






Rewilding watersheds: using nature's algorithms to fix our broken rivers

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Abstract. Rewilding is an ecological restoration concept that promotes the natural recovery of ecosystems, through (initial) active or passive removal of human influence. To support the application of rewilding approaches in rivers and their watersheds, we propose a framework to assess ‘rewilding potential’ based on measurement of basic river ecosystem functions (e.g. restoring flood and nutrient pulses), including examples of specific indicators for these processes. This includes a discussion of the challenges in implementing rewilding projects, such as lack of spatio-temporal data coverage for certain ecosystem functions or tackling ongoing problems once active management is removed. We aim to stimulate new thinking on the restoration of wild rivers, and also provide an annotated bibliography of rewilding studies to support this.

Keywords: freshwater, ecosystem processes, biodiversity, ecology, floodplains, restoration.

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Introduction

Rivers have played a critical role in human history, providing communication routes for trade and access to resources, as sources of food and fibre, and as a result, have become modified and degraded through over-use. Rivers are defined by connectivity, and yet, as societies have developed, rivers have become fragmented, disconnecting floodplains and impounding channels. River alteration has proceeded over millennia, and it is often no longer possible to identify a historical baseline to support restoration goals (e.g. [Brown *et al.* 2018](#)). Restoration of river habitats is a highly active discipline within river science, yet many restoration efforts have been performed by engineers, geomorphologists and community groups, focusing on restoration of

physical habitat through flow management or placement of in-channel structures. These activities rarely consider or address the recovery of basic ecosystem functions, and can require constant injections of cash and resources for their maintenance ([Palmer *et al.* 2014](#)). Moreover, the bulk of restoration efforts tend to focus on <1 km reaches, often in low-order cobble streams ([Palmer *et al.* 2014](#)), rather than entire watersheds incorporating headwaters, tributaries, main channels, floodplains and the surrounding drainage basin. We argue that a new paradigm in river management is urgently required, to renew degraded rivers by first restoring ecosystem functions and reconnecting species to functioning habitats. To achieve this, we believe that a new conservation approach, namely rewilding,

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offers an exciting alternative to incremental, small-scale interventionist approaches.

Pettorelli *et al.* (2018) defined rewilding as ‘the reorganisation of biota and ecosystem processes to set an identified social–ecological system on a preferred trajectory, leading to the self-sustaining provision of ecosystem services with minimal ongoing management’ (p. 1114). We support this reframing of ecosystem restoration around ecosystem ‘self-healing’, but expand thinking in the area of ecosystem services, moving from an anthropocentric – ‘what benefits can the ecosystem provide for humans’ – towards a holistic viewpoint, based on ecosystem functions. This will allow the equitable incorporation of the needs and interdependencies of all species experiencing rapid global change. Although the necessity and pragmatism of rewilding watersheds will differ geographically, according to regional and local context, the first step to applying rewilding approaches to rivers will require an assessment of the ‘rewilding potential’ of a system. To support this, we present a framework below to advance watershed-scale rewilding. By integrating assessment of key ecosystem structures and functions, we propose reconnecting habitats to restore flux and processing of materials across the watershed, promoting self-sustaining and resilient ecological networks, including the maintenance or re-establishment of apex predators, which is a critical indicator of healthy wild rivers. In this way, rewilding offers a fresh approach to restoration that builds on previous knowledge to improve and sustain river health for future generations.

Developing a systematic framework to support river rewilding

Perino *et al.* (2019) described a generic rewilding framework, which identifies species dispersal, trophic complexity, and stochastic disturbance as fundamental properties of natural ecosystems. Incorporating these elements is critical for rewilding regulated rivers, where dams currently obstruct dispersal of migratory fish (Radinger and García-Berthou 2020), reducing trophic complexity through replacement of native species by invasives (Radinger and García-Berthou 2020), and reducing stochastic disturbance through flow homogenisation (Poff *et al.* 2007). We further propose to move beyond vague ‘goal-setting’ (often never achieved, if even achievable), which ignores the restoration of high-level ecosystem processes, towards a science-based rewilding framework designed for rivers and their associated watersheds, including measurable and trackable restoration of basic ecological functions, providing metrics of rewilding success. These should focus on delivering self-sustaining ‘rewilding actions’ that support recovery along a natural trajectory, where feasible (Pettorelli *et al.* 2018).

