Towards Biogeomorphic River Restoration: Vegetation as a Critical Driver of Physical Habitat

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Abstract

The current focus of river restoration on flow and sediment transfer without proper consideration of vegetation as a key structuring agent, beyond its stabilising effect, is too simplistic. We contend that vegetation has an essential role in shaping the physical fluvial environment and should be considered equally alongside hydrogeomorphic processes in restoration projects. In support, we introduce engineer plants as important controls, along with flowing water and transported sediments, on the morphodynamics of river systems and associated physical habitat development. The effect of vegetation on channel planform is then summarised, the influence of vegetation on hydrogeomorphic connectivity is outlined, and then the role of vegetation in landform development and habitat provision, as encapsulated in the fluvial biogeomorphic succession model, is described. We then present examples demonstrating how vegetation has contributed to the recovery of degraded rivers through biogeomorphic processes. Finally, we advance the concept of biogeomorphic river restoration by proposing principles to support a closer synthesis of the component sciences and list key areas for practitioners to focus on.

Keywords: riverscape, hydrogeomorphology, connectivity, habitat recovery, riparian vegetation, succession

1 Introduction

Rivers incorporate the active wet channel(s), hyporheic zone, riparian zone and floodplain, and are variously referred to as the river corridor, river landscape or riverscape (Ward, 1989; Fausch et al., 2002). Human activities have altered the riverscape over millennia to such an extent that most rivers now exist in anthropogenic landscapes (Brown et al., 2018). In many watersheds, this is reflected by multiple physical alterations, including impoundment and flow regulation, channelization, sediment mining and land cover change. The scale of these pressures means that many rivers are ecologically degraded and require habitat restoration to support their biological communities (Palmer et al., 2007; Feld et al., 2011). Ultimately, most river restoration projects aim to enhance biodiversity and ecological function by improving habitat conditions. Restoration measures typically involve manipulation of the active channel bed, bank profile, adjacent riparian areas and floodplains, and the water, sediment, and solute inputs to rivers to improve hydrologic, geomorphic, and/or ecological processes, to restabilise lost or degraded system components (Wohl et al., 2015). Initially, restoration approaches sought to engineer specific habitat structures that were considered necessary for certain target species (e.g., salmonids), but this often resulted in unnaturally static conditions with little scope for channel evolution (Wohl et al., 2005). As river restoration practice evolved, it was recognised that riverscapes
are not in a static state reflecting fixed conditions, but rather, fluctuate in response to changes in system drivers and this dynamism is central to habitat creation, maintenance, and renewal (Ward et al., 2002). This led to calls for more holistic approaches to river management (Ward et al., 2001; Newson and Large, 2006; Palmer and Allan, 2006), and for a restoration approach focused on the reestablishment of normative rates and magnitudes of the hydrogeomorphic, chemical, and ecological processes that support river ecosystems (Beechie et al., 2008). Moreover, usage of the term ‘riverscape’ has proliferated in recognition of the interconnectedness of the watershed in terms of physicochemical, ecological processes and human influence. This also reflects the requirement for a more integrated field of enquiry to inform management approaches (Amoros and Bornette, 2002; Allan, 2004; Haslam, 2008).

There is now a greater awareness of the linkages between hydrogeomorphic and ecological processes in shaping fluvial habitat and the critical role of connectivity between these processes in habitat provision (Fausch et al., 2002). For example, the flow regime, its central role in erosion, sediment transport and deposition processes, and how natural flow disturbance is key to maintaining habitat diversity in the riverscape (Poff et al., 1997; Ward et al., 2002). Hence, rivers are commonly viewed as bottom-up, hierarchal systems with hydrology driving channel morphology through its effect on sediment processes and this interaction shaping the physical habitat template for river biota. The same construct has led to significant gains in understanding river hydrosystems, including the spatial distribution of geomorphic units/habitat features and energy pathways, as rivers and their biota are shaped by a changing gradient of physical conditions from their headwaters to mouth (Vannote et al., 1980; Frissell, 1986; Hawkins et al., 1993; Townsend, 1996; Poole, 2002).

This view of rivers is now the dominant paradigm in restoration projects. By applying this bottom-up perspective to restoration projects, stream functions are classed into a hierarchy of categories (Figure 1). High-level functions are supported by lower-level functions. Level 1 (hydrology) underpins all other functions, whereas level 5 (biology) depends on all other functions (Harman et al., 2012; Speed et al., 2016). The pyramid shows the primary direction of cause-and-effect relationships structuring the river system and the assumption that addressing deficiencies in underlying hydrologic and geomorphic processes will also address deficits in biodiversity and ecological function. Fundamental to this approach is matching the slope and cross-sectional dimensions of the target (alluvial) channel with its capacity to transport sediment from upstream to downstream. The presumption is that when this relationship is balanced, it will result in a channel morphology that is in dynamic equilibrium and will replicate key physical habitats (e.g., eddies, pools, riffles, undercut banks, alluvial bars, etc.), even as the channel migrates laterally over time. Correspondingly, restoration approaches are increasingly dominated by the geomorphic and engineering sciences, with physics as the driver and biology as the product (Johnson et al., 2020).

