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ESEX Commentary

Disturbance regimes at the interface of geomorphology and ecology

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ESPL
Earth Surface Processes and Landforms

ABSTRACT: Geomorphological processes are an integral part of ecosystem functioning and ecosystem functioning affects geomorphological processes. Increasingly widespread acknowledgement of this simple idea is manifest in a vigorous research community engaged with questions that address the two-way interaction between biota and geomorphology, at a range of scales and in a variety of terrestrial and aquatic environments. Geomorphological disturbances are a core element of biogeomorphological interest, and although the disciplines of geomorphology and ecology have each developed languages and theories that help to explore, model and understand disturbance events, little attempt has been made to draw together these approaches. Following a brief review of these issues, we introduce thirteen papers that investigate the interactions and feedbacks between geomorphological disturbance regimes and ecosystem functions. These papers reveal the singularity of wildfire impacts, the importance of landsliding for carbon budgeting and of vegetation accumulation for landsliding, the zoogeomorphic role of iconic and 'Cinderella' animals in fluvial geomorphology, biophysical interactions in aeolian, fluvial and torrential environments and the utility of living ecosystems as archives of geomorphic events. Most of these papers were first presented in a conference session at the European Geoscience Union General Assembly in 2010 and several others are from recent volumes of *Earth Surface Processes and Landforms*. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: biogeomorphology; zoogeography; disturbance; recovery; interaction; diversity

Interactions between geomorphological processes and the plants and animals that make up ecosystems occur in all terrestrial and aquatic environments and across all scales; from the relations between lithobiontic communities of micro-organisms and rock breakdown at millimetre scales (Viles, 1995; Souza-Egipsy *et al*., 2004; Hall *et al*., 2005; Naylor *et al*., 2012), to the relations between biomes and landforming processes at regional and planetary scales (Dietrich and Perron, 2006; Corenblit and Steiger, 2009; Phillips, 2009; Davies *et al*., 2011). Quantifying and understanding the feedbacks between biotic and abiotic systems or 'life and its landscape' have been identified as key contemporary challenges for geomorphologists (Reinhardt *et al*., 2010).

Research at the interface between ecology and earth science has a long track record, but much of this work has emphasized the impact of physical and chemical processes on evolutionary biology and the ecological distribution of plants and animals, while significantly less work has investigated biotic agency in geomorphological systems and the feedbacks to ecological success. Notwithstanding notable, earlier exceptions (Darwin, 1881; Cowles, 1899; Olsen, 1958) geomorphological interest in these intriguing questions re-emerged in the 1980s (Thornes, 1985; Viles, 1988) and 1990s (Butler, 1995; Hupp *et al*., 1995) – see Wheaton *et al*. (2011) for a review. At the time of writing, it is evident in the increasing number of papers published and in recent journal special issues (Darby, 2009; Hession *et al*., 2010; Wheaton *et al*., 2011; Butler and Sawyer, 2012), that the research community is engaged with the challenge laid down by Reinhardt *et al*. (2010) and that there is an acceleration of interest in unravelling the inter-linkages and feedbacks between biotic and abiotic systems. Moreover, it is clear that Geomophology's role in ensuring ecosystem health has moved beyond mapping and defining physical habitat (Rice *et al*., 2012), supported and extended by complementary developments in ecology – especially the emergence of ecosystem engineering (Jones *et al*., 1994; Moore, 2006; Wright and Jones, 2006). It is notable that in 2012 the two most cited papers in

Earth Surface Processes and Landforms from 2009 and 2010 (Thomson ISI Web of Science) are discussions of the interactions between geomorphology and ecology (Corenblit and Steiger, 2009; Reinhardt *et al.*, 2010) and that approximately 50% of all the papers published in *Earth Surface Processes and Landforms* on these topics have appeared since 2008 (33 of 69 biogeomorphological research papers in the back catalogue).

