

PERSPECTIVE



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Beaver: The North American freshwater climate action plan

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Abstract

Rivers and streams, when fully connected to their floodplains, are naturally resilient systems that are increasingly part of the conversation on nature-based climate solutions. Reconnecting waterways to their floodplains improves water quality and quantity, supports biodiversity and sensitive species conservation, increases flood, drought and fire resiliency, and bolsters carbon sequestration. But, while the importance of river restoration is clear, beaver-based restoration—for example, strategic coexistence, relocation, and mimicry—remains an underutilized strategy despite ample data demonstrating its efficacy. Climate-driven disturbances are actively pushing streams into increasingly degraded states, and the window of opportunity for restoration will not stay open forever. Therefore, now is the perfect time to apply the science of beaver-based low-tech process-based stream restoration to support building climate resilience across the landscape. Not every stream will be a good candidate for beaver-based restoration, but we have the tools to know which ones are. Let us use them.

This article is categorized under:

Science of Water > Hydrological Processes

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beaver, climate change, floodplain connectivity, process-based restoration, water security, wildfire

1 | INTRODUCTION: BEAVERS, THE CLIMATE ACTION PLAN

Low-tech process-based stream restoration (LTPBR)—a suite of simple, low-cost practices focused on floodplain reconnection—is rapidly gaining traction in the face of looming climate and biodiversity crises (Ciotti et al., 2021;

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Davee et al., 2019; Davis et al., 2021; Johnson et al., 2019; Keeble-Toll, 2018; Munir & Westbrook, 2020; Pearce et al., 2021a, 2021b; Silverman et al., 2019; Wade et al., 2020; Weber et al., 2017; Wheaton et al., 2019). Though the implementation of these methods has a strong theoretical and technical foundation, skepticism lingers—particularly about the efficacy of hand-built, beaver-inspired structures, and beaver coexistence. In particular, recent publications have called into question the practicality of achieving watershed-scale changes through beaver landscape modifications or anthropogenic beaver mimicry (Nash et al., 2018; Nash et al., 2021; Pilliod et al., 2017). This is despite countless of years of Indigenous knowledge on sustainable riparian and beaver management (Albert & Trimble, 2000; Blackfoot Nation, 2018; Blackfoot Nation & Levitus, 2019; Feit, 1986; Gadgil et al., 1993; Keeble-Toll, 2018; Kimmerer, 2000; Kimmerer & Lake, 2001; Sherriff, 2021) and over a century of published data, experiments and analyses (Ives, 1942; Morgan, 1868; Neff, 1957; Ruedemann & Schoonmaker, 1938; Seton, 1929) documenting enhanced hyporheic engagement (Briggs et al., 2013; Janzen & Westbrook, 2011; X. Wang et al., 2018), improved water quality (Cornell et al., 2011; Lazar et al., 2015; Puttock et al., 2017, 2018; Shepherd & Nairn, 2020, 2021), naturalized flow timing (Burchsted et al., 2010), failure of traditional engineering approaches to restoration (D. M. Thompson & Stull, 2002), and wildfire resilience (Fairfax & Whittle, 2020; Foster et al., 2020; Weirich, 2021; Whipple, 2019). Fully floodplain-connected, beaver-occupied riverscapes (Brazier et al., 2021; Larsen et al., 2021) are natural process domains we can no longer afford to ignore.

It may seem trite to say that beavers are a key part of a national climate action plan, but the reality is that they are a force of 15–40 million (Naiman et al., 1988) highly skilled environmental engineers. We cannot afford to work against them any longer; we need to work with them. In most cases, the first step will be starting the physical restoration process before beavers move into a system—setting the stage for functioning floodplain processes (flow, space, structure; Beechie et al., 2010; Cluer & Thorne, 2014; Wheaton et al., 2019). Human intervention may be necessary to restore severely impacted floodplain processes to the point at which beavers and beaver mimicry can be applied (e.g., deeply incised channels, ongoing disruptive land-use practices). In other situations, our first step may be policy changes: for example, if floodplains are intact, but beaver management actions (e.g., the lethal removal of beavers that impact the built environment) prevent population persistence sufficient to further recover these landscapes. Regardless of our role in the conversation, beaver inspired or implemented process-based restoration should be a primary strategy to achieving healthy riverscapes (Macfarlane et al., 2015; Pollock et al., 2015). A stream where beavers thrive is a resilient, productive stream (Pollock et al., 2014). Flourishing beaver populations can be our partner in combating climate change and a bellwether of our progress.

2 | RIVERSCAPE RESTORATION IS THE LOW-HANGING FRUIT

A changing climate amplifies the impacts of impaired riverscapes: more frequent extreme precipitation events in over-capacity channels lead to more flooding (Stott, 2016); increasing air temperature and drier conditions stress valley-bottom vegetation already isolated from hyporheic aquifers, driving wildfires into “megafires” (Finco et al., 2012; Goss et al., 2020; Mori & Johnson, 2013; Swain, 2021; J. Williams, 2013; A. P. Williams et al., 2019); and snow-driven flow regimes shifting to rain-driven bring lower, warmer base-flows and further degraded biotic conditions (Beechie et al., 2013). However, we are not developing riverscape-scale nature-based climate action strategies (Skidmore & Wheaton, 2022). Restoring floodplain connectivity and function is both a climate change mitigation and adaptation strategy because it reverses degradation and recovers natural resilience (Johnson et al., 2019; Pollock et al., 2015; Silverman et al., 2019; Wheaton et al., 2019). Natural riverscape resilience is only achieved through a restoration of floodplain processes (Cluer & Thorne, 2014), not the engineering or imposition of form (ELI, 2016).

The US EPA's latest assessment rates the flowing waters of the United States (CONUS only) as being in less than good condition (e.g., 25%–50% in poor condition; USEPA, 2013). Human activity has drastically reduced floodplain connectivity across the continent, converting valley spanning wetlands to narrow riparian corridors. For example, in the Sacramento Valley of California, riparian forests on well-connected floodplains have been reduced from 24% to less than 0.5% of the land area (Sands & Howe, 1977). Our activities over the last two centuries have reduced active floodplain area by an order of magnitude and degraded half the flowing waters in the United States. Human degradation of riverscapes, left unchecked, creates positive feedback cycles of further degradation under a changing climate (Figure 1). However, beaver-based restoration creates profound opportunities for initiating positive feedback cycles and increasing riverscape resilience.