Yet this stream functions pyramid framework on its own is insufficient to communicate the influence of biology on hydrology and geomorphology (and to a lesser extent, geology), and on overall habitat provision. Here, we focus on the physical riverscape structure and processes that shape it. Substantial evidence that organisms influence fluvial geomorphology exists, specifically regarding the ability of vegetation (Gurnell, 2014) and animals (Jones et al., 1994; Wright, 2002; Rice, 2021) to modify flow velocities and sediment deposition and transport, thus, challenging the hierarchical nature of the stream functions pyramid framework. Researchers increasingly recognise the need for biogeomorphic frameworks that conceptualise the influence of biota on sediment transport and geomorphic structure. Hence, fluvial biogeomorphology represents an integration of river ecology, fluvial geomorphology, geology, and hydrology (Figure 2a) with a focus on the role of interactions and
feedback between hydrogeomorphic and ecological components in structuring rivers (Hughes, 1997; Thoms and Parsons 2002; Castro and Thorne, 2019). Since the hydrogeomorphic conditions are significantly influenced by ecological processes, any efforts towards river restoration must realise the nature of this relationship to derive a long-term benefit (Johnson et al., 2020). This entails shifting the focus of river restoration from flow and sediment processes to also harnessing the power of biology to influence river processes and habitat provision (Figure 2b).

Concomitantly, we assert that river structuring forces are not always bottom-up or unidirectional, with abiotic forces driving ecological systems, but often bi-directional and variable depending on time and system attributes. In particular, vegetation dynamics are a key agent structuring the physical environment and should be considered equally alongside hydrogeomorphic processes in restoration projects. The presence of vegetation in river systems has several roles in shaping physical habitat for biota, including:

- Regulation of run-off – hillslope and floodplain vegetation acts as a control on hydrological run-off and associated sediment transport into river channels from the surrounding valley (Tabacchi et al., 2000; Jencso et al., 2011).
- Altered flow dynamics – plants and large fallen dead wood influence flow patterns. They may obstruct and/or deflect flow, creating areas of slower and faster water, side channels, or complex hydraulic conditions that enhance habitat heterogeneity and diversity (Tsujimoto, 1999; Cornacchia et al., 2018).
- Bank cohesiveness – riparian vegetation contributes to channel stability by anchoring sediment and resisting bank erosion (Perucca et al., 2007; Camporeale et al., 2013).
- Landform development – riparian and channel vegetation can slow down water flow, allowing sediment to settle and be retained, leading to the creation of pioneer landforms/habitats such as bars, islands, backwaters and, in the longer term, floodplain features such as scroll bars and oxbow lakes (Corenblit et al., 2007; Corenblit et al., 2015).

Therefore, we focus on the many and varied ways that vegetation shapes the physical environment across space and time in the riverscape. We first establish the basis for plants as river engineers from an applied perspective. Elaborating on this, the role of vegetation in river planform development is reviewed because common practice in restoration design is to consider analogue or near natural/reference river planform in relation to future channel design (Newson and Large, 2006; Brown et al., 2018; Nardini and Conte, 2021). Hydrogeomorphic connectivity (defined here as the degree to which a system facilitates the transfer of water, sediment, and organic matter through itself), another key focus of contemporary restoration is then discussed concerning the influence vegetation exerts on this system property at different scales. We then consider feedbacks between hydrogeomorphic processes and vegetation in directing channel evolution and how these biogeomorphic feedbacks are fundamental to provision of spatially diverse and temporally dynamic habitats in the riverscape. Case study examples demonstrating how biogeomorphic processes have contributed to habitat recovery in degraded rivers are also presented to support our thesis. Finally, we examine how vegetation dynamics can be better integrated into river restoration and outline principles to help set goals for river restoration approaches that incorporate biogeomorphic processes.
In the absence of human interventions, river channels adjust their size and shape in response to interactions among flowing water, transported sediment and colonising plants within the river channel and margins, all of which are affected by local climate (Corenblit et al., 2007, 2011; Gurnell et al., 2012; Gurnell, 2014). These interactions and the relative importance of the contributing processes regulate vegetation growth and successional phases and related habitat turnover in rivers. Some plant species act as physical ecosystem engineers (sensu Jones et al., 1994) by colonising bare riverine sediments and then retaining and reinforcing fine sediments, organic matter and nutrients to build landforms that provide a variety of physical habitats (for a review, see Polvi and Sarneel, 2018). In this way, engineer riparian (e.g., Tabacchi et al., 2019) and aquatic (e.g., Gurnell et al., 2012; O’Hare et al., 2016; O’Briain et al., 2022) plants play a central role in the fluvial biogeomorphic succession (FBS) process (Corenblit et al., 2007), where their impact on progressive landform development facilitates both, their own growth and the colonisation of the habitats they create by other plant species and biota.

Engineer plant species occur across an extensive range of river settings and typically refer to plants that initially colonise bare sediment and then trap further sediment to form embryonic landforms that may become larger as the process evolves. The term ‘engineer’ plant species may include not only pioneers but also secondary species that establish later when conditions are suitable, and they may also have a pronounced effect on river morphodynamics. In higher-energy and more frequently disturbed reaches such as those found in the middle sections of rivers, flow-resistant woody species such as Salix, Alnus and Populus inhabiting the riparian zone are important engineers. In lower-energy reaches, macrophytes are typically abundant and may act as system engineers (Gurnell et al., 2016; O’Hare et al., 2016; O’Briain et al., 2017). These engineers can affect ecological succession dynamics by creating and modifying habitats and facilitating colonisation by other plant species (and biota) in river reaches where sufficient sediment supply exists for landform building and related physical habitat creation. The presence, type and abundance of engineer plant species in a river corridor may determine whether river morphology is dominated by disturbance-related landforms associated mainly with hydrogeomorphic processes (e.g., flood disturbance and sediment mobilisation), or by biogeomorphic landforms (e.g., islands, backwaters, strip levees, bank levees and oxbow lakes), linked to the effects and response of the engineer plant species (Corenblit et al., 2011). In river systems where vegetation dynamics are tightly coupled with flow and landform processes, plants may be the dominant control on river planform.