Nevertheless information gaps remain. This special issue contains a number of papers delivered at a session organized by the authors at the European Geosciences Union (EGU) General Assembly in 2010, designed to explore biogeomorphic interactions with a particular focus on disturbance. Geomorphological events like floods and landslides are important agents of ecological disturbance while the magnitude, frequency and geomorphic impact of such events may be moderated by ecosystem conditions. In addition, ecosystems may have a memory of geomorphological disturbances and thereby provide a record of event frequency and magnitude. The disciplines of geomorphology and ecology have developed their own terminology and conceptual models of disturbance that provide frameworks for investigating the non-linear impacts of disruptions on geomorphic and ecological systems. For example, geomorphological ideas of reaction, relaxation and response times (Graf, 1977) and, in aquatic ecology, of resilience, resistance, pulse, press and ramp (Lake, 2000). In addition, there have been some attempts to define biogeomorphological models of disturbance (Hugenholtz and Wolfe, 2005). Summarizing this work, Viles *et al.* (2008) conclude that improved quantitative understanding of processes and rates are required if proposed conceptual models of biogeomorphological disturbance are to be developed into more useful numerical, predictive models. In this context, the EGU session aimed to bring together researchers interested in:

1. quantifying plant and animal impacts on geomorphological disturbance regimes and geomorphological disturbances on aquatic and terrestrial ecosystems;
2. elucidating the interactions and feedbacks between process geomorphology and ecosystems at any scale;
3. investigating how ecosystems might be used to infer past geomorphic disturbance histories.

In addition to the papers generated by the session, several papers from the 2010 and 2011 volumes of *Earth Surface Processes and Landforms* are included that further seek to understand, model and quantify some of the interactions between organisms and geomorphic processes.

Singularity, whereby similar external forcing yields different geomorphic outcomes, is a common attribute of geomorphic response (Schumm, 1991) and Viles *et al.* (2008) suggested that diversity of ecological interactions at different places and times are a primary reason for this. Two of the papers in this special issue nicely highlight this effect in the context of geomorphological responses to a common form of ecosystem disturbance – wildfire. Martin *et al.* (2011) seek to explain low rates of soil erosion measured beneath a closed-canopy subalpine forest in British Columbia, Canada following a high-intensity crown fire. Detailed field work revealed the survival of a significant duff layer and it was hypothesized that this may have inhibited generation of overland flow and thence soil erosion by providing detention storage for rainfall. This hypothesis was tested in a programme of numerical experiments simulating rainfall penetration and the generation of infiltration excess ponding for a broad range of soil types and a duff layer under a range of rainfall intensities. It was found that in contrast to the soils, duff was an extremely effective buffer against overland flow generation. These experiments therefore supported the proposal that patchy duff consumption during wildfires was a key attribute of the subalpine forest ecosystem studied, which minimized geomorphic response, conserved soil integrity and thereby promoted ecosystem recovery. In contrast, within the subalpine–alpine ecotone of the North Tyrolean Austrian Alps, Sass *et al.* (2012) discovered long-lasting and quite profound geomorphological impacts of wildfires. Examination of more than 450 wildfires across a 1700 km^2 area revealed that vegetation removal was often complete, vegetation recovery took between 50 and 500 years, and elevated erosion rates persisted for decades. The authors suggest that very slow recovery reflected, in part, the paucity of surface water in the karstic terrain once vegetation and soil organics were removed by fire. The lack of regeneration meant that elevated soil erosion continued unchecked which, in turn, further hindered vegetation reestablishment. They go on to highlight some interesting topographic and scale effects; slope steepness and the size of the burnt area affect this feedback process. While the subalpine forest stand examined by Martin *et al.* (2011) showed significant recovery within 1 year of the fire, the mountainous slopes studied by Sass *et al.* (2012) exemplify a non-resilient biogeomorphological system where recovery may require decades to centuries.

