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Dynamic riverine landscapes: the role of ecosystem engineers

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Abstract

An important and highly active research agenda has developed at the interface of fluvial geomorphology and ecology that addresses the capacity for vegetation and animals to act as ecosystem engineers within fluvial systems. This paper briefly introduces this research domain and describes the fifteen papers that contribute to the special issue on 'Dynamic riverine landscapes: the role of ecosystem engineers'. The papers illustrate the breadth of research activity at this interface, investigating the influence of a range of ecosystem engineering organisms through a combination of field study, laboratory experiments, numerical simulation and analysis of remotely sensed data. Together, the papers address a series of key themes: conceptual frameworks for feedbacks between aquatic biota, hydraulics, sediment dynamics and nutrient dynamics and their quantification through experimental and field research; the potential contribution of ecosystem engineering species to assist river recovery and

restoration; and the contribution of riparian vegetation to bank stability and morphodynamics across a range of spatio-temporal scales.

Keywords: biogeomorphology, ecosystem engineering, fluvial processes

The ecosystem engineering role of aquatic and riparian biota in driving morphodynamics, habitat complexity and biodiversity at a variety of spatio-temporal scales represents an important and rapidly advancing research agenda in river science. The term ‘ecosystem engineer’ refers to organisms that directly or indirectly modulate the availability of ecosystem resources and hence modify, maintain or create habitat (Jones *et al.*, 1994). Within river corridors, a range of organisms including invertebrates, fish, mammals and aquatic and riparian vegetation are influenced by fluxes of water, sediment and nutrients. These organisms, in turn, modify fluvial processes across scales ranging from individual sediment grains to river-floodplain systems (Reinhardt *et al.*, 2010; Bertoldi *et al.*, 2011; Rice *et al.*, 2012a; Gurnell, 2014).

Biogeomorphological interactions can initiate and maintain morphological complexity in pristine or semi-natural systems and have the capacity to assist the geomorphological recovery and restoration of degraded rivers in a way that minimises management intervention (Palmer *et al.*, 2005; Beechie *et al.*, 2010; Gurnell *et al.*, 2012). In contrast, invasive species acting as ecosystem engineers can represent a system disturbance with potential for negative impacts on the delivery of ecosystem services (e.g. Harvey *et al.*, 2011; Greenwood and Kuhn, 2014). As a result, ecosystem engineering plays a critical role in the functioning and management of dynamic riverine landscapes. A deeper understanding of bi-directional interactions between the biotic and abiotic components of fluvial systems within a range of environmental contexts is crucial, particularly in light of the significant and increasing pressures arising from climatic change, management interventions and invasive species.

This special issue arose from a session at the European Geosciences Union General Assembly in 2012, which addressed the role of ecosystem engineers in driving fluvial processes and landform dynamics. The session and special issue contribute to a highly active area of research at the interface between geomorphology and ecology (e.g. Darby, 2010; Wheaton *et al.*, 2011; Butler and Sawyer, 2012; Rice *et al.*, 2012b). Rice *et al.* (2012b), for example, present a special issue of *Earth Surface Processes and Landforms* focusing on disturbance regimes at this interface and note a substantial increase in papers on biogeomorphology published by the journal in the six years previous. This trend has continued. For instance in a 'State of Science' themed issue of ESPL in January 2015 three out of seven papers focus on the importance of feedbacks between vegetation and geomorphological processes in fluvial systems and (at the time of writing) five out of the twelve most cited papers published in the journal since 2012 address the impact of vegetation or animals on sediment dynamics and river evolutionary trajectories (Osterkamp *et al.*, 2012; Polvi and Wohl, 2012; Stoffell *et al.*, 2012; Fryirs, 2013; Gurnell, 2014).

The papers in this special issue explore the interactions between fluvial processes and a variety of engineering organisms (including animals, aquatic vegetation and riparian vegetation) achieved through a combination of literature review, development of conceptual models, laboratory experiments, numerical simulations and the analysis of remotely sensed data. The papers address a series of key themes: frameworks for conceptualising the feedbacks between aquatic biota, hydraulics, sediment dynamics and nutrient dynamics and their quantification through experimental and field research; the potential contribution of ecosystem engineering species to assist river recovery and restoration within degraded systems; and the contribution of riparian vegetation to bank stability and morphodynamics across a range of spatio-temporal scales.