River restoration projects often start with efforts to establish the historic planform and related reference conditions. Insights from this exercise provide managers with a tool to determine a restoration target state that bridges the gap between near-natural conditions and future planform potential in the contemporary setting. Reconstructions of historical planform morphology can provide important insights into channel processes, alterations to those processes by humans and legacy effects impacting current planform. For example, sediment legacy supplies need to be accounted for to determine the feasibility of a restored planform and its long-term sustainability.
Important physical variables such as gradient and discharge vary along the length of a river from its headwaters to sea, resulting in channel adjustments as patterns of erosion, sediment loading, transport, and storage vary to generate relatively predictable planform configurations (Schumm, 1985). While flow disturbance and sediment transport may be the dominant drivers of channel form in steep upland sections, it is apparent that biogeomorphic processes, and plants as biological agents, are the dominant drivers for several planform types in lower-energy settings (Polvi and Wohl, 2013), where erosional forces are reduced, and the presence of plants increase resistance to flow disturbance. As an example, Figure 3 shows changes to planform (or typologies) as gradient and associated vegetation communities transition from upland to downstream locations along a river course.

3.1 Straight channels

In straight, downcutting channels, typically found in uplands, flood frequency and high shear stress are the dominant controls on channel form. Here, low growing, streamlined plant species such as aquatic mosses have evolved to cope with high shear stress (O’Hare, 2015). However, as flow disturbance becomes more benign in lower river sections, plants increase in abundance and size and may assert considerable control over channel morphology (Gurnell, 2014).

3.2 Braiding channels

Braided channels occur in a wide range of environments associated with moderate to high-energy, coarse-beded rivers and where the influence of riparian vegetation on bank stability is limited. Braided channels form progressively by channel migration and avulsion, leading to dynamic turnover of the multi-thread channels and bar patterns. Establishment of woody species such as *Salix* sp. and *Populus* sp. on gravel bars can lead to the development of pioneer islands and associated multi-thread channel patterns. Once these plants establish in the active channel, they trap sediment and other plant propagules as they grow, leading to enlargement of the landform and, potentially, to larger islands where they may merge with similar pioneer features to form larger post-pioneer and mature islands (Gurnell et al., 2001). These woody plants resist moderate flood events and continue to grow until they are buried by either excessive deposition or scoured by a high-magnitude flood disturbance, and thus, the bar-forming process starts over.

3.3 Sinuous and meandering channels

Moving downstream from braided to increasingly sinuous planforms, riparian vegetation plays a key role in meander dynamics through its effect on bank erodibility. Laboratory and field studies demonstrate that woody riparian vegetation sufficiently increases stream-bank cohesion, overbank roughness and the associated sediment aggradation to cause braided channels to transition to a meandering or anastomosing river planform (Nadler and Schumm, 1981; Braudrick et al., 2009). Some authors have contended that vegetation is so crucial to meander dynamics that meandering rivers may have been very rare before the evolution of land plants (Ielpi et al., 2022). In that sense, riverbank stability is essential to forming and developing sustained channel meanders (for a review, see McMahon and Davies, 2018). In particular, the root system of riparian trees and shrubs may greatly influence meander dynamics by conferring higher erosion resistance on vegetated compared to unvegetated riverbanks, leading to bank areas with higher or lower soil erodibility depending on root density and depth (Perucca et al., 2007; Camporeale et al., 2013).
In the flat lowlands, where flow disturbance is least, macrophytes usually achieve their greatest biomass by developing large leaf surface area for greater photosynthesis and rooting in fine nutrient-rich sediments. In this low gradient, depositing environment, macrophyte stands can exert considerable control on channel morphology (Larsen, 2019). Species such as bur-reed (Sparganium erectum) (O’Hare et al., 2012; Gurnell et al., 2013) and fool’s watercress (Helosciadium nodiflorum) (O’Briain et al., 2017; O’Briain et al., 2022) induce sidebar formation by establishing and trapping fine sediment and propagules of other species on the channel margins, and thus embryonic patches increase into more extensive stands. This process is central for initiating channel adjustments, including narrowing and aggradation.

### 3.4 Anastomosing channels

Finally, anastomosing channels overlaid by floodplain forests in humid biomes may best demonstrate the coupled assembly of plant communities, fluvial landforms and ecosystem evolution over long-time scales. Anastomosing channels can be differentiated from braided channels, in which the latter have flows separated by bars within shallow, unstable channels, and the former, in which relatively deeper individual channels are separated by stabilised vegetated bars and islands that exist over longer periods. In these biogeomorphic systems, riparian tree root complexes maintain island stability by resisting erosion and vertically aggrading sediment, and the addition of large wood drives the formation of new channel patterns through obstruction and diversion (Nanson and Knighton, 1996; Makaske, 2001; Francis et al., 2008). Anastomosing rivers may be formed by avulsions or flow diversions that cause the formation of new channels on the floodplain. At other locations, large fallen wood originating from mature islands may lead to channel infilling and island enlargement where it creates debris dams and living vegetation subsequently establishes to further trap and stabilise sediments.