Three papers in the special issue focus on the impacts of animals on geomorphological processes, or zoogeomorphology (Butler, 1995). In a series of flume experiments, Johnson *et al.* (2011) showed that on water-worked gravel beds the activities (walking, foraging, pit construction) of signal crayfish (*Pacifastacus leniusculus)* disturb the structuring effects of antecedent flows, rendering bed particles more susceptible to entrainment when compared with control beds that were water-worked but not exposed to crayfish. By destabilizing transport-limiting structures, crayfish increased the availability of mobile bed particles and promoted higher bedload fluxes under a particular hydraulic stress distribution. Similar arguments relating to the impact of crayfish on fine sediment dynamics have been outlined by Harvey *et al.* (2011). Johnson *et al.* (2011) emphasize the importance of establishing the transferability of experimental observations like theirs, from laboratories or small-scale field trials to larger scales, and offer two conceptual models to guide work in this arena. Recent reviews (Rice *et al.*, 2012; Stazner, 2012) reveal that a large number of widely distributed and abundant invertebrate and piscine fauna disturb bed sediments, potentially affecting fluvial sediment transport processes in many rivers. This raises the tantalizing possibility that such ‘Cinderella’ species, which do not leave obvious or spectacular impressions on the landscape, nevertheless may collectively and cumulatively have a profound, watershed-scale impact on fluvial dynamics (Rice *et al.*, 2012).

In contrast to these hidden zoogeomorphic effects two papers in the special issue focus on one of most iconic geomorphic agents, the North American beaver (*Castor canadensis*), which does have spectacular impacts on the geomorphology of mountain valleys and on sediment and water dynamics at catchment scales (Naiman *et al.*, 1988; Butler, 2006; Westbrook *et al.*, 2010). Butler (2012) adds to a large portfolio of work on this animal's geomorphological importance by exploring the characteristics of ponds formed by beaver dams on lacustrine deltas, extending earlier work on the more common valley ponds that interrupt downstream sediment routing and can affect mountain valley floodplain morphology (Butler and Malanson, 2005; Westbrook *et al.*, 2006). Delta ponds in Glacier National Park (Montana, USA), were found to be longer-lived than their valley counterparts such that their influence on sediment retention, water chemistry and the immediate ecosystem were potentially greater. For example, first-order calculations suggest a much greater sediment storage capacity than in valley ponds.

In an interesting departure from previous work on the biogeomorphological impact of beavers, Polvi and Wohl (2012) examined Holocene sedimentation in two beaver-affected valleys of Rocky Mountain National Park (Colorado, USA), seeking to ascertain the role of beaver in floodplain evolution and post-glacial valley alluviation on this longer timescale. Interpretation of near surface seismic refraction data and floodplain sedimentology recovered from shallow, dated, cores indicated that between 30 and 50% of Holocene floodplain sedimentation was caused directly by beaver dams. These are significant percentages given the broader scale importance of the affected valleys as depositional hotspots along the catchment sediment cascade. Moreover, Polvi and Wohl (2012) document a clear association between twentieth century declines in beaver populations and reduced channel complexity revealed by aerial photography. They suggest that there is an important feedback at work, whereby the creation of complex channel networks by beaver, through dam building and other activities that promote avulsion and multiple channels, in turn promotes even greater sedimentation and channel complexity by generating greater lengths of channel for the construction of dams. In this case, the major ecosystem disturbance reflected in declining beaver numbers (over-exploitation by European settlers) has not only affected the morphology and sediment dynamics of these valleys but, by removing the beaver-engineered geomorphological complexity, has also affected the contemporary riparian/wetland habitat mosaic and reduced the capacity of the ecosystem to support historical beaver populations.

The remaining papers in the special issue focus on the relations between vegetation and geomorphological processes. Osterkamp *et al.* (2012) offer a wide-ranging exposition of the vigour of plant biogeomorphology and its importance for developing adequate understanding of how stable ecosystems operate and how watershed-scale ecosystem services can be protected, not least under the biophysical impacts of climate change. They highlight the broad and healthy level of research output and the importance of current research for understanding, for example: the routing, deposition and long-term storage of sediment and carbon in fluvial networks; the role of biota in soil conservation and management; the fate of sediment-attached toxins that interact with catchment vegetation; and river channel stability and riparian management. Looking forward, Osterkamp *et al.* (2012) suggest that better understanding of vegetative debris fluxes is an important core theme for biogeomorphological research, with particular emphasis on biochemical processing within depositional landforms, and carbon storage, budgeting and sequestration issues.