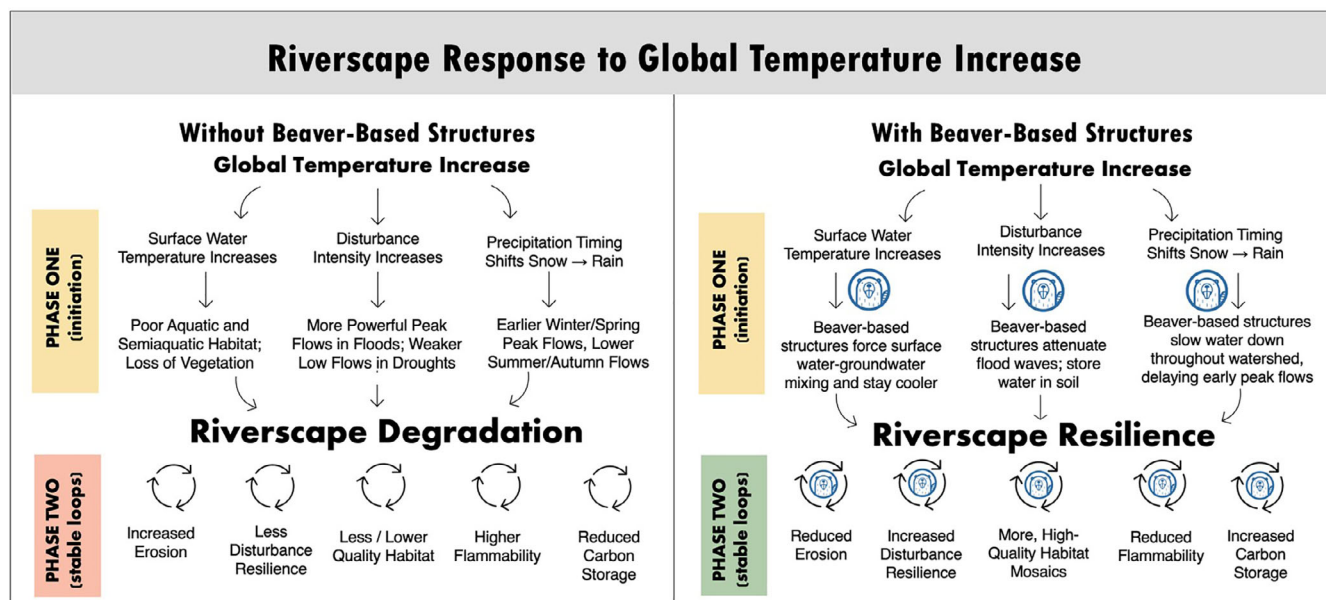


FIGURE 1 Comparison of riverscape feedback cycles with increased global temperature. Phase 1 indicates processes that are initiated by warming global temperatures and lead to either degradation or resilience. Phase 2 indicates processes that occur once riverscapes have already reached a degraded or resilient state. Left: Cycle of increasing riverscape degradation occurring without beaver or beaver mimicry. Right: Cycle of maintained riverscape resilience that can be achieved by partnering with beaver and utilizing beaver-based designs

3 | THE INTERCONNECTED BIOLOGY, HYDROLOGY, AND GEOMORPHOLOGY OF FLOODPLAIN RESILIENCE

Watersheds are typically described by the physical aspects (e.g., flow direction and rate, area, gradient, precipitation, geology) that are thought to drive all characterizing properties (Kasprak et al., 2016). However, watersheds are much more than the sum of their physical properties (Fausch et al., 2002). Watersheds, as riverscapes, are energetically rich, dynamic, bio-geomorphic systems. In temperate mesic climate zones, riverscapes have up to six orders of magnitude more potential energy (chemical) stored in organic material (both live and in the decomposer cycle) than the potential energy (physical) of the in-channel flow (Phillips, 2016). Connected floodplains are more productive than disconnected floodplains in part because of their ability to retain and extract the chemical potential energy of the watershed's biotic (organic) components (Puttock et al., 2018; Wegener et al., 2017). Functioning floodplains are connected because plan-form and longitudinal structures increase resistance to surface water movement, force water up onto floodplain surfaces, and form a diversity of flow paths across the entire valley-bottom (Pollock et al., 2014; Wheaton et al., 2019). This in-channel and across-floodplain hydraulic roughness dissipates flow energy, keeping the transport-deposition balance more to the deposition side, but more importantly, increasing the residence time of surface and hyporheic aquifer water, thereby shortening the length scales of nutrient spirals and increasing ecosystem productivity (Briggs et al., 2013; Helton et al., 2014). Connected-floodplain systems are hydrologically inefficient, a necessary, but often overlooked characteristic.

Many impaired streams, rivers, and associated floodplains are in a state that is physically stable, but simplified and degraded (Cluer & Thorne, 2014). Connected-floodplain systems are dynamic (Naiman et al., 2010). They are in a quasi-equilibrium state across many forcing processes, and thus are inherently more resilient to disturbance than impaired streams (Silverman et al., 2019; Wohl, 2021a; Wohl et al., 2017, 2021). But, maintaining the quasi-equilibrium condition of a connected floodplain requires continual energetic input. This situation is similar to many well-studied coastal marine bio-geomorphic systems—including fringing coral reefs, mangrove swamps, and salt marshes—systems driven by the physics of waves, tidal currents and flowing freshwater, but forced by their biological components (Alongi, 2008; Dame & Patten, 1981; Johnson et al., 2019; Pethick, 1992).

In bio-geomorphic systems, plants and animals form structures that modify the physical environment, resulting in a more productive ecosystem (biomass generated per unit area per unit time) than the same location would be without the structure (Viles, 1988; C. Wang et al., 2020). However, once a bio-geomorphic system has been degraded, it does not

take much to keep it that way (Castro & Thorne, 2019). Restoring high-energy, simplified systems requires re-establishing the biological control of the geomorphic setting (Johnson et al., 2019). In floodplains many of the most important sources of external energy are biological inputs, including organic material deposition, vegetation growth, and beaver dam building. Therefore, embracing ecosystem engineers like beaver is the fast track to low-cost, high-impact sustainable riverscape connectivity (Brazier et al., 2021; Dittbrenner et al., 2018; Johnson et al., 2019; Pollock et al., 2007, 2014).

4 | BENEFITS OF FLOODPLAIN-CONNECTED RIVERS IN A WARMING WORLD

Restoring and reconnecting floodplains clearly provides a myriad of benefits. A floodplain-connected valley is inherently more diverse and productive, not only for aquatic species, but across the entire floodplain (Bellmore & Baxter, 2014). On the seasonally wet floodplain surface, vegetation productivity and plant and animal species richness and diversity are higher than on a disconnected, permanently dry terrace (Stella et al., 2011). In the channels of a connected floodplain reach, primary productivity is higher, macroinvertebrate communities are richer and more productive (Nummi et al., 2021; Robinson et al., 2020), and amphibian and fish productivity is higher (Anderson et al., 2015; Bouwes et al., 2016; Dauwalter & Walrath, 2018; Romansic et al., 2021; Wathen et al., 2019) than in simple channels of a disconnected reach. But, while these internal benefits are independently valuable, they are only a small fraction of the potential benefits that restored riverscapes can provide in the face of climate change. When we reconnect streams and rivers to their floodplains, we perform both climate mitigation work (slowing/stopping the trajectory of global warming) and climate adaptation work (building resilience and resistance to climate-driven disturbances that are already occurring; see Table 1).

4.1 | Slow water—flood, drought, and fire resilience

A diversity of water residence times in a river system enhances the riverscape's ability to attenuate peak flows during wet periods and release stored water as base flow during dry periods, simultaneously mitigating against both drought and flood (Fairfax & Small, 2018; G. A. Hood & Bayley, 2008; G. A. Hood & Larson, 2015; Puttock et al., 2021; Westbrook et al., 2006, 2020). This also helps keep water in the soil during periods of prolonged drought, where it is accessible to riparian vegetation (Amlin & Rood, 2003; Dittbrenner et al., 2018; Fairfax & Small, 2018; Puttock et al., 2021; Silverman et al., 2019; Vivian et al., 2014). However, floodplain-connected riverscapes function as speed bumps to fire spread because the soil, vegetation, and stream channels are wet throughout, and thus do not readily burn (Fairfax & Whittle, 2020; Weirich, 2021; Whipple, 2019; Wohl et al., 2022). Therefore, long stretches of restored floodplains could function as a network of firebreaks, slowing the spread of wildfires and giving humans time to contain runaway wildfires before they reach a dangerous, out-of-control state (Fairfax & Whittle, 2020).

4.2 | Clean, cool water—bolstered aquatic biodiversity

Floodplain-connected riverscapes have more large wood (loose wood, logjams) both on the ground and in the channel. Woody deposits in general increase the physical forcing of stream and floodplain structure and increase water residence time and primary productivity at the floodplain surface (Appling et al., 2014; Briggs et al., 2013; Collins et al., 2012; Helton et al., 2014; Magilligan et al., 2008; Osei et al., 2015; Poole et al., 2008). But, beaver-managed vegetation and stream hydraulic modification (dams, lodges, canals) function similarly, because they directly increase hydraulic diversity and vegetation productivity (Silverman et al., 2019). Thus, hydraulic inefficiency, no matter the source, results in longer water residence time and increased nutrient cycling, which in turn enhances biological productivity across all trophic levels.