Rewilding actions would occur at the watershed scale, promoting restoration of critical ecosystem functions, and re-establishing ecosystem linkages across all four dimensions of riverine connectivity (*sensu* Ward 1989). These actions would be explicitly nature-focused, and thus deviate from the current focus on anthropocentric ecosystem services. Fig. 1 illustrates an alternative, nature-based rewilding framework emphasising ecosystem functions, identifying functional, biotic and structural components (*sensu* Palmer and Ruhi 2019). Rewilding is holistic, and thus has a greater chance of ‘success’ when

multiple actions are followed (Fig. 1), reflecting our multi-stressor reality. Previous studies (e.g. Palmer *et al.* 2014) have shown that addressing single components (e.g. flow management) will not guarantee a healthy ecosystem. Rewilding actions must simultaneously address the diverse challenges faced by regulated rivers, such as altered natural sediment and flow regimes, habitat fragmentation, loss of riparian vegetation, reduced water quality and climate warming. Moreover, terrestrial rewilding has focused on the reintroduction of keystone species including apex predators, which is equally important in rivers and their riparian corridors (e.g. river otters; Holland *et al.* 2018). Although interventions in the early stages of rewilding highly degraded rivers are likely to be necessary, we should also be mindful that the most powerful aspect of rewilding is its inherently passive nature, helping humans to ‘get out of the way’, allowing nature to regenerate, rather than being forced to an unsustainable anthropocentric state (Holmes *et al.* 2020).

Rewilding actions can have varying effects on function, depending where in the watershed they are located. Fig. 2 provides an example of the restoration of a river’s natural flow and sediment regime through dam removal, describing the consequences for key ecosystem functions in headwater, main channel and floodplain habitats. Rewilding outcomes by restoration of flows and habitat connectivity could include increased viability of river-edge egg-laying insects in hydropeaking headwater reaches (secondary production; Palmer and Ruhi 2019), improved dispersal of macrophyte propagules in the main channel, promoting primary production (Jones *et al.* 2020), as well as deposition and transport of organic matter into floodplains (decomposition; Langhans and Tockner 2006). Similarly, biotic components in river ecosystems show spatio-temporally varying responses to the restoration of the flow regime. For example, restoring the magnitude and variability of seasonal flow affects the distribution of allochthonous and autochthonous subsidies to the river food web, leading to enhanced food-web structure (Delong 2010; Wellard Kelly *et al.* 2013). Rewilding of structural ecosystem components is supported by removing barriers, providing access to spawning grounds for migratory fish species (habitat provisioning; Barbarossa *et al.* 2020), which, in turn, transport nutrients and organic matter upstream of the former dam (nutrient cycling; Bellmore *et al.* 2019). Moreover, reintroduction of keystone species, including apex predators in the watershed, can support trophic cascades, altering the structure and function of aquatic communities, as shown by recovery of riparian vegetation, songbird communities and beaver populations after the return of wolves in Yellowstone (Beschta and Ripple 2016). Restoring riparian vegetation and reintroducing ecosystem engineers (e.g. beavers) to create thermal or hydraulic refugia both represent actions to mitigate climate warming and, thus, support rewilding (Thakur *et al.* 2020). This will be critical in the future because many ecosystem functions are vulnerable to worsening climate extremes.

Successful implementation of rewilding frameworks into river monitoring will require indicators, data sources and methods that quantify dynamic responses of ecological functions. Although data availability and coverage may currently be sparse for many potential metrics, many data sources and methods exist that can facilitate rewilding efforts (Table 1), including national networks for hydrological and water-quality monitoring and



Fig. 1. Proposed linkages between rewilding goals (curves) on river ecosystem functions. Rewilding goals are coloured according to how many ecosystem functions they affect, with a darker colour corresponding to more functions affected. See Table S1 of the Supplementary material for linkages between functions and actions.

high-resolution, open-source remote sensing data (e.g. satellite imagery). These data sources can be used to compute metrics, supporting ongoing monitoring of the impact of rewilding actions.

Challenges and opportunities for rewilding rivers

A key challenge in rewilding rivers is the need for spatial and temporal upscaling of data collection for all ecosystem components to remove our current data bias arising from point source

collection, with biotic coverage limited to several taxonomic groups (particularly freshwater megafauna; He *et al.* 2018). In temperate rivers, data collection tends to be restricted to the open-water season (e.g. late spring–early fall), with many ecosystem dynamics being largely ignored for the winter months. This is particularly evident in biotic and functional measures, although less apparent in structural components, such as flow monitoring. These data gaps are improving, although slowly, with wide-scale implementation by many governments of