### 4 Hydrogeomorphic connectivity

Having previously established the important role of vegetation in the planform development, this section provides greater detail on the mechanistic influence of plants on hydrogeomorphic connectivity and its implications for habitat provision within the riverscape. In fluvial hydrosystems, water, sediment, and organic matter are connected across lateral, longitudinal, and vertical dimensions that span spatial and temporal scales. Vegetation intersects with geology and topography to regulate the extent of hydrologic and geomorphic connectivity across scales. The resultant interactions produce a mosaic of nested connections and associated processes operating in the riverscape that support a variety of habitats and associated biological communities (Frissel, 1986; Wiens, 2002) (Figure 4).

#### 4.1 Hydrological connectivity

The transmission of water and nutrients, on which biota depend, is dependent on hydrological connectivity within a system because hydrological processes are critical to nutrient transfer between the land surface and river channel (Jencso et al., 2010; Covino, 2017; Wang et al., 2023). Review studies generally agree that stream flow generation is shaped by vegetation land cover and that different vegetation types reflect different patterns in hydrological connectivity (Bormann et al., 2009; Wei et al., 2013). Broadly, current research shows that forest cover, compared to grassland, may reduce...
average catchment discharge because of (i) increased rainfall interception, (ii) increased transpiration, (iii) reduced soil moisture, and (vi) increased permeability of soils (e.g., Andréassian, 2004; Brown et al., 2005). In catchments located in the mid-eastern (Jencso et al., 2011) and north-western USA (Emanuel et al., 2014), where seasonal run-off from snowmelt is a primary driver of hydrological variability, both studies found coniferous woodland vegetation to be a significant control on hydrological connectivity. Specifically, Jencso et al. (2011) reported that vegetation land cover was an important determinant of annual streamflow during high run-off events and between events through transpiration processes. Similarly, Emanuel et al. (2014) reported that vegetation density interacted with other variables, such as topography, to create variable hydrological connectivity between hillslope, riparian and stream areas with transpiration having a pronounced seasonal effect.

At a more local scale, riparian vegetation affects hydrological processes in several ways (for a review, see Tabacchi et al., 2000). The main impacts include changes to discharge and control of run-off via root storage and evapotranspiration; promotion of overbank flow by stems, branches, and leaves where they act as obstacles; diversion and slowing of flows by log jams; change in the infiltration rate of flood waters and rainfall by leaf litter; increase of substrate porosity by root penetration; the concentration of rainfall by leaves, branches and stems. In relation to macrophytes, they can be very abundant in lowland rivers. In these systems, discharge and flow velocity influence macrophyte colonisation and expansion. However, macrophyte stands can strongly modify flow patterns once established through flow obstruction, deflection, and sediment stabilisation (Cotton et al., 2006; Janauer et al., 2013; Biggs et al., 2018).

4.2 Sediment connectivity

In a given catchment, multiple sediment sources exist, and sediment transfer occurs through coupled relationships within lateral, longitudinal, and vertical dimensions of connectivity. For example, sediment transfer takes place on hillslopes, “between hillslopes and channels (lateral transfer in a slope-channel coupling), between floodplain and channel (bank erosion, floodplain deposition: lateral and vertical accretion) and within channels (longitudinal connectivity associated with downstream sediment transport)” (Fuller and Death, 2018). Hydrogeomorphic connectivity means that sediment loads generated by hydrological and associated erosion events are effectively transferred through the system. The process affects bank erosion, bar development at the local scale and related phenomena at the landscape scale, e.g., channel migration across the valley floor. During high-magnitude flow events, it may also generate avulsions and mass movement (e.g., hillslope collapse) that contribute to geomorphic diversity.

Sediment connectivity enabled by hydrological disturbance events (i.e., flooding) enhances ecological connectivity and biodiversity by promoting a diversity of geomorphic features. In-channel features (e.g., riffles, pools, side bars), meander loops, side channels, braids, backwaters and floodplain features such as scroll bars, abandoned meanders and wetlands can also be considered as a mosaic of habitat patches, ecotones, and successional stages inhabited by different aquatic and terrestrial biological communities (Ward and Wiens, 2001). However, under certain conditions, high hydrogeomorphic connectivity can be potentially detrimental to fauna and flora. For example, high flows and related sediment mobility can directly damage habitat and/or biota through scour and abrasion and intolerable levels of suspended sediment that impair respiratory function, partial or complete burial or sediment dumping on reproduction/spawning sites (Newcombe and McDonald, 1991; Hastie et al., 2001). Indirectly, excessive habitat turnover resulting from high hydrogeomorphic connectivity can degrade biological communities by limiting (spatially and temporally) habitat quality.
and abundance. For example, Madej and Ozaki (2009) documented channel recovery in a coastal Californian river after several large floods in the 1960s-1970s. Vegetation loss associated with intensive logging and road building prior to the floods was responsible for reducing structural resistance, leading to extensive mass movement and high levels of channel aggradation that contributed to extensive geomorphic change. Sediment impacts have persisted for several decades and consequently have reduced the quality and availability of aquatic habitats for anadromous salmonids and retarded population recovery.

In other examples highlighting the role plants play in regulating hydrogeomorphic connectivity and rates of flux, the effects of floodplain and riparian vegetation on system stability have been a subject of research for some time (Millar, 2000; Eaton and Giles, 2009; Andreoli et al., 2020; Zhu et al., 2022). As previously stated, the presence of plants affects lateral geomorphic connectivity by regulating floodplain/bank stability and erosion rates by increasing mechanical resistance to flow disturbance. In a broad geographic study, Ielpi and Lapôtre (2020) investigated vegetation impacts on meandering rates in 483 unvegetated rivers in arid regions and 500 heavily vegetated river meanders in cold, temperate, and tropical regions worldwide. Channel migration rates were, on average, tenfold slower where vegetation was present. The observed slowdown in migration rate was not related to any physical attributes of the river systems, such as channel width, riverbed slope, catchment size or confinement within a valley, but attributed to plants as a dominant control on erosion. This example emphasises the key role of plants in affecting channel patterns at a landscape scale, and the resilience of these landscapes to fluvial disturbance.

