Opinion

Of wood and rivers: bridging the perception gap

Ellen Wohl*

Wood and beaver dams were historically much more abundant along river corridors from the tropics to the boreal zone. An extensive scientific literature documents the physical and ecological functions created by instream and floodplain wood. By enhancing physical diversity, wood mediates fluxes of water, solutes, organic matter, and sediment; enhances habitat abundance and diversity; promotes retention and biogeochemical uptake of nutrients; and increases biodiversity. Perceptions of wood in rivers, however, remain largely negative and wood is seldom incorporated in river management and restoration plans outside of the U.S. Pacific Northwest. People are unused to seeing wood in river corridors as a result of a long history of deliberate wood removal from rivers, combined with altered land cover and river engineering that reduced quantities of wood in rivers. Negative perceptions of wood in rivers may also reflect hazards, including damage to infrastructure from mobile wood or wood accumulations at bridges that enhance flood damages. People are also unused to seeing beavers in river corridors because of a long history of beaver trapping and substantially reduced beaver populations throughout Eurasia and North America. Extensive and sustained removal of wood and beavers from river corridors has created substantial changes in the appearance and function of rivers. As river restoration increasingly emphasizes re-creation of processes rather than static forms, the river science community has an opportunity to increase public recognition of the vital role played by wood and beavers in sustaining physically and biologically diverse and resilient river ecosystems.

How to cite this article:
WIREs Water 2015. doi: 10.1002/wat2.1076

INTRODUCTION

The concept of a shifting baseline—a change in how a system is measured in terms of previous reference points—has been applied to understanding scenarios as diverse as landscape configuration, commercial fisheries, and ecosystem health. A shifting baseline is present when expectations for a particular system change through time. For example, people who have only seen second growth and managed forests are likely to consider these, rather than old-growth, as the standard for how a healthy forest appears and functions. Shifting baselines strongly influence perceptions and management of river corridors, particularly with respect to wood in river corridors. In this paper, I explore the perception gap between river scientists and the general public regarding wood in river corridors and suggest strategies for closing this gap.

RIVERS IN THE FOREST PRIMEVAL

A great many of the world's rivers, from tiny headwater creeks to the Amazon and Congo Rivers, flow through forested valley bottoms. When a tree falls in one of these forests, wood enters the river corridor, defined here as the channel and floodplain. Even if a tree does not fall over, it continually sheds parts of itself. Leaves or needles, flowers, seed cases, and branches fall to the ground in a steady rain of organic matter that ecologists subdivide based on size. Fine

*Correspondence to: Ellen.wohl@colostate.edu

Department of Geosciences, Colorado State University, Fort Collins, CO, USA

Conflict of interest: The author has declared no conflicts of interest for this article.

particulate organic matter is >0.45 μm to <1 mm in size. Coarse particulate organic matter is >1 mm in size. Entire trees or tree trunks are the coarsest organic matter. Size-based definitions vary among studies, but the most common thresholds for designating coarse wood pieces are 10 cm average diameter and 1 m length. Any portion of such a wood piece within the active stream channel constitutes instream wood and any portion within the floodplain is floodplain wood.

Beaver dams form a distinctive subset of wood within river corridors. Although individual pieces of wood within these dams can be smaller than the size thresholds listed above, the presence of the channel-spanning dam creates physical and ecological effects similar to those associated with larger wood pieces and logjams. Beaver dams are also distinctive in that they are actively maintained by beavers and, in suitable habitat, are closely spaced in a downstream direction and can completely span the floodplain.

An extensive scientific literature describes the structure and functions of wood and beaver dams within river corridors. Several salient points can be drawn from this literature. Within historically forested regions, wood was much more abundant in river corridors prior to clearing of native land cover and intensive manipulation of river corridors via channelization or river training, levees, floodplain drainage, and flow regulation. Drawing on diverse historical records, I have documented the existence of natural wood rafts—persistent accumulations of wood that extended for tens to hundreds of kilometers—along moderate to large rivers across forested regions of the United States.[1] The most famous of these, the Great Raft on Louisiana's Red River, affected nearly 500 km of the main channel and existed for more than a century.[2] The first written descriptions of individual rivers typically included phrases such as the 1818 assessment of Georgia's Oconee River as being 'very much infested with logs'.[3] Such rafts were also likely present along forested rivers in Eurasia, but wood has been removed from Eurasian rivers for so long[4,5] that little historical documentation exists of natural wood rafts.

Beavers and their dams were also much more abundant historically within forested portions of Eurasia and North America. Ecologists estimate that as many as 400 million beavers (*Castor canadensis*) occupied North American river corridors from the eastern coast to the western coast and from central Alaska to northern Mexico.[6] At present, only 6–12 million beavers remain in North America.[6] Although I have not seen historical population estimates for *Castor fiber*, the European beaver was present from Britain across Eurasia and from the Mediterranean Sea coast to the northern tundra.[7] An estimated 700,000 beavers remain in Eurasia at present.[8]

Wood has been systematically removed from river corridors for at least a century in most high-income countries and for several centuries in some regions of Eurasia. Historical records in the United States indicate that millions of individual pieces of wood were removed from the smallest headwater channels to the largest rivers on the continent.[1] Much of this removal was undertaken by individual communities, commercial entities, or the federal government in association with navigation, flood control, and floating of cut logs downstream to collection points. The scope of wood removal and associated channel engineering is relatively well documented in North America, where it occurred primarily during the 18th to 20th centuries, and in other regions settled by people of European descent after the 17th century, such as Australia[9] and New Zealand.[10] Wood removal of similar magnitude and geographic scope occurred in Eurasia, but began much earlier. River clearing and engineering in Europe, for example, date to the Roman era.[11] Similarly, beavers were commercially trapped and systematically exterminated from most of Eurasia before the 18th century. Beaver trapping began in eastern North America in the early 17th century and then continued to the western and northwestern regions of the continent during the 19th century.