Hilton *et al.* (2011) provide an excellent example of the high-quality carbon budgeting work envisaged by Osterkamp *et al.* (2012). Their paper focuses on carbon harvesting by bedrock landslides in the temperate montane forests of the Southern Alps (New Zealand), its routing to the fluvial network, its relevance for long-term sequestration and the interaction between these disturbance events and ecosystem productivity. Hilton *et al.* (2011) found that a large proportion of the organic carbon derived from landsliding was retained on hillslopes with only approximately 30% delivered to river channels. Nevertheless, and notwithstanding the difficulty of constraining budget estimates, landslide-derived carbon may represent up to 17% of the particulate organic carbon exported by the rivers that drain the Southern Alps. The authors point out that in sedimentary basins adjacent to actively eroding orogens, carbon trapping is expected to be high because of high rates of sediment accumulation, in which case landslide-derived carbon may still be important for long-term sequestration of atmospheric CO_2. In addition, high net ecosystem productivity on recovering landslide scars and the time-space abundance of landsliding events, mean that these disturbances may be a particularly efficient means of fixing atmospheric CO_2. Although not concerned with carbon budgeting, Vorpahl *et al.* (2012) also examined vegetation-landslide dynamics, in this case in tropical montane forests. From their study area in the rain forest of southern Ecuador, the authors describe massive organic landslides in which almost no mineral soil is mobilised, especially on shallower slopes. Their observations suggest that tree roots seldom penetrate to bedrock and instead grow in a deep organic layer composed almost entirely of decaying plants and roots. This leads them to propose a modified slope stability model in which a thick organic layer with distinct mechanical properties is treated separately from the underlying mineral soil. Sensitivity analysis revealed that within such a system, the mass of living vegetation and its contribution to the mass of the organic layer was a key destabilizing influence on steep slopes. Vorpahl *et al.* (2012) suggest that forest succession and associated biomass accumulation help drive landslide occurrence in these forests, which in turn drives succession, so that disturbance is characterised by a biophysical feedback mechanism.

In the second review paper in the special issue and drawing mainly on excellent examples from British Columbia (Canada) and the European Alps, Stoffel and Wilford (2012) review the disturbance interactions between vegetation and erosion on mountainous, valley fan settings, where debris flows, debris floods and floods are characteristic processes. They highlight work that has documented the importance of forest disturbance (either natural or anthropogenic) for the initiation of mass movements and floods, and review the role of living and dead in-channel and riparian trees for fluvial dynamics in steep, torrential watersheds. In turn, they consider the impact of these 'hydrogeomorphic' events on fan vegetation, emphasizing the central role of geomorphological disturbances in creating riparian forest complexity on fans, in which a patchy mosaic of stand ages, structures and species composition defines the ecosystem. Building on these clear inter-linkages between geomorphology and vegetation, Stoffel and Wilford (2012) review the foundational elements of dendrogeomorphology as a tool for reconstructing event histories. This technique makes use of the reaction of riparian trees to geomorphological disturbances that physically injure, tilt, decapitate or bury them, alongside traditional dendrochronology, to reconstruct the timing, magnitude, frequency and spatial extent of sediment transferring processes. Such information is highly valuable, not only because fans represent a key staging point in the sediment cascade, linking torrential watersheds to the downstream river network, but also because many fans are favoured, but hazardous, sites of human occupancy.