Whereas the above example highlights the critical role of plants in regulating lateral hydrogeomorphic connectivity (hillslope, floodplain, riparian and bank areas), aquatic and riparian vegetation is also crucial in moderating longitudinal connectivity. In low-energy rivers, aquatic macrophyte growth and senescence are intimately linked to sediment retention and loss (Jones et al., 2012; Wilkes et al., 2019). Gurnell and Bertoldi (2022) estimated fine sediment retention by vegetation across the active channels of three gravel-bed river types (near-straight, meandering and braided). Vegetation retained nearly all fine sediments found on the bed surface of these active channels, increasing from 78% in the lowest energy to 100% in the highest energy river reaches. In shallow, low-energy streams where macrophytes can grow abundantly, plants will greatly influence the functioning of the ecosystem, at least at the reach scale. Under these conditions, macrophytes, not only trap and stabilise sediment, but also function as a link between bed sediments and the water column. The uptake and temporary storage of nutrients by the plants and the retention of fine sediments within dense plant stands, means that macrophytes in rivers not only affect sediment transport and hydraulics, but are an integral component of nutrient dynamics (Clarke, 2002), which is critical to the ecological function of rivers.

5 Fluvial biogeomorphic succession

Fluvial biogeomorphic succession refers to the progressive changes in vegetation and geomorphic features over time in response to river dynamics and ecological processes (Corenblit et al., 2007). Figure 5 conceptualises a distinct cycle of destruction of fluvial landforms by flood events, and their regeneration via engineer plant species that stabilise sediment during the subsequent biogeomorphic succession process. Plants generate biogeomorphic feedbacks when they reach a critical density threshold. Eventually, as landform development proceeds, vegetated patches aggrade above the water flow and away from flow disturbance, ecological processes become dominant in the stabilisation

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phase. Flood events of varying intensity may reset the process at different phases to begin the renewal process.

Pioneer plants colonise bare substrate patches that are created by fluvial disturbance, where they further trap and aggrade sediments in their canopy and roots. This biogeomorphic succession promotes landform development. This process has ecological implications as landform development affects the very nature of the physical habitat template. For instance, altered hydraulics through flow obstruction or deflection, sediment sorting and related channel morphology may all be mediated by vegetation establishment and its influence on rates of erosion and deposition shape physical habitat (Gurnell and Petts, 2006; Gurnell, 2014). It is important to note that the specific trajectory and pace of fluvial biogeomorphic succession can vary depending on factors such as hydrology, sediment availability, disturbance regimes, vegetation species and types and biotic interactions. Understanding these processes is crucial for effective river restoration and management, as it allows for the implementation of strategies that support the natural progression of vegetation and geomorphic features. By shifting the focus from static patterns to dynamic processes along river networks and incorporating ecological processes alongside flow and sediment processes as a third system driver, advances can be made to understand the interactions and feedbacks at the nexus of habitat creation.

6 Examples of biogeomorphic processes in river restoration

This section provides case study examples demonstrating how biogeomorphic processes have contributed to the recovery of degraded rivers. The examples show the potential for a broad application of biogeomorphology in river restoration as they represent a variety of river settings and spatiotemporal scales alongside common anthropogenic pressures and constraints that can limit management options.

6.1 Recovery of low energy channelized streams following the establishment of macrophyte species (Ireland)

The biogeomorphic recovery period in a gravel bed lowland stream was documented over an eight-year study following the cessation of cyclical dredging and persistent livestock grazing (O’Briain et al., 2017; O’Briain et al., 2022). A review of historical maps from 1829-1841 showed that the Stonyford River previously flowed through wetlands and was liable to bank overtopping during high-flow events. Channelization was undertaken in the 1960s to promote land drainage and facilitate land use change to present-day grazing pastures. This process, together with cyclical maintenance, generated an over-deepened and widened channel with homogenous morphology and high fine sediment deposition on the bed.
Following cessation of dredging and exclusion of livestock from the channel, initiation of more natural vegetation dynamics and interactions with hydrogeomorphic processes occurred quickly to affect a biogeomorphic response. Over the years, the authors documented physical habitat recovery from uniform to more structurally complex habitat. Higher-level channel patterns, including landform development on the margins and promotion of a secondary sinuous channel, emerged from localised interactions and selection processes acting at lower levels, i.e., plant establishment, sediment trapping and subsequent succession (Figure 6). Physical habitat recovery was reflected in greater water depth and substrate diversity characterised by increasing substrate coarseness with higher and more diverse flow velocities. The observed recovery trajectory was analogous to the phases described in the FBS model (Corenblit et al., 2007; Gurnell et al., 2012). Engineer plant species colonised and initiated pioneer landform development on the channel margins. As the landforms aggraded above the flowing channel, they are increasingly disconnected from flow disturbance, indicated by replacement of aquatic plant species by wetland species in this example. Notably, very high macrophyte abundance created a lag in physical recovery evident after the stream became clogged with vegetation (Figure 6, in year 2017) before a more complex pseudo-meander form arose, indicating that recovery trajectories may be non-linear in naturally variable river systems and may require more time to affect change, in contrast to more interventionist approaches to habitat restoration.