The rapid advancement of this interdisciplinary research domain necessitates the development of new conceptual frameworks within which biogeomorphic interactions can be hypothesised and tested. Based on a detailed review of the literature, Corenblit *et al.* (2014) present the biogeomorphological life cycle of the European black poplar (*Populus nigra*); a conceptual model that links the biological development of poplars, from seed deposition to mature tree, with the processes by which they modify the hydrogeomorphological environment. The model outlines four phases, across which the nature and intensity of bi-directional interactions vary as the plant and fluvial landform co-evolve. The geomorphological and pioneer phases are dominated by fluvial processes, while reciprocal biogeomorphic interactions are strongest during the third, biogeomorphological phase. During the ecological phase, interactions between *P. nigra* and fluvial processes are limited to high magnitude flow events. The authors hypothesise that the ways in which *P. nigra* modifies its environment results in positive niche construction and outline the cutting-edge research agenda required to test their hypothesis.

Evidence for feedbacks between plant traits and the abiotic river environment is presented by Schoelynck *et al.* (2014) who explore the role of plant morphological plasticity in vegetation-sediment-flow interactions. Focusing on the floating-leaved, rooted aquatic macrophyte *Nuphar lutea*, their field measurements reveal higher numbers of submerged leaves and larger leaf areas in a lotic stream habitat compared to an adjacent oxbow lake. Sediments retained around *N. lutea* patches in flowing water were finer and richer in organic material with higher nutrient content than unvegetated patches while vegetated and unvegetated patches in the still water habitat showed no significant difference in sediment properties. The findings indicate important feedbacks between plant morphology and the hydrodynamic environment and an ecosystem engineering role of *N. lutea* with potential implications for local sedimentation processes and nutrient cycling.

Building on the work of Corenblit *et al.* (2014), Bätz *et al.* (2015) consider the role of soil in biogeomorphic succession within the geomorphically active environment of river braid plains. The authors propose that within such dynamic systems, the conventional mode of soil development requires adaptation in order to incorporate disturbances and supply of resources by erosional and depositional processes. A conceptual model for the co-evolution of braided river morphodynamics is presented, emphasising the critical role played by soil evolution in the early stages of fluvial landform development which can improve local environmental conditions and facilitate the co-evolution of vegetation and landforms. The model is tested using field data from a braided river-terrace system, highlighting the relatively rapid development of soils even within more geomorphically active areas as a result of these feedbacks.

Feedbacks induced by a geomorphic agent (Pacific salmon), known to modify bed material and nutrient delivery to streams, are explored experimentally by Rex *et al.* (2014). Outdoor flume experiments are used to simulate and to quantify the formation and delivery to the streambed of salmon-based flocs, comprising fine sediment and salmon organic matter, during active spawning and post-spawn periods. Interactions between inorganic and organic material through floc formation resulted in increased delivery of salmon organic matter to the river bed under simulated active spawning conditions, and substantial growth of flocs within the bed following infiltration which is attributed to microbial activity. The findings indicate a feedback loop whereby the sequestration of salmon organic matter and hence marine-derived nutrients within the streambed may influence stream productivity.

The influence of fish on river bed material properties is explored further by Pledger *et al.* (2014) who use laboratory flume experiments to quantify the impact of a benthic-feeding fish (*Barbus barbus*) on gravel bed sediment structures, entrainment and bedload fluxes. Benthic-feeding fish are widespread in rivers and disturb bed material through foraging behaviours but little is known of their impact on sediment dynamics. The flume simulations reveal that substrates exposed to fish feeding were associated with higher microtopographic roughness, and increased grain entrainment counts and bedload flux which are attributed to the alterations to bed material organization and structure. Given that benthic foraging is common among a large number of species, and is spatially widespread and temporally persistent the authors encourage further work to quantify these hitherto largely unexplored impacts on sediment dynamics.