The paper by Procter *et al.* (2012) then exemplifies the application of dendrogeomorphology in the case of a single fan in the Austrian Alps, again emphasizing the usefulness of relations between geomorphic and ecological disturbance for reconstructing event histories. In addition, however, the paper makes an important methodological contribution. Using an available orthophoto series, the authors were able to evaluate the quality of the data obtained and, in particular, assess the effect of severe tree loss on event reconstruction. Their analysis indicated that the dendrogeomorphic data alone might only have captured 20% of debris flow events in this extreme environment, because tree death following sediment deposition during some events eradicated parts of the forest, removing many potential records of earlier events. This work quantifies, for this type of environment, the extent to which dendrogeomorphically reconstructed event series represent conservative, minimum frequency estimates that can, nevertheless, be augmented by integrating other approaches like orthophoto analysis.

Charron *et al.* (2011) also examined riparian vegetation in mountain environments, but in this case along relatively small, headwater gravel-bed streams. The work reported contrasts with much of the existing literature on riparian biogeomorphology, which has focused on process interactions in lower gradient or much larger river corridors. Tree recruitment along a small stream (260 km^2 catchment area) in the Canadian Rockies revealed spatially patchy recruitment that reflected the dominance of patchy vertical accretion of fine sediments on bars. In turn, the distribution of tree species and ages were complex, lacking the spatial gradients that have been reported along lowland rivers where lateral point-bar accretion dominates and recruitment can be spatially ordered. Furthermore, they found that there was relatively continuous tree establishment through time. This contrasts with lowland studies that have found a close association between age density and the highest water years, when high flows are most likely to deliver fine sediment to favourable recruitment locations. Relating their findings back to the ecosystem functioning of these riparian forests, Charron *et al.* (2011) argue that the relatively intense disturbance regime of flooding in laterally constrained, mountainous gravel-bed streams and the patchy delivery of appropriate recruitment substrates, promote population dynamics that yield a relatively young multiple-age structure that is quite different from lowland riparian forests. Bertoldi *et al.* (2011) are also interested in the interactions between river flows and vegetation recruitment and colonization, but in this case in the riparian forests along a 21-km reach of the large, braided Tagliamento River, Italy. A key methodological contribution of this work was to demonstrate the utility of Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) data for mapping changes in vegetation cover at a relatively high temporal resolution. Over a 5-year study period that was characterized by increasing flood disturbance, they found that initial vegetation expansion was followed by retraction in two of three sub-reaches, while in the third sub-reach where vegetation expansion was particularly rapid, tree stands were highly resistant to fluvial erosion, surviving large floods late in the study period. They discuss the implications of this variable response in the context of conceptual models of island development and modelling interactions between vegetation and fluvial processes.

Moving into a different process regime Hesp *et al.* (2011) present, for the first time, a detailed assessment of the two-way interactions between common landforms in aeolian dunefields and their vegetation. Field observations from coastal Veracruz (Mexico) document how colonizing plants are instrumental in the formation of landforms including gegenwalle ridges, transverse dune trailing ridges, parabolic dunes and precipitation ridges and, in turn, how landform development affects vegetation association and succession patterns across the dunefield. Hesp *et al.*'s study provides an excellent example of how tight biophysical coupling between biotic and abiotic elements define the character and dynamics of a landscape.

Together, these thirteen papers exemplify the 'explicit and exciting reappraisal of geomorphology' (Darby, 2009; 370) that is being played out at this time. The science in these and similar papers is improving our understanding of the non-linear and complex geomorphology–ecology linkages in fluvial, hillslope, and aeolian settings. Moreover, the papers in this special issue, and in those others listed above, make credible and important connections to Earth system questions bigger than the immediate concerns of geomorphologists and ecologists: managing and maintaining healthy ecosystems and their biophysical, as well as biological services; understanding biophysical processing of carbon and its long-term sequestration; evaluating and managing risk in populated, steepland environments. Finally, several papers raise intriguing possibilities about geomorphologically significant, but as yet undiscovered and unquantified interactions between animals, plants and geomorphological processes, underscoring the potential importance of support for research in this arena and the pressing need for ecologists and geomorphologists to collaborate on mutually interesting questions (Rice *et al.*, 2010).

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