6.2 Recovery of low energy channelized streams following establishment of woody riparian species (Tennessee, USA)

Hupp (1992) is amongst the earliest investigations reporting biogeomorphic recovery driven by woody vegetation establishment and bank accretion. The study documented morphodynamic responses following channelization in fifteen low-energy sand bed streams in a watershed. Return time to a pre-channelization state was estimated at ~65 years. Typically, as part of the channelization process, all aquatic and riparian vegetation was removed during the construction of the engineered channel, creating conditions for secondary succession. The author’s description of revegetation post-channelization and the process of biogeomorphic recovery is summarised as follows. Establishment of vegetation on bank slopes and sediment accretion acted together to increase bank cohesiveness as roots of woody plant species acted to aggrade and stabilise sediment. The engineer plant species comprised a mix of woody, fast-growing riparian species (e.g., *Salix* sp.) adapted to flow disturbance and sediment burial, conditions prevalent at the land-water interface. Presence of these species on channel banks and slopes also reduced flow velocities locally during high-flow events, which further enhanced sediment deposition. Increasing bank slope accretion and vegetation on inside bends prompted point-bar development and concomitant vegetation expansion. Correspondingly, point bar expansion increased flow deflection towards the opposite bank, accelerating bank erosion on the outside bend, and ultimately increasing channel sinuosity as meanders developed. Recovery was characterised as a return to a meandering planform, associated point bar features and diverse bank vegetation that extended from the bank top and down the bank slope.

6.3 Post-mining recovery in a moderate energy river (Wales)

Dawson et al. (2022) investigated changes to river planform caused by metal mining, followed by a century of post-mining recovery from 1880 onwards, and the subsequent biogeomorphic impact of common gorse (*Ulex europaeus*) establishment in the floodplain from the late 20th century onwards. The study describes how erosive flood events affected a shift from a pre-mining meandering to a post-
mining braided planform in the absence of stabilising floodplain vegetation because of heavy metal contamination of soils. The authors then propose that a later reduction in grazing pressure by rabbits and subsequent establishment of extensive areas of *U. europaeus* from the late 20th century onwards initiated a relatively rapid process of floodplain and bar stabilization. Channel pattern has responded by returning to a meandering planform (Figure 7) as colonisation of point bars by *U. europaeus* has enhanced sediment accretion. Correspondingly, amplified erosion of outer bends resulting from flow deflection by point bar features has increased lateral space for further bar enlargement through a process of ‘bar-push’ and ‘bank-pull’ that promotes meander development (Allmendinger et al., 2005; Parker et al., 2011; Zen et al., 2017), similar to the process described by Hupp (1992) (Section 5.1.2).

6.4 Moderate-high energy river altered by channelization, gravel abstraction and flow regulation (France)

Corenblit et al. (2020) have shown on the moderate-high energy Isère River (France) that feedbacks between hydrogeomorphic processes and riparian vegetation play a pivotal role in shaping the landscape and guiding vegetation succession within a channelized river corridor constrained by embankments, resulting in a predominantly straightened course. Over three decades, from the early 1970s to the late 1990s, dynamic alternate bars within the river channel were colonised gradually by riparian species, notably poplars and willows (Figure 8). This provided an opportunity to analyse the reciprocal adjustments between fluvial landforms and vegetation, transitioning from bare gravel bars to fully developed upland forests. The spatiotemporal arrangement of vegetated bars within the constrained river channel was a result of the constructive and stabilizing effects of vegetation, as well as interactions among bars of varying age, size and mobility. Analysis revealed strong positive feedback between sedimentary dynamics and vegetation succession, ultimately forming stabilized and raised vegetated bars. These dynamics align with the fluvial biogeomorphic succession (FBS) model, as previously described by the authors (Corenblit et al., 2007). Due to the channelization and confinement of the Isère River within embankments, its ability to naturally adapt its channel plan geometry is constrained. However, even within this highly impacted context, vegetation operated within the artificial confines. Notably, the process of vegetated bars accreting within this channel resulted in the manifestation of fluvial biogeomorphic habitat features in the landscape. The vegetated bars represent structurally complex habitat elements in the riverscape. Their evolution over a relatively short period of time illustrates the important role of biogeomorphic interactions in landform development and associated habitat provision.

6.5 Recovery of a channelized stream in a highly urbanized area (Spain)

The Manzanares River in the city of Madrid (Central Spain) was channelized between the 1910s and 1960s. The channel was transformed into a fixed rectangular concrete form, and a series of retention gates were built to maintain constant water levels. For these reasons, the river was categorised as a heavily modified river due to the presence of multiple pressures such as bank modifications, flow regulation, water pollution and related ecological degradation (Díaz-Redondo et al., 2022). In 2016, a programme to renaturalise the urban river section was initiated by adopting a process-based
7 Integrating vegetation processes into river restoration

Alongside physical scientists, landscape ecologists have invoked dynamic constructs such as the fluvial riverscape to describe river ecosystems (Ward, 2002; Wiens, 2002; Poole, 2002). Synthesis of ideas is not accidental; fluvial processes shape the physical habitat template against which river ecosystems operate. Ecologists and physical scientists have continued to describe the complex interplay between fluvial and ecosystem processes with several conceptual advances including a hierarchical framework for stream habitat classification (Frissell et al., 1986); the river continuum concept (Vannote et al., 1980); the ecological significance of flow disturbance (Junk et al., 1989; Poff et al., 1997); hierarchical patch dynamics (Poole, 2002); hydrogeomorphology as a physical science basis to inform stream ecology (Poole, 2010) and biogeomorphic succession (Gurnell et al., 2001; Corenblit et al., 2007) as key mechanisms explaining spatiotemporal patterns of landforms and communities organization in the riverscape. Each of these has contributed to the hydrological and geomorphological underpinnings of river ecology, and increasingly, the influence of biota on the habitat-landform complex. Full integration of the biogeomorphic dimension of rivers is now necessary to capture the suite of river processes that support the long-term provision of habitat.

