landscapes within the context of resilience theory.

Regardless of the terminology employed, zoogeomorphological agents and impacts need to be more widely considered and quantified in order to fully understand how landscapes respond to those agents. Doing so could have perhaps prevented the population explosions with attendant zoogeomorphic impacts of rabbits in Australia and beavers in Tierra del Fuego. Rates of recovery from phase-state shifts need to be established for a variety of climates and ecosystems. Specific important zoogeomorphic agents of the past now reintroduced, such as North American and Eurasian beavers, provide opportunities for monitoring to determine if recovery is occurring (in the case of converting entrenched landscapes to multi-thread alluvial landscapes) and under what conditions; but also if reintroduced populations are stressing the landscapes and pushing them toward tipping points. In this context, the differences between reintroduced species and their impacts, and exotic species and their impacts, need to be determined. Why is reintroducing Eurasian beavers in northern and western Europe a good idea, but introducing North American beavers to Tierra del Fuego such a seemingly bad idea? Should all zoogeomorphically impactful exotic species be removed in an attempt to restore or stabilize a landscape? How are any of these questions impacted by ongoing human-induced climate change? A myriad of questions exists in the study of zoogeomorphology and resilience. Data needs to be collected, and a great deal of it, before policy decisions about the resilience of a landscape can be made. It's time to get to work.

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