Wetlands, inundated floodplains, deep pools, and other areas of slow water within riverscapes help sink out and process common aquatic pollutants such as nitrates, phosphates, metals, and excess sediments (Klotz, 1998, 2010; Kroes & Bason, 2015; Maret et al., 1987; Muskopf, 2007; Puttock et al., 2017, 2018; Shepherd & Nairn, 2020, 2021; Short et al., 2015). Some pollutants bind onto fine sediments which remain suspended in the water column until reaching

TABLE 1 Briefly summarizes how connected- and disconnected-floodplain riverscapes generally respond to several key aspects of climate change (with abbreviated selected references)

	Disconnected floodplains	Connected floodplains	Abbreviated selected references
Water temperature (adaptation)	Homogenous, warmer	Heterogenous, cooler	Majerova et al., 2015, Weber et al., 2017, Dauwalter & Walrath, 2018; Lowry, 1993, Romansic et al., 2021
Carbon (mitigation)	Lower sequestration potential	Higher sequestration potential	Wohl, 2013, Laurel & Wohl, 2019
Floods (adaptation)	Low capacity to accommodate flood waves, higher erosion rates on channel banks from more powerful peak flows	High capacity to accommodate flood waves, lower erosion on channel banks from dissipated peak flows	Westbrook et al., 2006, Westbrook et al., 2020, Puttock et al., 2021
Droughts (adaptation)	Low capacity to maintain primary productivity during extended dry periods	High capacity to maintain primary productivity during extended dry periods	G. A. Hood & Bayley, 2008, Fairfax & Small, 2018, Dittbrenner et al., 2018
Fires (adaptation)	Higher fuel flammability. Loss of riparian vegetation leads to intense post-fire debris entering river from surrounding area	Lower fuel flammability. Intact riparian vegetation slows debris entering river from surrounding area. In-stream structures trap sediment and aggrade within channel, reversing prior channel incision	Fairfax & Whittle, 2020, Wohl et al., 2022, Weirich, 2021, Whipple, 2019

low velocity reaches. Once these fine sediments are either deposited on the floodplain or settled at the bottom of ponds and wetlands, naturally occurring biogeochemical processes transform potent nutrients (e.g., nitrate) into inert compounds (e.g., gaseous nitrogen) or facilitate re-uptake in aquatic vegetation (Yousaf et al., 2021). But, systematic approaches to nature-based riverscape-scale pollution mitigation are lacking, and re-establishing the natural biogeochemical balance of recently restored stream-wetland systems takes time (Weigelhofer et al., 2018). Therefore, structures within streams and rivers, such as natural or artificial beaver dams or better floodplain connection can serve as a network-wide natural mitigation tactic. For example, implementation of LTPBR, especially Beaver Dam Analogs (BDAs), is gaining popularity as a post-fire, land-management strategy to attenuate post-fire debris flows and reduce the suspended ash and soot in the water column (Short et al., 2015).

Many aquatic species have strict water temperature requirements that are regularly exceeded as the climate warms. Structures within rivers, whether human built bio-geomorphic mimics (e.g., Post-Assisted Log Structure [PALS, BDAs]) or naturally occurring (beaver dams, woody debris), generate vertical hydraulic pressure gradients, forcing some of the streamflow down through the river bottom and into the hyporheic zone (Munir & Westbrook, 2020; Scamardo & Wohl, 2020; Wade et al., 2020). There, warm surface water and typically cooler subsurface water can mix before returning to the river downstream (Weber et al., 2017). The residence time of water on these flow paths varies; as a result, so does the temperature of the water as it returns to the river. However, the resulting highly heterogeneous thermal profile of the riverscape supports a variety of aquatic life with different temperature needs (Dauwalter & Walrath, 2018; Lowry, 1993; Majerova et al., 2015, 2020; Romansic et al., 2021). Therefore, in-stream structure, or connected floodplains are a critical component of naturally functioning riverscapes.

4.3 | Complex water pathways—carbon storage and habitat mosaics

Hydrologically complex riverscapes provide a diversity of intermingled habitats that support a vast array of plant and animal species. Naturally occurring beaver dam complexes are uniquely rich and varied components of riverscapes that contain highly heterogeneous water velocities, temperatures, depths, vegetation communities, and geomorphic structures within relatively small areas of the riverscape (Larsen et al., 2021; Rosell et al., 2005; Stringer & Gaywood, 2016). This heterogeneity results in particularly diverse and resilient habitats and is a large part of why beavers are keystone

species (Hammerson, 1994; Naiman et al., 1986; Naiman et al., 1988; Pollock et al., 1995). But, this key bio-fluvial component of riverscapes is rare because a long history of anthropogenic impacts has simplified and disconnected streams from their floodplains (Fouty, 2018). Therefore, floodplain reconnection is often invoked to improve the quantity and quality of physical and biological habitat characteristics needed by fish, amphibians, waterfowl, and other aquatic and semi-aquatic species (Anderson et al., 2015; Baldwin, 2015; Dauwalter & Walrath, 2018; W. G. Hood, 2012; Kauffman et al., 1997; McKinstry et al., 2001; Pollock et al., 2004; Romansic et al., 2021; Snodgrass & Meffe, 1998; Wathen et al., 2019; Wohl, 2021b; Wohl et al., 2021).

The complexity of floodplain-connected rivers increases carbon storage via several mechanisms, including bolstered sequestration in riparian forests and enhanced deposition of organic-rich sediments and deposits of fibrous carbon in periodically and regularly flooded environments (Laurel & Wohl, 2019). But, beaver dam-building activity can increase carbon storage even further via additional streamflow velocity reduction, regular tree coppicing, the expansion of periodically flooded land area, and the frequent inundation of between 10% and 30% of the valley bottom at baseflow. Even relic/inactive beaver-dammed areas store significantly more carbon than those without a recent history of beaver. Recent research indicates that grasslands (which often replace riparian forest in degraded river systems) store on average 40–100 metric tons of carbon per hectare while active and inactive/relic beaver complexes store 1150–1400 and 300–400 metric tons of carbon per hectare, respectively (Wohl, 2013). However, the complete carbon budget of beaver modified floodplains is a spatially and temporally complex balance. Carbon locked up in dead standing vegetation and in organic material deposited in the stream and pond bed is offset by CO₂ and CH₄ emissions from the decomposer cycle. Though not well documented, the net balance is estimated to range from source to sink, depending on pond age, temperature, and soil and vegetation type (Nummi et al., 2018). Thus, riverscape restoration, particularly floodplain restoration with beaver, can support a significant increase in landscape carbon storage, and provide climate mitigation as well as adaptation benefits, though questions remain regarding the factors mediating net carbon storage and thus our ability to design and generalize across all settings.

4.4 | Floodplain dynamics

Overstory vegetation drives photosynthetically active radiation (PAR) levels at the surface of the floodplain terraces and in the stream channels. PAR levels, mediated by nutrient availability, determine the rates of primary productivity on the floodplain surface and in the stream channel. As such, a closed riparian forest canopy is less productive than a multi-level, diverse vegetation stature riparian floodplain plant assemblage of floodplain plants of diverse stature (Ecke et al., 2017). A mature, large-stature riparian plant assemblage only develops on a low disturbance, stable floodplain surface which, in turn, exists when channel migration and braiding rates are minimal. However, channel migration and braiding rates are reduced by processes that stabilize channel location, such as incision and deep, strong plant root growth (Hawley & MacMannis, 2019). Thus, a maximally productive riparian plant assemblage is one with a range of height and structure that tolerates disturbance due to channel migration and formation. But, beaver are also a key structuring agent for floodplain plants (Johnson et al., 2019; Westbrook, 2021). Beaver browse pressure selects for riparian plant species that tolerate the removal of stems, sprouts, or branches. Many browse-adapted plant species are more productive under browse pressure than not. Thus, beavers strongly alter stream and floodplain hydraulics through the digging of beaver canals, tunnels and burrows, and the constructions of dams, food caches, and lodges (G. A. Hood & Larson, 2015).