Tellingly, changes in river patterns caused by human activities are often associated with enforced changes to vegetation within river catchments (Gurnell et al., 2009). For example, deforestation has caused some formerly braiding European rivers to shift to single-thread patterns and resulted in pronounced re-alignment of rivers in Australia and North America (Williams et al., 2014). The current focus on flow and sediment transfer without proper consideration of vegetation as a key structuring agent, beyond its stabilising effect, is too restrictive for sustainable restoration because the prerequisites for its use: universality and simple causality, seldom apply in natural systems where biota and their abiotic environment are characterised by multiple causalities across space and time. The contemporary view in river restoration practice is that a planform design can be maintained given the appropriate sediment supply, and biota will use associated geomorphic features as habitats. This perspective is too simplistic. As established, biota often interact with hydrogeomorphic processes to initiate and affect the direction of channel evolution. Forced planform change through engineering measures and subsequent flow-sediment dynamics may not be successful or socially acceptable if the spatiotemporal biotic processes controlling planform are not accounted for. For instance, in low-energy rivers, cessation of dredging as part of restoration measures can lead to choking of the channel by aquatic vegetation, and vegetation colonisation and associated expansion of sidebars can increase lateral instability through flow deflection to the opposite bank. As another example, restoration projects returning single-thread channels to historical braided planforms must account for longer-term
succession dynamics, including riparian vegetation establishment and encroachment. Riparian species will not only enhance accretion and/or bank stability but also vertical incision rather than the desired instability necessary for temporary bar formation in braiding systems.

7.1 Principles for biogeomorphic river restoration

Here, we propose principles to support a closer synthesis of the hydrogeomorphic and ecological sciences to advance the concept of biogeomorphic river restoration, but first, the role of plants in biogeomorphic processes can be briefly summarised as follows: (i) biostabilization - the stabilization of sediment as well as the opposite effect, i.e., bioerosion due to mortality of individual plants or vertical incision caused by increased bank strength; (ii) bioconstruction - aggradation of mobile sediment, leading to landform development; (iii) the regulation of soil/sediment moisture regime through physiological processes (e.g., transpiration) and the creation of preferential flow pathways, for example, through root system growth in the subsurface; (iv) surface flow routing, for example, through the formation of physical obstructions that deflect the flow, e.g., as a result of bioconstruction. Moreover, plants established on bare sediment or embryonic landforms facilitate the expansion and complexity of landforms and habitats. The restoration strategy, therefore, becomes one that encourages the propagation of the biological agents that are integral to biogeomorphic processes.

With this knowledge, four principles incorporating the biogeomorphic dimension of vegetation are outlined for consideration in restoration projects:

- Vegetation constitutes an important control on the hydrogeomorphic processes of rivers and related habitat provision. Restoration of natural vegetation dynamics can facilitate normative rates of hydrological and sediment flux. Therefore, restoration interventions should assess whether vegetation dynamics are natural or can be reinstated as part of a holistic strategy to address system deviation.
- When planning river restoration projects, the starting point typically involves establishing how far the location has departed from the historical planform and the potential to reestablish those conditions. Given the importance of vegetation in some planforms, this part of the planning process should consider likely vegetation communities under undisturbed conditions, not just the physical form. Since altered rivers often lack comparative pristine locations, historical analyses of the river system and likely vegetative land cover can produce valuable reference data for reconstructing the character of the riverine system prior to alteration, including the (semi) natural vegetation components.
- Channel evolution and associated landform development are linked to biogeomorphic trajectories. Thus, restoration planning should identify where and when these processes can be encouraged. Such an approach should consider specified river typologies and associated vegetation types and seek to operationalise pathways for appropriate engineer plant species to establish via the phases (Geomorphic, Pioneer, Biogeomorphic and Ecological phase) conceptualised in the FBS model. For vegetation, with reference to engineer plant species, this requires a propagule source and suitable conditions for establishment and expansion as the river evolves in the long term.
- Unless restoration practices are holistic and consider biogeomorphic trajectories, they may fail to understand recovery processes in working towards an eventual planform and the behaviour of a river. Vegetation-induced sediment accretion and/or stability influence channel evolution, but this is not linear. It depends on the traits of the plant species and the spatial and temporal strength of the feedbacks with hydrogeomorphic processes in determining the direction and magnitude of
biogeomorphic change. This means that the nature of the three-way flow-sediment-vegetation relationship must be considered over short, medium and long-time frames for realistic targets to be set at the start of any project.

- Plants can act as agents of recovery, with recolonisation and successional processes facilitating improvement in degraded river ecosystems. Process-based restoration should encourage ecological processes and their biological agents to take a central role in habitat maintenance, without the need for regular human interventions. Biota has evolved to improve their survivorship and, in so doing, they drive biogeomorphic processes and can influence fluvial processes strongly. It is no coincidence that plants are well adapted to the fluvial environment, are adept at responding to disturbance, and can adjust to environmental change by maintaining and modifying habitat.