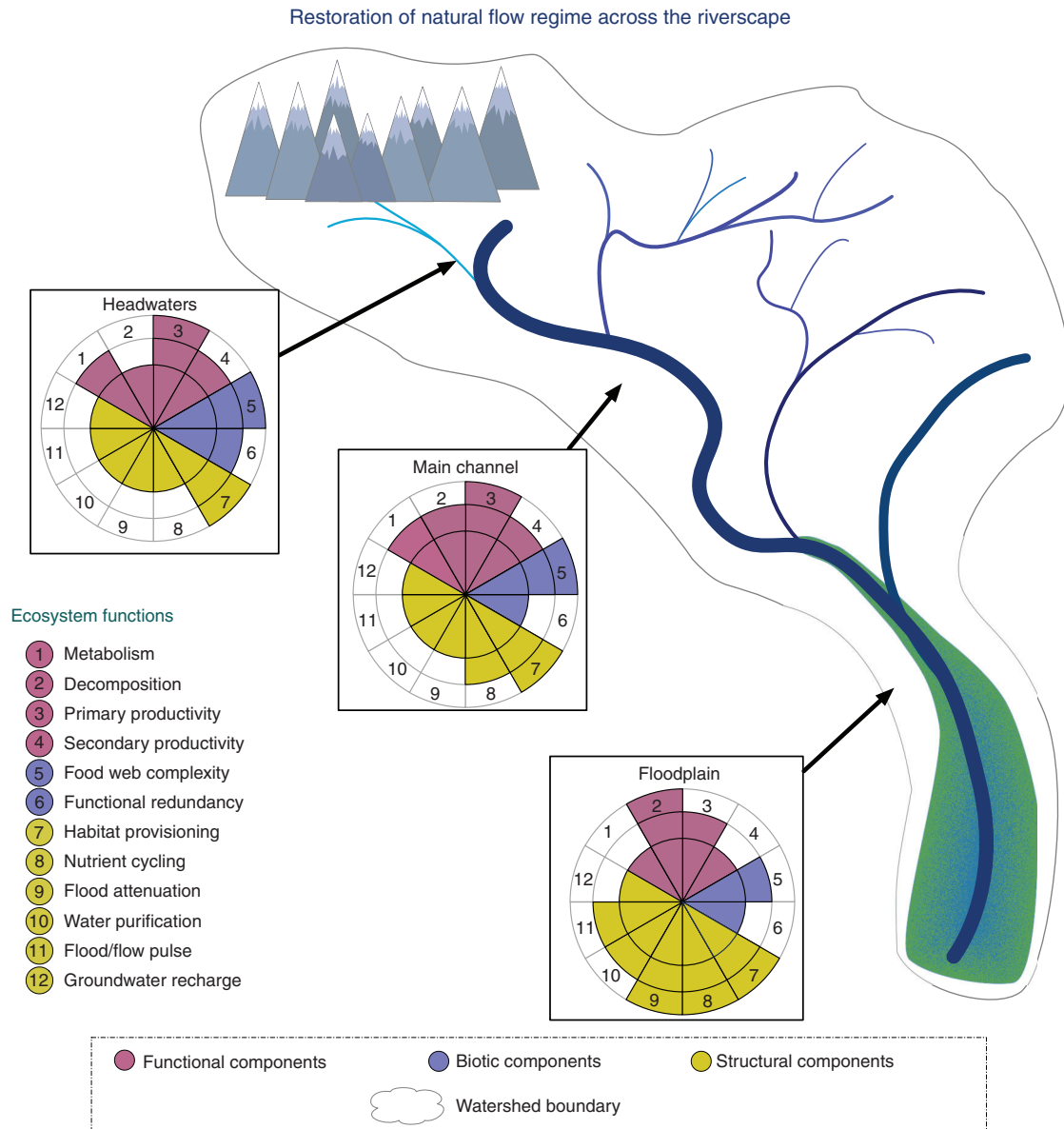


Fig. 2. Conceptualisation of how a rewilding goal (i.e. restoration of natural flow regime) could differentially affect ecosystem functions across headwaters, main channel and floodplain habitats, accounting for linkages among terrestrial, riparian and aquatic components.

remote sensing data (e.g. habitat access for migratory species, monitoring of harmful algal blooms), as well as a rapid expansion of biomonitoring based on DNA-metabarcoding and eDNA observation, covering a wider range of taxa (e.g. Baird and Hajibabaei 2012). Such approaches can identify biodiversity hotspots as priority areas for rewilding, because they contain endemic species and are more likely to be vulnerable in the face of climate change (e.g. Strassburg *et al.* 2020). Moreover, microbes and fungi are overlooked biodiversity elements that play a key role in regulating biogeochemical and nutrient cycling processes, and decomposition. These critical functions ultimately depend on the metabolic capacities and efficiencies, and environmental tolerances, of the microbial and fungal

groups present in an ecosystem. However, immediate consequences in the variation and availability of resources required by microbes strongly control microbial processing rates (Fierer *et al.* 2009; Sinsabaugh *et al.* 2016). This has important implications for climate warming, as rewilding actions could mitigate or accelerate greenhouse-gas emissions through altered microbial activity (Sinsabaugh *et al.* 2016; Andriuzzi and Wall 2018).