4.5 | Ecosystem services

Should we entrust a large rodent with such critical environmental engineering tasks? If restoring riverscapes is really such an important piece of our national climate action plan, should not we do it ourselves? Ultimately, the scale of changes that need to occur are beyond what we can accomplish and maintain on our own. However, beaver-based riverscape restoration has a high return on investment in both revenue and expense control (Baldwin, 2015; Blackfeet Nation, 2018; Blackfeet Nation & Levitus, 2019; Pollock et al., 2015; S. Thompson et al., 2021; Wheaton et al., 2019). Revenue generation typically results from increased tourism and outdoor recreation (e.g., hunting, fishing, hiking, camping, wildlife viewing), while expense reduction from lower expenditures in disaster mitigation, carbon management, water quality assurance, and water conservation. These ecosystem services by beaver, as well as many others not

discussed in detail here, is estimated at \$69,000 per square kilometer, per year (S. Thompson et al., 2021). Secondary economic benefits of utilizing beaver coexistence and beaver mimicry in riverscape restoration would help offset the already low cost of implementing beaver mimicry and managing human–beaver conflict (Boyles & Savitzky, 2009).

4.6 | Overcoming institutional constraints to beaver-based restoration

Our fish, water, and forests depend on our willingness to act. We cannot just continue to study the situation without also taking action. There is absolutely more research that needs to be done to optimize and quantify beaver-based restoration impacts across all spatial and temporal scales. In an ideal world, we could wait to act until every last detail was sorted out. However, given the trajectory of climate change and increasingly threatened water resources we simply do not have that kind of time. Thus, we should implement, and continue to study, process-based methods in degraded streams across the continent, now. We should start rewriting our beaver management policies today to actively support coexistence over lethal management so that if and when beavers arrive in a riverscape they can thrive. We should proactively educate wildlife managers, land managers, and the public about the incredible value that these ecosystem engineers bring to our communities. Science and practice can, and should, go hand-in-hand.

There are certainly barriers that stand in the way of implementing beaver-based restoration. In the United States, high-level economic questions linger about the legality of water rights on beaver-impacted streams and the economics of stream restoration credits and whether beaver-created wetlands would count toward those. On a more fundamental sociocultural level, landowners worry that beavers will cut down all the trees, flood the roads, introduce waterborne diseases, and eat threatened fishes if they are allowed to recolonize streams. Some of these worries are founded in reality, for example, beavers do cut down trees, but they will not cut down all of them and there are non-lethal management strategies like wire-wrapping to protect important trees. However, some of these worries are founded in myth, for example, beavers are herbivores and do not eat fish. Understanding the conflicts—both real and perceived—between beavers, humans, and human infrastructure is a critical step for successfully developing and promoting effective coexistence strategies (Auster et al., 2019; Auster et al., 2021; Auster et al., 2022; Charnley et al., 2020; McKinstry & Anderson, 1999; Siemer et al., 2013). Continued education and outreach efforts are key to incentivize beaver-based restoration work (Morzillo & Needham, 2015).

Questions linger on the physical and ecological impacts of beaver-based restoration as well. For example, it is not entirely clear whether the impacts of beaver-based restoration will produce a linear or nonlinear response in the landscape when done at larger scales than researchers have previously examined. The different configurations and constructions of BDAs are still being tested and compared against one another (Davis et al., 2021; Munir & Westbrook, 2020), and more research is needed to determine the optimal configurations for a specific site. There is no clear consensus on how to maximize the chances of success when performing beaver relocation—how to live-trap the beavers, how long to quarantine them, whether or not the relocation site is intentionally prepared or not, if the impacts of relocated beavers versus *in situ* beavers differ, are all important considerations, with relatively little rigorous research published in the scientific literature (Dittbrenner et al., 2018; McCreesh et al., 2019; McKinstry et al., 2001). These unknowns are valid, but they should not completely paralyze beaver-based river restoration efforts. Not every stream will have these issues, and not every project needs to achieve fully optimized maximum restoration on the first attempt. Small restoration gains are better than no restoration gains, and from a precautionary, risk mitigating perspective, incremental progress has enormous value. Focusing beaver-based restoration efforts on streams and rivers with the lowest potential for human conflict and highest potential for restoration gains is a prudent path forward. There are so many streams and rivers that need restoration—it will take time to complete just the simplest, most straightforward projects. But, as projects progress, more data can and will be collected to inform future projects. This is the nature of science and land management in general, and applying this philosophy to beaver-based restoration is not a radical idea.

5 | CONCLUSION: WE NEED (NATURE'S) ENGINEERS

To return the full process-based functionality of connected floodplain systems we must acknowledge the critical role that biological components play—particularly beaver. When we remove beaver from streams and rivers, or prevent them from re-establishing in their ancestral watersheds, the stream-floodplain system falls into disrepair (Wohl, 2021b). Once they are disconnected from their floodplain, down-cut, incised streams simplify into single-threaded channels.

Sediment and carbon are exported from long-term storage, water warms and becomes eutrophic, the landscape dries out and fires run for miles across a uniform expanse of fuel, all leaving little in the way of healthy habitat for fish and wildlife. But, beaver managed floodplains are biodiversity hotspots because beaver ponds and wetlands serve as sinks for carbon, processing centers for nitrogen and phosphorus, reservoirs for the storage and cooling of water, and mitigation sites for both drought and flooding. Thus, it is imperative that we foster beaver-dominated areas for the many services they provide.

We need to apply our knowledge of the physical and biological processes of functioning riverscapes and the role that beavers play to drive rapid, comprehensive, and durable action. Actions that address the pervasive degradation of North America's streams, rivers, and floodplains. Actions that rebuild the natural, functioning dynamics of riverscapes to permit robust responses to disturbance. Riverscape restoration, and in particular process-led and beaver-based restoration, should be the foundation of our national freshwater climate action plan.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Chris E. Jordan: Conceptualization (equal); project administration (equal); writing – original draft (equal); writing – review and editing (equal). **Emily Fairfax:** Conceptualization (equal); project administration (equal); writing – original draft (equal); writing – review and editing (equal).

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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REFERENCES

- Albert, S., & Trimble, T. (2000). Beavers are partners in riparian restoration on the Zuni Indian Reservation. *Ecological Restoration*, 18(2), 87–92 <http://www.jstor.org/stable/43440851>
- Alongi, D. M. (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, 76(1), 1–13.
- Amlin, N. M., & Rood, S. B. (2003). Drought stress and recovery of riparian cottonwoods due to water table alteration along Willow Creek, Alberta. *Trees*, 17, 351–358.
- Anderson, N. L., Paszkowski, C. A., & Hood, G. A. (2015). Linking aquatic and terrestrial environments: Can beaver canals serve as movement corridors for pond-breeding amphibians? *Animal Conservation*, 18, 287–294.
- Appling, A. P., Bernhardt, E. S., & Stanford, J. A. (2014). Floodplain biogeochemical mosaics: A multidimensional view of alluvial soils. *Journal of Geophysical Research: Biogeosciences*, 119(8), 1538–1553.
- Auster, R. E., Barr, S. W., & Brazier, R. E. (2021). Improving engagement in managing reintroduction conflicts: Learning from beaver reintroduction. *Journal of Environmental Planning and Management*, 64(10), 1713–1734. <https://doi.org/10.1080/09640568.2020.1837089>
- Auster, R. E., Barr, S. W., & Brazier, R. E. (2022). Renewed coexistence: Learning from steering group stakeholders on a beaver reintroduction project in England. *European Journal of Wildlife Research*, 68, 1. <https://doi.org/10.1007/s10344-021-01555-6>
- Auster, R. E., Puttock, A., & Brazier, R. (2019). Unravelling perceptions of Eurasian beaver reintroduction in Great Britain. *Area*, 52, 364–375. <https://doi.org/10.1111/area.12576>
- Baldwin, J. (2015). Potential mitigation of and adaptation to climate-driven changes in California's highlands through increased beaver populations. *California Fish and Game*, 101(4), 218–240.