7.2 Key focus areas for biogeomorphic restoration

Biogeomorphic processes can be extended to existing river restoration frameworks, e.g., the natural flow regime (Poff et al., 1997; Palmer and Ruhi, 2019) or process-based restoration (Beechie et al., 2010) to better link the hydrogeomorphic and biological structure of rivers interacting over temporal and spatial scales. Key biogeomorphic phenomena for river managers to focus on include:

- Retention of fine sediments – macrophytes have a primary role in trapping and regulating fine sediment transport, which is critical to the ecological function of rivers.
- Woody vegetation establishment – their root systems aggrade sediment and/or strengthen bars and banks and their canopy structure creates complex habitats for other organisms.
- Engineer plant species – their establishment in disturbed or newly formed channels and their role in embryonic landform/habitat development.
- Channel evolution and biogeomorphic trajectories – the biogeomorphic template on which landforms/habitat develop is constantly undergoing change depending on the strength of interactions with the flow and sediment regime. The growth and development of vegetation influence the river’s dynamics, leading to changes in channel morphology. In particular, the presence of vegetation can both retard and promote lateral erosion, resulting in the formation of meanders and bank slope vegetation.
- Resiliency – rivers support a mosaic of habitats that are spatially and temporally resilient because their dynamism supports turnover and renewal. This is not a one-way process, with hydrogeomorphology as the creator and biology as the response. The feedback between plants and hydrogeomorphic processes change with rates of colonisation, growth and death, which, in turn, affect channel patterns through its influence on erodibility and sediment movement. In this sense, while every river is unique, the form of rivers and their characteristic vegetation community patterns are repeated across space because physical disturbance acts as a filter on species establishment and plants act as a control on fluvial disturbance. This means that re-establishing natural vegetation dynamics can aid geomorphic function, with recolonisation and successional processes facilitating habitat recovery of degraded river ecosystems.

8 Conclusions
Understanding the mechanisms that contribute to physical habitat diversity is critical because river restoration relies heavily upon the manipulation of channel structure (e.g., sediment patterns, channel dimensions) as a means of managing ecosystem function. Some plant species act as systems engineers by intercepting and stabilising riverine sediments and organic material. This interaction with hydrogeomorphic processes contributes to the development of land forming sequences and a variety of physical habitats. Concomitantly, ecological succession processes serve a crucial role in determining channel planform among braided, meandering, and anastomising types by increasing bank bar and bank stability and the probability of avulsions through large wood delivery in the case of anastomising channels.

Hillslope, floodplain, riparian, and aquatic vegetation all play a role in regulating the timing and magnitude of flood events and the transfer of sediment and organic material through the system. Flood disturbance may partially or completely destroy existing habitats but also provides fresh opportunities for ecological processes and the biological activity that follows during lower flow conditions. Colonisation by plants after flood disturbance and subsequent expansion of vegetation patches percolate through the river ecosystem. Ecological succession on the margins and banks of rivers influences local sediment characteristics (e.g., particle size distributions and cohesion) and hydraulics (flow obstruction and deflection). The same process drives population growth of animals (insects, fish, and other plant species) by stimulating landform and associated physical habitat development. These interactions are responsible for the coupled assembly of plant communities, river landforms and ecosystem development. Incorporation of biogeomorphic processes into river restoration planning and target setting is now required for a more complete approach to long-term provision of habitat in degraded systems. In general, we recommend that river restoration strategies should encourage propagation of the biological agents that are integral to biogeomorphic processes in moderate-low energy valley settings, and the maintenance of physical habitat across spatial and temporal scales.

References


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Data availability statement

The manuscript contains no original or secondary data. All external information contained in the manuscript is referenced and available at those locations.
Figure 1. Stream functions pyramid framework (adapted from Harman et al., 2012).
Figure 2. A biogeomorphic framework conceptualising: (A) the relative controlling influence (grey shaded triangles) of vegetation, hydrology and geology/geomorphology on river morphology, depending on the physical system properties (all capitals) (sensu Castro and Thorne, 2019); (B) vegetation as a control (black line) on hydrogeomorphic processes and feedbacks (broken line) that influence landform development and habitat provision in rivers.
**Figure 3.** A) Illustration of classical river planform types and the dominant controlling force on channel morphology and evolution depending on valley location. B) The dominant vegetation types found in or by each channel planform. C) Typical biogeomorphic landforms that emerge from interactions and feedbacks between hydrogeomorphic processes and vegetation dynamics to influence the overall planform (Images are from rivers in west and southwest of Ireland).
Figure 4. (A) Illustration of vegetation features/habitats interacting with hydrogeomorphic connectivity in a river catchment. (B) Control mechanisms of vegetation as a control on hydrogeomorphic connectivity at locations in the catchment (black text), associated vegetated habitat features and the three dimensions of spatial connectivity (blue text).
Figure 5. Fluvial biogeomorphic succession of rivers (adapted from Corenblit et al., 2007).

Figure 6. Time series (2013-2020) of photographs at two locations (top and bottom) in the Stonyford River, illustrating biogeomorphic trajectory from disturbed to recovering (from left to right) over the study period. Note progressive pioneer landform development on the channel margins.
Figure 7. Planform of the River Ystwyth during mining operations (up to circa 1880), post-mining recovery (1886-1987) and following common gorse (*Ulex europaeus*) establishment (late 20th century-2021) (re-drawn from Dawson et al., 2022).
Figure 8. A simplified spatiotemporal representation of biogeomorphic succession occurring on alternate channel bars and its subsequent effect on landform development in the Isère River, France. Initial colonisation by pioneer grasses and riparian tree species (Willow and Poplar) of lateral bars has contributed to vertical aggradation and stabilisation of sediment over time and facilitated establishment of other tree species (Alder and Ash) that have further enhanced this process (adapted from Corenblit et al., 2020).