River rewilding offers an integrated, nature-based solution for climate adaptation and mitigation. This could include prioritisation of dam removal to restore habitat connectivity, with particular focus on thermal refugia for coldwater species, including fish. Moreover, reprovisioning of habitat through rewilding has implications at the wider riverscape scale, chiefly

Table 1. Rewilding goals focusing on targeted ecosystem functions, including indicators, methods and data sources
References, including URLs, to data sources are available in Supplementary material S2

Goal	Supporting rewilding action	Targeted ecosystem function	Indicator	Indicator methodology	Data source example
Restoring natural flow and sediment regime	Implementing e-flows	Flood/flow pulse	Frequency and duration of high and low flow pulses	Use of raw data from hydrometric networks	Canada's Hydrometric Station Network
Reduce habitat fragmentation	Dam and barrier removal	Habitat provisioning	Barrier density and fragmentation indices	Use of raw data, geographic information systems and modelling to calculate indices	European AMBER Barrier Atlas
Reintroduce extirpated species	Reintroduce ecosystem engineers (e.g. beavers, freshwater mussels)	Nutrient cycling	Trophic state index or water quality index	Use of real-time water quality monitoring and geographic information systems to quantify habitat change	USGS WaterQualityWatch
Improve water quality	Reduce agricultural and industrial runoff	Food-web complexity	Species and functional diversity indices	Use of raw macro-invertebrate community data from monitoring	Canadian Aquatic Biomonitoring Network (CABIN)

for riparian ecosystems. Emerging insects serve as necessary nutritional subsidies for riparian predators, including aerial insectivores. With climate change, increasing water temperature can shift emergence cues earlier into the spring, raising the potential for phenological mismatches or trophic asynchrony (Twining *et al.* 2016; Renner and Zohner 2018). Both of these examples highlight the need to incorporate base-level rewilding to support reintroduction of top predators through enhancing of bottom-up processes including microbial elements, generating healthy ecological interaction networks, and maintaining carbon sink capacity.

Societal perceptions of what is 'wild' or 'natural' change over time (shifting baseline syndrome; Pauly 1995), particularly in human-dominated landscapes where people are reliant on past alterations, and where general adaption has occurred (e.g. Seidl and Stauffacher 2013). Applying a rewilding strategy in such landscapes can appear to threaten traditional livelihoods, causing socio-political conflict. Moreover, the application of rewilding practices could generate adverse consequences, which could reduce societal buy-in for rewilding. For example, dam removal can result in downstream contamination from reservoir-legacy contaminants or facilitate the expansion of invasive species (Hart *et al.* 2002). Consequently, where to prioritise renewal of rewilding potential becomes a critical decision in conservation planning, particularly in highly degraded and fragmented watersheds, as highlighted by a recent study identifying over a million barriers in European rivers (Belletti *et al.* 2020).

Concluding remarks and path forward

We are not alone in suggesting that a new paradigm in river management is urgently needed to reverse multi-stressor driven freshwater ecosystem decline (e.g. the 'curve-bending' approach suggested by Tickner *et al.* (2020)). We argue that rewilding rivers should start with a focus on base-level ecosystem processes, following a nature-based approach. Given that nature and culture are intricately connected, and humans

inhabit landscapes, all have the right to participate within the space of ecological democracy, but it is often more difficult to define who has the right to be heard or to participate in rewilding (Takacs 2020). In North America, for example, application of an *etuaptmunk*, or two-eyed seeing, approach partners ways of knowing from both Western science and Indigenous peoples perspectives, allowing for shared ethical space supporting environmental, social and cultural components of rewilding (Bartlett *et al.* 2012). Co-creating such approaches can incorporate Indigenous ways of knowing and knowledge to provide observations of spatial patterns and temporal trends on the landscape, supported by environmental variables measured by routine Western science methods (e.g. hydrometric stations, remote sensing). Despite the need for rewilding practices on our highly degraded rivers, broad-scale societal uptake is hindered by hydropower dam expansion, particularly in developing nations where individual or societal agency is often restricted by the economic needs of industry (e.g. Latrubesse *et al.* 2017). This signifies an urgent need to seek more nuanced policies surrounding river conservation, prioritising the implementation of rewilding principles and ecological functions identified in our framework.

Applying these rewilding concepts offers a new paradigm that provides a more sustainable and holistic approach to the restoration of functions and structures within river ecosystems. To further promote this new rewilding approach, we have compiled an annotated bibliography of rewilding publications (S3), which is provided as a resource to stimulate new thinking in its application in large-scale river restoration and beyond.

Ethics statement

This research did not involve animal or human research.

Conflicts of interest

Donald J. Baird is an Associate Editor for *Marine and Freshwater Research*. Despite this relationship, he did not at any stage

have editor-level access to this manuscript while in peer review, as is the standard practice for manuscripts submitted by an editor to this journal. *Marine and Freshwater Research* encourages its editors to publish in the journal and has protocols that keep editors completely separate from the decision-making processes for their manuscripts. The authors have no further conflicts of interest to declare.

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