- Beechie, T. J., Imaki, H., Greene, J., Wade, A. A., Wu, H., Pess, G. R., Roni, P., Kimball, J. S., Stanford, J. A., Kiffney, P. M., & Mantua, N. J. (2013). Restoring salmon habitat for a changing climate. *River Research and Applications*, 29(8), 939–960. <https://doi.org/10.1002/rra.2590>
- Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., Roni, P., & Pollock, M. M. (2010). Process-based principles for restoring river ecosystems. *Bioscience*, 60, 209–222.
- Bellmore, J. R., & Baxter, C. V. (2014). Effects of geomorphic process domains on river ecosystems: A comparison of floodplain and confined valley segments. *River Research and Applications*, 30(5), 617–630.
- Blackfoot Nation. (2018). *Blackfoot climate change adaptation plan*. <https://blackfeetclimatechange.com/our-environment/climate-change-adaptation-plan/>
- Blackfoot Nation, & Levitus, J. (2019). *The Ksik Stakii Project beaver mimicry guidebook*. <https://bcapwebsite.files.wordpress.com/2019/12/beaver-mimicry-guidebook.pdf>
- Bouwes, N., Weber, N., Jordan, C. E., Saunders, W. C., Tattam, I. A., Volk, C., Wheaton, J. M., & Pollock, M. M. (2016). Ecosystem experiment reveals benefits of natural and simulated beaver dams to a threatened population of steelhead (*Oncorhynchus mykiss*). *Scientific Reports*, 6, 28581. <https://doi.org/10.1038/srep28581>
- Boyles, S. L., & Savitzky, B. A. (2009). An analysis of the efficacy and comparative costs of using flow devices to resolve conflicts with North American beavers along roadways in the coastal plain of Virginia. In R. M. Timm & M. B. Madon (Eds.), *Proceedings of the 23rd Vertebrate Pest Conference* (Vol. 2008, pp. 47–52). University of California, Davis.
- Brazier, R. E., Puttock, A., Graham, H. A., Auster, R. E., Davies, K. H., & Brown, C. M. L. (2021). Beaver: Nature's ecosystem engineers. *WIREs Water*, 8(1), e1494 <https://www.ncbi.nlm.nih.gov/pubmed/33614026>
- Briggs, M. A., Lautz, L. K., Hare, D. K., & González-Pinzón, R. (2013). Relating hyporheic fluxes, residence times, and redox-sensitive biogeochemical processes upstream of beaver dams. *Freshwater Science*, 32(2), 622–641.
- Burchsted, D., Daniels, M., Thorson, R., & Vokoun, J. (2010). The river discontinuum: Applying beaver modifications to baseline conditions for restoration of forested headwaters. *Bioscience*, 60(11), 908–922.
- Castro, J. M., & Thorne, C. R. (2019). The stream evolution triangle: Integrating geology, hydrology, and biology. *River Research and Applications*, 35(4), 315–326.
- Charnley, S., Gosnell, H., Davee, R., & Abrams, J. (2020). Ranchers and beavers: Understanding the human dimensions of beaver-related stream restoration on western rangelands. *Rangeland Ecology & Management*, 73(5), 712–723.
- Ciotti, D. C., McKee, J., Pope, K. L., Kondolf, G. M., & Pollock, M. M. (2021). Design criteria for process-based restoration of fluvial systems. *Bioscience*, 71(8), 831–845.
- Cluer, B., & Thorne, C. (2014). A stream evolution model integrating habitat and ecosystem benefits. *River Research and Applications*, 30(2), 135–154.
- Collins, B. D., Montgomery, D. R., Fetherston, K. L., & Abbe, T. B. (2012). The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. *Geomorphology*, 139–140, 460–470.
- Cornell, R., Andronesco, A., & Nguyen, K. (2011). *The effects of beaver dams on water quality and habitat*. Dept. of Earth and Atmospheric Sciences, Metropolitan State College of Denver.
- Dame, R. F., & Patten, B. C. (1981). Analysis of energy flows in an intertidal oyster reef. *Marine Ecology Progress Series*, 5(2), 115–124.
- Dauwalter, D. C., & Walrath, J. D. (2018). Beaver dams, streamflow complexity, and the distribution of a rare minnow, *Lepidomeda copei*. *Ecology of Freshwater Fish*, 27, 606–616. <https://doi.org/10.1111/eff.12374>
- Davee, R., Gosnell, H., & Charnley, S. (2019). *Using beaver dam analogues for fish and wildlife recovery on public and private rangelands in eastern Oregon* (Res. Pap. PNW-RP-612; pp. 29). US Department of Agriculture, Forest Service, Pacific Northwest Research Station.
- Davis, J., Lautz, L., Kelleher, C., Vidon, P., Russoniello, C., & Pearce, C. (2021). Evaluating the geomorphic channel response to beaver dam analog installation using unoccupied aerial vehicles. *Earth Surface Processes and Landforms*, 46(12), 2349–2364.
- Dittbrenner, B. J., Pollock, M. M., Schilling, J. W., Olden, J. D., Lawler, J. J., & Torgersen, C. E. (2018). Modeling intrinsic potential for beaver (*Castor canadensis*) habitat to inform restoration and climate change adaptation. *PLoS One*, 13(2), e0192538 <https://www.ncbi.nlm.nih.gov/pubmed/29489853>
- Ecke, F., Levanoni, O., Audet, J., Carlson, P., Eklöf, K., Hartman, G., McKie, B., Ledesma, J., Segersten, J., Truchy, A., & Futter, M. (2017). Meta-analysis of environmental effects of beaver in relation to artificial dams. *Environmental Research Letters*, 12(11), 113002.
- Environmental Law Institute (ELI). (2016). *Stream mitigation: Science, policy, and practice*. Environmental Law Institute <https://www.eli.org/sites/default/files/eli-pubs/stream-mitigation-science-policy-and-practice-finalreport.pdf>
- Fairfax, E., & Small, E. E. (2018). Using remote sensing to assess the impact of beaver damming on riparian evapotranspiration in an arid landscape. *Ecohydrology*, 11(7), 1–14. <https://doi.org/10.1002/eco.1993>
- Fairfax, E., & Whittle, A. (2020). Smokey the beaver: Beaver-dammed riparian corridors stay green during wildfire throughout the western United States. *Ecological Applications*, 30(8), 1–8.
- Fausch, K. D., Torgersen, C. E., Baxter, C. V., & Li, H. W. (2002). Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes: A continuous view of the river is needed to understand how processes interacting among scales set the context for stream fishes and their habitat. *Bioscience*, 52(6), 483–498. [https://doi.org/10.1641/0006-3568\(2002\)052\[0483:LTRBTG\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2002)052[0483:LTRBTG]2.0.CO;2)
- Feit, H. A. (1986). James Bay Cree Indian Management and Moral Considerations of Fur bearers. In *Native people and renewable resource management. 1986 symposium of the Alberta Society of Professional Biologists (ASPB)* (pp. 49–65). ASPB.