The impact of ecosystem engineering animals on the physical environment may be amplified where individuals are present in large numbers as is often the case for invasive species. Harvey *et al.* (2014) explore the impact of invasive signal crayfish (*Pacifastacus leniusculus*) on fine sediment dynamics within river channels. Laboratory mesocosm experiments demonstrate the ability of signal crayfish to mobilise pulses of fine sediment by burrowing into constructed clay banks and bed substrates, while field data reveal similar pulsed fine sediment events and an increase in ambient turbidity levels. The findings indicate that signal crayfish have the potential to influence suspended sediment yields in rivers, with potential implications for morphological change, physical habitat quality and the transfer of nutrients and pollutants.

In contrast to the potentially deleterious impacts of invasive species, Curran and Cannatelli (2014) discuss an example of beavers as a tool in the restoration of degraded river systems. The paper reports on changes in channel morphology following beaver dam construction in a low-gradient, fine-sediment dominated channel that was adjusting to the breaching of a downstream dam. The beaver dams concentrated flow into a single channel and encouraged deposition at channel margins, contributing to increased channel stability and sediment storage. The authors suggest that in cases where dam removal can lead to bank erosion and channel migration, beaver dams may be used to enhance lateral stability and support the removal of structures.

Aquatic plants can also contribute to the recovery of channels from human interventions through their role in retaining fine sediments and building fluvial landforms. Gurnell *et al.* (2013) use a large national data set combined with field survey and germination trials to explore the distribution and geomorphic impact of the linear emergent macrophyte *Sparganium erectum*. Results demonstrate that *S. erectum* is widespread across river types but achieves significant cover and hence has greater potential for landform development in low gradient, low energy stretches with relatively fine bed material. Sediment retention by *S. erectum* is primarily influenced by the size and density of the plant stand, rather than the size of the individual plants, with tightly packed stands retaining more sediment than low density stands. The retained sediments create landforms that emerge as benches and trap large numbers of viable seeds, generating a terrestrialising marginal habitat that can promote channel narrowing in over-widened reaches.

River restoration may increase cover of instream vegetation and hence potential for fine sediment retention. Within this context, the paper by Gibbs *et al.* (2014) highlights the importance of accounting for sediment-associated contaminant mobilisation and storage in restoration design in order to optimise the benefits of restoration for ecosystem and human health. Their field research highlights the potential for retention of heavy metals within vegetated and unvegetated sediment patches in urban river reaches. High concentrations of Cu, Pb and Zn in excess of sediment quality guidelines for ecological and human health were found in gravel patches, and in both vegetated and unvegetated fine sediments. The fine sediments were also associated with greater bioavailability of metals, reflecting the smaller grain size and higher organic matter content of these patches. The results contribute to the scientific basis for river restoration design, particularly in relation to enhancing outcomes for urban river restoration projects.

Riparian vegetation has wide ranging impacts on fluvial processes and river behaviour across multiple scales, from the stabilising effect of individual roots in river banks, to the effects of large wood on reach-scale river morphology, to the influence of floodplain vegetation development river planform. At the microscale, Edmaier *et al.* (2014) use laboratory experiments to quantify the uprooting characteristics of seedlings of *Medicago sativa* and *Avena sativa*. These species are used to represent riparian vegetation in physical models as a result of their simple root architectures and ability to grow in sandy substrates. The experiments demonstrate positive relationships between total root length and uprooting force/work and a higher resistance for the multi-root system (*A. sativa*) compared to the single-root system (*M. sativa*). Sediment particle size and moisture content also influence the ability of a seedling to withstand uprooting, with smaller forces required to uproot seedlings growing in wetter and coarser sediments. The results contribute to the understanding of plant uprooting resistance and will aid the design of ecomorphodynamic flume experiments.