- Finco, M., Quayle, B., Zhang, Y., Lecker, J., Megown, K. A., & Brewer, C. K. (2012). *Monitoring trends and burn severity (MTBS): Monitoring wildfire activity for the past quarter century using Landsat data*. Paper presented at the In: Morin, Randall S.; Liknes, Greg C. comps. Moving from status to trends: Forest Inventory and Analysis (FIA) symposium 2012; 2012 December 4–6; Baltimore, MD. Gen. Tech. Rep. NRS-P-105 (pp. 222–228). US Department of Agriculture, Forest Service, Northern Research Station [CD-ROM].
- Foster, C. N., Banks, S. C., Cary, G. J., Johnson, C. N., Lindenmayer, D. B., & Valentine, L. E. (2020). Animals as agents in fire regimes. *Trends in Ecology & Evolution*, 35(4), 346–356.
- Fouty, S. C. (2018). *Euro-American beaver trapping and its long-term impact on drainage network form and function, water abundance, delivery, and system stability*. In Johnson, R., Carothers, S. W., Finch, D. M., Kingsley, K. J., Stanley, J. T. (Tech. eds.). Riparian research and management: Past, present, future: Volume 1. Gen. Tech. Rep. RMRS-GTR-377. USDA USFS Rocky Mountain Research Station (pp. 226). <https://doi.org/10.2737/RMRS-GTR-377>.
- Gadgil, M., Berkes, F., & Folke, C. (1993). Indigenous knowledge for biodiversity conservation. *Ambio*, 22(2), 151–156.
- Goss, M., Swain, D. L., Abatzoglou, J. T., Sarhadi, A., Kolden, C. A., Williams, A. P., & Diffenbaugh, N. S. (2020). Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters*, 15(9), 094016.
- Hammerson, G. A. (1994). Beaver (*Castor canadensis*): Ecosystem alterations, management, and monitoring. *Natural Areas Journal*, 14(1), 44–57.
- Hawley, R. J., & MacMannis, K. R. (2019). Tree roots as a dominant agent of streambed habitat, profile pattern, and grade control. *Geomorphology*, 343, 81–91.
- Helton, A. M., Poole, G. C., Payn, R. A., Izurieta, C., & Stanford, J. A. (2014). Relative influences of the river channel, floodplain surface, and alluvial aquifer on simulated hydrologic residence time in a montane river floodplain. *Geomorphology*, 205, 17–26 <https://www.sciencedirect.com/science/article/pii/S0169555X12000189>
- Hood, G. A., & Bayley, S. E. (2008). Beaver (*Castor canadensis*) mitigate the effects of climate on the area of open water in boreal wetlands in western Canada. *Biological Conservation*, 141(2), 556–567.
- Hood, G. A., & Larson, D. G. (2015). Ecological engineering and aquatic connectivity: A new perspective from beaver-modified wetlands. *Freshwater Biology*, 60(1), 198–208.
- Hood, W. G. (2012). Beaver in tidal marshes: Dam effects on low-tide channel pools and fish use of estuarine habitat. *Wetlands*, 32(3), 401–410.
- Ives, R. L. (1942). The beaver-meadow complex. *Journal of Geomorphology*, 5(3), 191–203.
- Janzen, K., & Westbrook, C. J. (2011). Hyporheic flows along a channelled peatland: Influence of beaver dams. *Canadian Water Resources Journal*, 36(4), 331–347.
- Johnson, M. F., Thorne, C. R., Castro, J. M., Kondolf, G. M., Mazzacano, C. S., Rood, S. B., & Westbrook, C. (2019). Biomic river restoration: A new focus for river management. *River Research and Applications*, 36(1), 3–12.
- Kasprak, A., Hough-Snee, N., Beechie, T., Bouwes, N., Brierley, G., Camp, R., Fryirs, K., Imaki, H., Jensen, M., O'Brien, G., Rosgen, D., & Wheaton, J. (2016). The blurred line between form and process: A comparison of stream channel classification frameworks. *PLoS One*, 11(3), e0150293.
- Kauffman, J. B., Beschta, R. L., Otting, N., & Lytjen, D. (1997). An ecological perspective of riparian and stream restoration in the Western United States. *Fisheries*, 22(5), 12–24.
- Keeble-Toll, A. K. (2018). *Braiding pine: Weaving traditional knowledge, community need, and scientific method in Sierra Nevada meadow restoration*. <https://ui.adsabs.harvard.edu/abs/2018AGUFMPA51C0784K>
- Kimmerer, R. W. (2000). Native knowledge for native ecosystems. *Journal of Forestry*, 98(8), 4–9.
- Kimmerer, R. W., & Lake, F. K. (2001). The role of indigenous burning in land management. *Journal of Forestry*, 99(11), 36–41.
- Klotz, R. L. (1998). Influence of beaver ponds on the phosphorus concentration of stream water. *Canadian Journal of Fisheries and Aquatic Sciences*, 55, 1228–1235.
- Klotz, R. L. (2010). Reduction of high nitrate concentrations in a Central New York state stream impounded by beaver. *Northeastern Naturalist*, 17(3), 349–356.
- Kroes, D. E., & Bason, C. W. (2015). Sediment-trapping by beaver ponds in streams of the mid-Atlantic Piedmont and coastal plain, USA. *Southeastern Naturalist*, 14(3), 577–595.
- Larsen, A., Larsen, J. R., & Lane, S. N. (2021). Dam builders and their works: Beaver influences on the structure and function of river corridor hydrology, geomorphology, biogeochemistry and ecosystems. *Earth-Science Reviews*, 218, 103623.
- Laurel, D., & Wohl, E. (2019). The persistence of beaver-induced geomorphic heterogeneity and organic carbon stock in river corridors. *Earth Surface Processes and Landforms*, 44(1), 342–353.
- Lazar, J. G., Addy, K., Gold, A. J., Groffman, P. M., McKinney, R. A., & Kellogg, D. Q. (2015). Beaver ponds: Resurgent nitrogen sinks for rural watersheds in the northeastern United States. *Journal of Environmental Quality*, 44(5), 1684–1693.
- Lowry, M. M. (1993). *Groundwater elevations and temperature adjacent to a beaver pond in central Oregon* (Thesis). Dept. of Forest Engineering, Oregon State University.
- Macfarlane, W. W., Wheaton, J. M., Bouwes, N., Jensen, M. L., Gilbert, J. T., Hough-Snee, N., & Shvick, J. A. (2015). Modeling the capacity of riverscapes to support beaver dams. *Geomorphology*, 277, 72–99.
- Magilligan, F. J., Nislow, K. H., Fisher, G. B., Wright, J., Mackey, G., & Laser, M. (2008). The geomorphic function and characteristics of large woody debris in low gradient rivers, coastal Maine, USA. *Geomorphology*, 97(3–4), 467–482.

- Majerova, M., Neilson, B. T., Schmadel, N. M., Wheaton, J. M., & Snow, C. J. (2015). Impacts of beaver dams on hydrologic and temperature regimes in a mountain stream. *Hydrology and Earth System Sciences Discussions*, 12(1), 839–878.
- Majerova, M., Neilson, B. T., & Roper, B. B. (2020). Beaver dam influences on streamflow hydraulic properties and thermal regimes. *Science of the Total Environment*, 718(134853), 1–14. <https://www.sciencedirect.com/science/article/pii/S0048969719348454>
- Maret, T. J., Parker, M., & Fannin, T. E. (1987). The effect of beaver ponds on the nonpoint source water quality of a stream in southwestern Wyoming. *Water Research*, 21(3), 263–268.
- McCreesh, R. K., Fox-Dobbs, K., Wimberger, P., Woodruff, K., Holtgrieve, G., & Pool, T. K. (2019). Reintroduced beavers rapidly influence the storage and biogeochemistry of sediments in headwater streams (Methow River, Washington). *Northwest Science*, 93(2), 112–121.
- McKinstry, M. C., & Anderson, S. H. (1999). Attitudes of private-and public-land managers in Wyoming, USA, toward beaver. *Environmental Management*, 23(1), 95–101.
- McKinstry, M. C., Caffrey, P., & Anderson, S. H. (2001). The importance of beaver to wetland habitats and waterfowl in Wyoming. *Journal of the American Water Resources Association*, 37(6), 1571–1577.
- Morgan, L. H. (1868). *The American beaver and his works*. JB Lippincott.
- Mori, A. S., & Johnson, E. A. (2013). Assessing possible shifts in wildfire regimes under a changing climate in mountainous landscapes. *Forest Ecology and Management*, 310, 875–886.
- Morzillo, A. T., & Needham, M. D. (2015). Landowner incentives and normative tolerances for managing beaver impacts. *Human Dimensions of Wildlife*, 20(6), 514–530. <https://doi.org/10.1080/10871209.2015.1083062>
- Munir, T. M., & Westbrook, C. J. (2020). Beaver dam analogue configurations influence stream and riparian water table dynamics of a degraded spring-fed creek in the Canadian Rockies. *River Research and Applications*, 37(3), 330–342.
- Muskopf, S. A. (2007). *The effect of beaver (Castor canadensis) dam removal on total phosphorus concentration in Taylor Creek and wetland, South Lake Tahoe*. Humboldt State University.
- Naiman, R. J., Decamps, H., & McClain, M. E. (2010). *Riparia: Ecology, conservation, and management of streamside communities*. Elsevier.
- Naiman, R. J., Johnston, C. A., & Kelley, J. C. (1988). Alteration of North American streams by beaver. *Bioscience*, 38(11), 753–762.
- Naiman, R. J., Melillo, J. M., & Hobbie, J. E. (1986). Ecosystem alteration of boreal forest streams by beaver (*Castor canadensis*). *Ecology*, 67(5), 1254–1269.
- Nash, C. S., Grant, G. E., Charnley, S., Dunham, J. B., Gosnell, H., Hausner, M. B., Pilliod, D. S., & Taylor, J. D. (2021). Great expectations: Deconstructing the process pathways underlying beaver-related restoration. *Bioscience*, 71(3), 249–267. <https://doi.org/10.1093/biosci/biaa165>
- Nash, C. S., Selker, J. S., Grant, G. E., Lewis, S. L., & Noël, P. (2018). A physical framework for evaluating net effects of wet meadow restoration on late-summer streamflow. *Ecohydrology*, 11(5), e1953.
- Neff, D. J. (1957). Ecological effects of beaver habitat abandonment in the Colorado Rockies. *The Journal of Wildlife Management*, 21(1), 80–84.
- Nummi, P., Liao, W., van der Schoor, J., & Loehr, J. (2021). Beaver creates early successional hotspots for water beetles. *Biodiversity and Conservation*, 30(10), 2655–2670.
- Nummi, P., Vehkaoja, M., Pumpanen, J., & Ojala, A. (2018). Beavers affect carbon biogeochemistry: Both short-term and long-term processes are involved. *Mammal Review*, 48(4), 298–311. <https://doi.org/10.1111/mam.12134>
- Osei, N. A., Gurnell, A. M., & Harvey, G. L. (2015). The role of large wood in retaining fine sediment, organic matter and plant propagules in a small, single-thread forest river. *Geomorphology*, 235, 77–87.
- Pearce, C., Vidon, P., Lautz, L., Kelleher, C., & Davis, J. (2021a). Impact of beaver dam analogues on hydrology in a semi-arid floodplain. *Hydrological Processes*, 35(7), e14275. <https://doi.org/10.1002/hyp.14275>
- Pearce, C., Vidon, P., Lautz, L., Kelleher, C., & Davis, J. (2021b). Short-term impact of beaver dam analogues on streambank erosion and deposition in semi-arid landscapes of the western USA. *River Research and Applications*, 37(7), 1032–1037.
- Pethick, J. (1992). Saltmarsh geomorphology. In *Saltmarshes: Morphodynamics, conservation and engineering significance* (pp. 41–62). Cambridge, England: Cambridge University Press.
- Phillips, J. D. (2016). Landforms as extended composite phenotypes. *Earth Surface Processes and Landforms*, 41(1), 16–26.
- Pilliod, D. S., Rohde, A. T., Charnley, S., Davee, R. R., Dunham, J. B., Gosnell, H., Grant, G. E., Hausner, M. B., Huntington, J. L., & Nash, C. (2017). Survey of beaver-related restoration practices in rangeland streams of the Western USA. *Environmental Management*, 61(1), 58–68. <https://doi.org/10.1007/s00267-017-0957-6>
- Pollock, M. M., Beechie, T. J., & Jordan, C. E. (2007). Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. *Earth Surface Processes and Landforms*, 32(8), 1174–1185.
- Pollock, M. M., Beechie, T. J., Wheaton, J. M., Jordan, C. E., Bouwes, N., Weber, N., & Volk, C. (2014). Using beaver dams to restore incised stream ecosystems. *Bioscience*, 64(4), 279–290.
- Pollock, M. M., Castro, J., Jordan, C. E., Lewallen, G., & Woodruff, K. (2015). *The beaver restoration guidebook: Working with beaver to restore streams, wetlands, and floodplains* (Version 1.02) (p. 189). United States Fish and Wildlife Service.
- Pollock, M. M., Naiman, R. J., Erickson, H. E., Johnston, C. A., Pastor, J., & Pinay, G. (1995). Beaver as engineers—Influences on biotic and abiotic characteristics of drainage basins. *Linking Species & Ecosystems*, 117–126. Boston, MA: Springer. <https://doi.org/10.1007/978-1-4615-1773-3>

- Pollock, M. M., Pess, G., & Beechie, T. J. (2004). The importance of beaver ponds to Coho Salmon production in the Stillaguamish River basin, Washington, USA. *North American Journal of Fisheries Management*, 24, 749–760.
- Poole, G. C., O'Daniel, S. J., Jones, K. L., Woessner, W. W., Bernhardt, E. S., Helton, A. M., Stanford, J. A., Boer, B. R., & Beechie, T. J. (2008). Hydrologic spiralling: The role of multiple interactive flow paths in stream ecosystems. *River Research and Applications*, 24(7), 1018–1031. <https://doi.org/10.1002/rra.1099>
- Puttock, A., Graham, H. A., Ashe, J., Luscombe, D. J., & Brazier, R. E. (2021). Beaver dams attenuate flow: A multi-site study. *Hydrological Processes*, 35(2), e14017 <https://www.ncbi.nlm.nih.gov/pubmed/33678948>
- Puttock, A., Graham, H. A., Carless, D., & Brazier, R. E. (2018). Sediment and nutrient storage in a beaver engineered wetland. *Earth Surface Processes and Landforms*, 43, 2358–2370. <https://doi.org/10.1002/esp.4398>
- Puttock, A., Graham, H. A., Cunliffe, A. M., Elliott, M., & Brazier, R. E. (2017). Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands. *Science of the Total Environment*, 576, 430–443 <https://www.ncbi.nlm.nih.gov/pubmed/27792958>
- Robinson, C. T., Schweizer, P., Larsen, A., Schubert, C. J., & Siebers, A. R. (2020). Beaver effects on macroinvertebrate assemblages in two streams with contrasting morphology. *Science of the Total Environment*, 722, 137899.
- Romansic, J. M., Nelson, N. L., Moffett, K. B., & Piovita-Scott, J. (2021). Beaver dams are associated with enhanced amphibian diversity via lengthened hydroperiods and increased representation of slow-developing species. *Freshwater Biology*, 66(3), 481–494. <https://doi.org/10.1111/fwb.13654>
- Rosell, F., Bozser, O., Collen, P., & Parker, H. (2005). Ecological impact of beavers *Castor fiber* and *Castor canadensis* and their ability to modify ecosystems. *Mammal Review*, 35(3), 248–276.
- Ruedemann, R., & Schoonmaker, W. J. (1938). Beaver dams as geologic agents. *Science*, 88(2292), 523–525.
- Sands, A., & Howe, G. (1977). Riparian forests in California, their ecology and conservation. Paper presented at the Importance, Preservation and Management of Riparian Habitat: A Symposium, Tuscon, AZ.
- Scamardo, J., & Wohl, E. (2020). Sediment storage and shallow groundwater response to beaver dam analogues in the Colorado front range, USA. *River Research and Applications*, 36(3), 398–409.
- Seton, E. T. (1929). *Lives of game animals* (Vol. 4, pp. 441–501). Doubleday, Doran and Co.
- Shepherd, N. L., & Nairn, R. W. (2020). Metals retention in a net alkaline mine drainage impacted stream due to the colonization of the North American beaver (*Castor canadensis*). *Science of the Total Environment*, 731, 139203.
- Shepherd, N. L., & Nairn, R. W. (2021). Induced mobilization of stored metal precipitates from beaver (*Castor canadensis*) created wetlands on a mine drainage impacted stream. *Wetlands Ecology and Management*, 30, 127–137.
- Sherriff, L. (2021). *Beaver believers: Native Americans promote resurgence of 'nature's engineers'*. The Guardian.
- Short, L. E., Gabet, E. J., & Hoffman, D. F. (2015). The role of large woody debris in modulating the dispersal of a post-fire sediment pulse. *Geomorphology*, 246, 351–358.
- Siemer, W. F., Jonker, S. A., Decker, D. J., & Organ, J. F. (2013). Toward an understanding of beaver management as human and beaver densities increase. *Human-Wildlife Interactions*, 7(1), 114–131.
- Silverman, N. L., Allred, B. W., Donnelly, J. P., Chapman, T. B., Maestas, J. D., Wheaton, J. M., & White, J. (2019). Low-tech riparian and wet meadow restoration increases vegetation productivity and resilience across semiarid rangelands. *Restoration Ecology*, 27(2), 269–278. <https://doi.org/10.1111/rec.12869>
- Skidmore, P., & Wheaton, J. M. (2022). Natural infrastructure—Can restored riverscapes help us adapt to climate change. *Anthropocene*. <https://doi.org/10.13140/RG.2.2.33525.86248>
- Snodgrass, J. W., & Meffe, G. K. (1998). Influence of beavers on stream fish assemblages: Effects of pond age and watershed position. *Ecology*, 79(3), 928–942.
- Stella, J. C., Hayden, M. K., Battles, J. J., Piégay, H., Dufour, S., & Fremier, A. K. (2011). The role of abandoned channels as refugia for sustaining pioneer riparian forest ecosystems. *Ecosystems*, 14(5), 776–790.
- Stott, P. (2016). How climate change affects extreme weather events. *Science*, 352(6293), 1517–1518.
- Stringer, A. P., & Gaywood, M. J. (2016). The impacts of beavers *Castor* spp. on biodiversity and the ecological basis for their reintroduction to Scotland, UK. *Mammal Review*, 46(4), 270–283.
- Swain, D. L. (2021). A shorter, sharper rainy season amplifies California wildfire risk. *Geophysical Research Letters*, 48(5), 1–5.
- Thompson, D. M., & Stull, G. N. (2002). The development and historic use of habitat structures in channel restoration in the United States: The grand experiment in fisheries management. *Géographie Physique et Quaternaire*, 56(1), 45–60.
- Thompson, S., Vehkaoja, M., Pellikka, J., & Nummi, P. (2021). Ecosystem services provided by beavers *Castor* spp. *Mammal Review*, 51(1), 25–39.
- USEPA. (2013). *National rivers and streams assessment 2013–2014: A collaborative survey* (EPA-841-R-19-001).
- Viles, H. A. (1988). *Biogeomorphology*. B. Blackwell.
- Vivian, L. M., Godfree, R. C., Colloff, M. J., Mayence, C. E., & Marshall, D. J. (2014). Wetland plant growth under contrasting water regimes associated with river regulation and drought: Implications for environmental water management. *Plant Ecology*, 215(9), 997–1011.
- Wade, J., Lautz, L., Kelleher, C., Vidon, P., Davis, J., Beltran, J., & Pearce, C. (2020). Beaver dam analogues drive heterogeneous groundwater–surface water interactions. *Hydrological Processes*, 34(26), 5340–5353.