Polvi *et al.* (2014) explore the functional role of different vegetation types in stabilising river banks through a combination of field measurement and numerical modelling. Differences in tensile strength, density and morphology of riparian root systems were quantified for four functional groups (trees, shrubs, graminoids and forbs) using field measurements, while numerical modelling was used to predict the additional cohesion provided by each plant species for different bank material textures. Woody vegetation (tree and shrub groupings) was associated with greater tensile strength, root diameter and lateral root extent as well as added cohesion in comparison to the non-woody vegetation (graminoids and forbs). The paper offers a framework that can be used to explore the functional role of a wider range of vegetation types in bank stabilisation and is of direct relevance to the management and restoration of river corridors.

Riparian vegetation becomes an important component of the instream environment when vegetated margins are eroded and vegetation (e.g. large wood) is supplied to the channel. Bertoldi *et al.* (2014) use flume experiments to explore wood dynamics in braided streams. Patterns of wood deposition and remobilization are investigated using wooden dowels in three parallel flumes filled with uniform sand. The experiments show that wood is dispersed on bar tops, generally in small accumulations containing fewer than five logs. Turnover rates of deposited logs are very high as a result of the highly dynamic evolution of the channel network and bar locations, and do not depend on the wood input rate or the presence of roots. In these model runs, the presence of large wood alone does not affect the morphodynamics of the braided system, highlighting the role of vegetative regeneration and fine sediments in creating stable wood jams and associated fluvial landforms.

Finally, three papers in this special issue explore how interactions between vegetation development and hydromorphological processes (stream power, flow regime and channel migration) control morphodynamic behaviour and evolutionary trajectories in braided rivers. Perona *et al.* (2014) present a 1D ecomorphodynamic model developed to predict vegetation distribution in river reaches with converging banks. 1D equations for flow and sediment transport were modified to include representation of vegetation dynamics in order to predict the minimum channel width below which vegetation is expected to disappear (the vegetation ‘front’). The mathematical model is tested through laboratory flume experiments using a sand bed uniformly seeded with *Avena sativa*. The analysis confirms the role of stream power in setting suitable conditions for vegetation development and the longitudinal position of the vegetation front by increasing uprooting capacity along the convergent reach. The experiments also demonstrate the importance of hydrological timescales (time between flood events) relative to biological timescales (vegetation growth) in controlling the extent of vegetation colonisation.

The relationship between vegetation colonization and hydrological regime is explored in detail by Surian *et al.* (2015) who analyse aerial images of the

Tagliamento River (Italy) for a 60 year period. In this very dynamic, high energy river the turnover of riparian vegetation is high. Half of the vegetated areas persist for less than 5-6 years, and less than 10% persists for more than 20 years. The analysis demonstrates that riparian vegetation can be significantly eroded by relatively frequent, low magnitude flood events (recurrence interval 1–2.5 years), with more densely vegetated areas showing a higher threshold. These findings suggest the ecosystem engineering effect of riparian vegetation is strongly dependent on the hydrological regime and the available stream power and the authors highlight additional controls on vegetation dynamics including occurrence of erodible vegetated margins (for generating wood supply) that influence the development of new islands.

Gran *et al.* (2015) analyse the evolution of feedbacks between riparian vegetation and channel dynamics in an active braided system where sediment loads are decreasing following a volcanic eruption (Mount Pinatubo, Philippines). Following a highly dynamic post-eruption phase, vegetation is now able to persist year-round and actively influence sediment dynamics. Results from a cellular model informed by field data illustrate the importance of the ratio between biological (vegetation development) and morphodynamic (channel migration) timescales in controlling the capacity of vegetation to modify river morphology. In addition, local effects such as strong seasonality of precipitation and sediment load, as well as groundwater level fluctuations, may affect the ability of vegetation to colonise sediment bars and hence determine the evolutionary trajectory of the morphology-vegetation interactions.

The 15 papers in this special issue demonstrate the diversity and breadth of research at the interface between geomorphology and ecology. The findings reported deepen our understanding of the bi-directional interactions between biotic and abiotic components of riverine landscapes, but also make significant contributions to the scientific basis of sustainable river management and restoration. Many of the papers identify key questions requiring further investigation, providing opportunities for novel interdisciplinary collaborations that employ the wide variety of research approaches illustrated in this issue.

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