- Wang, C., Smolders, S., Callaghan, D. P., van Belzen, J., Bouma, T. J., Hu, Z., Wen, Q., & Temmerman, S. (2020). Identifying hydrogeomorphological conditions for state shifts from bare tidal flats to vegetated tidal marshes. *Remote Sensing*, 12(14), 2316. <https://doi.org/10.3390/rs12142316>
- Wang, X., Shaw, E. L., Westbrook, C. J., & Bedard-Haughn, A. (2018). Beaver dams induce hyporheic and biogeochemical changes in riparian areas in a mountain peatland. *Wetlands*, 38(5), 1017–1032.
- Wathen, G., Allgeier, J. E., Bouwes, N., Pollock, M. M., Schindler, D. E., & Jordan, C. E. (2019). Beaver activity increases habitat complexity and spatial partitioning by steelhead trout. *Canadian Journal of Fisheries and Aquatic Sciences*, 76(7), 1086–1095.
- Weber, N., Bouwes, N., Pollock, M. M., Volk, C., Wheaton, J. M., Wathen, G., Wirtz, J., & Jordan, C. E. (2017). Alteration of stream temperature by natural and artificial beaver dams. *PLoS One*, 12(5), e0176313 <https://www.ncbi.nlm.nih.gov/pubmed/28520714>
- Wegener, P., Covino, T., & Wohl, E. E. (2017). Beaver-mediated lateral hydrologic connectivity, fluvial carbon and nutrient flux, and aquatic ecosystem metabolism. *Water Resources Research*, 53, 4606–4623.
- Weigelhofer, G., Hein, T., & Bondar-Kunze, E. (2018). Phosphorus and nitrogen dynamics in riverine systems: Human impacts and management options. In S. Schmutz & J. Sendzimir (Eds.), *Riverine ecosystem management: Aquatic ecology series 8*. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-73250-3_10
- Weirich, J. J. (2021). *Beaver moderated fire resistance in the north cascades and potential for climate change adaptation* (Masters thesis collection 660). Eastern Washington University. <https://dc.ewu.edu/theses/660>
- Westbrook, C. J. (2021). Beaver as agents of plant disturbance. In *Plant disturbance ecology* (pp. 489–528). Elsevier.
- Westbrook, C. J., Ronnquist, A., & Bedard-Haughn, A. (2020). Hydrological functioning of a beaver dam sequence and regional dam persistence during an extreme rainstorm. *Hydrological Processes*, 34(18), 3726–3737.
- Westbrook, C. J., Cooper, D. J., & Baker, B. W. (2006). Beaver dams and overbank floods influence groundwater–surface water interactions of a Rocky Mountain Riparian area. *Water Resources Research*, 42(6), 06404. <https://doi.org/10.1029/2005WR004560>
- Wheaton, J. M., Bennett, S. N., Bouwes, N. W., Maestas, J. D., & Shahverdian, S. M. (2019). *Low-tech process-based restoration of Riverscapes: Design manual*. Utah State University Restoration Consortium.
- Whipple, A. (2019). *Riparian resilience in the face of interacting disturbances: Understanding complex interactions between wildfire, erosion, and beaver (Castor canadensis) in grazed dryland riparian systems of low order streams in North Central Washington State, USA* (Masters thesis collection 586). Eastern Washington University.
- Williams, A. P., Abatzoglou, J. T., Gershunov, A., Guzman-Morales, J., Bishop, D. A., Balch, J. K., & Lettenmaier, D. P. (2019). Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future*, 7(8), 892–910.
- Williams, J. (2013). Exploring the onset of high-impact mega-fires through a forest land management prism. *Forest Ecology and Management*, 294, 4–10.
- Wohl, E. (2013). Landscape-scale carbon storage associated with beaver dams. *Geophysical Research Letters*, 40(14), 3631–3636.
- Wohl, E. (2021a). An integrative conceptualization of floodplain storage. *Reviews of Geophysics*, 59(2), e2020RG000724.
- Wohl, E. (2021b). Legacy effects of loss of beavers in the continental United States. *Environmental Research Letters*, 16(2), 025010.
- Wohl, E., Castro, J., Cluer, B., Merritts, D., Powers, P., Staab, B., & Thorne, C. (2021). Rediscovering, reevaluating, and restoring lost river-wetland corridors. *Frontiers in Earth Science*, 9, 511.
- Wohl, E., Lininger, K. B., & Scott, D. N. (2017). River beads as a conceptual framework for building carbon storage and resilience to extreme climate events into river management. *Biogeochemistry*, 141(3), 365–383.
- Wohl, E., Marshall, A. E., Scamardo, J., White, D., & Morrison, R. R. (2022). Biogeomorphic influences on river corridor resilience to wildfire disturbances in a mountain stream of the Southern Rockies, USA. *Science of the Total Environment*, 820, 153321.
- Yousaf, A., Khalid, N., Aqeel, M., Noman, A., Naeem, N., Sarfraz, W., Ejaz, U., Qaiser, Z., & Khalid, A. (2021). Nitrogen dynamics in wetland systems and its impact on biodiversity. *Nitrogen*, 2, 196–217. <https://doi.org/10.3390/nitrogen2020013>

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