Wood and beaver dams strongly influence physical and ecological process and form along river corridors. The net effect is to increase physical diversity and retention of materials in flux, including water, mineral sediment, solutes, and particulate organic matter. By increasing physical diversity of river systems, wood and beaver dams also increase habitat diversity, retention and biological uptake of nutrients, biodiversity, and animal production (Table 1).

As Robert Naiman has noted,[38] one effect of beaver dams and logjams is to promote sediment and organic matter retention and thus store carbon, nitrogen, and other nutrients within watersheds, rather than allowing dissolved and particulate forms of these elements to continue downstream and ultimately into the atmosphere or the ocean. Recent synthesis papers have highlighted how significantly humans have altered global nitrogen cycles, both by putting more nitrogen into the atmosphere[40] and by reducing the ability of river corridors and wetlands to store nitrogen.[41] Analogously, global carbon budgets suggest that river process and form strongly influence how much terrestrially derived organic carbon is released to the atmosphere,[42] stored within sediments along river corridors,[43,44] and transported to the ocean.[45]

TABLE 1 | Patterns and Processes Associated with Wood and Beavers in River Corridors

Influence of Wood	Example References
Wood within the channel	
Increases hydraulic roughness	Curran and Wohl[12]
Deflects flow, creating local scour of bed and banks, including increased pool volume	Buffington et al.[13]
Creates low velocity zones with enhanced deposition of mineral sediment and particulate organic matter	Bilby and Likens[14] and Brooks et al.[9]
Alters the type and dimensions of bedforms	MacFarlane and Wohl[15]
Creates forced-alluvial reaches	Montgomery et al.[16]
Logjams that force channel migration, overbank flow, and multiple channel planforms	Collins and Montgomery[17] and Wohl[18]
Enhances habitat diversity with respect to substrate, flow depth, velocity, and overhead cover	Nagayama et al.[19]
Enhances hyporheic exchange	Sawyer et al.[20]
Enhances nutrient retention and biological uptake	Buckley and Triska[21] and Beckman and Wohl[22]
Increases biodiversity and biomass of aquatic communities	Benke and Wallace[23] and Nagayama et al.[19]
Beaver dams within the channel	
Reduce the downstream velocity of peak flows	Pollock et al.[24]
Reduce bed and bank erosion	Marston[25] and Green and Westbrook[26]
Enhance storage of sediment	Butler and Malanson[27] and Pollock et al.[28]
Enhance retention of organic matter and nutrients	Correll et al.[29]
Enhance hyporheic exchange	Briggs et al.[30]
Increase habitat diversity	Levine and Meyer[31]
Increase biodiversity and biomass of aquatic communities	Pollock et al.[32]
Increase magnitude, duration, and frequency of overbank flows	Westbrook et al.[33]
Wood on the floodplain	
Increases hydraulic roughness for overbank flows	Jeffries et al.[34]
Creates erosionally resistant 'hard points' that influence the rate of floodplain turnover	Collins et al.[35]
Increases habitat diversity and abundance for amphibians, reptiles, birds, and small mammals and, during overbank flows, for aquatic macro invertebrates and fish	Sedell et al.[36]
Provides germination sites for plants	Harmon et al.[37]
Beaver dams on the floodplain	
Reduce the velocity of overbank flows and increase floodplain sediment storage	Westbrook et al.[33]
Increase habitat abundance and diversity	Rosell et al.[8]
Increase retention and biological uptake of nutrients	Naiman et al.[38]
Increase biodiversity and biomass of floodplain communities	Wright et al.[39]

Retention of nitrogen and carbon within river corridors has immediate implications for human health. Excess nitrates in drinking water supplies have been linked to a form of cancer known as non-Hodgkin's lymphoma and to blue-baby syndrome, a potentially fatal condition in which reduced oxygen in the blood of an infant creates a blue tinge in the baby's skin.[46] Dissolved organic carbon creates unpleasant taste and odor that water-treatment facilities address by adding chlorine, creating the carcinogenic by-product of trihalomethanes. Consequently, the presence of wood in rivers has diverse environmental effects, from moderating fluxes of water, sediment, and solutes, to increasing habitat abundance, biodiversity, and water quality.

Removal of wood and beaver dams from river corridors has substantially reduced these diverse physical and ecological influences. It would be difficult to exaggerate how different forested river corridors looked prior to this removal. Historian

Martin Reuss[47] describes an extensive wood raft on Louisiana's Atchafalaya River. The raft, which extended nearly 70 km along the river, may have started to form during the 16th century. So much vegetation grew on the raft that people passing over it sometimes were unaware of its existence. The raft effectively diverted flow across the broad alluvial valley, creating a complex of branching and rejoining channels so large that each channel had its own name (Bayous Courtableau, Boeuf, Plaquemine, Teche, Pigeon, Black, and des Glaises). Each of these secondary channels was also full of wood. Every year, employees of the state engineer found new wood in streams they had cleared the year before. As Reuss (Ref 47, p. 35) wrote, 'The Atchafalaya Basin supplied an inexhaustible conglomeration of stumps, limbs, [and] branches ....' Inexhaustible, that is, until most of the adjacent old-growth forest was cut.

I have gradually become aware of how fundamentally different smaller river corridors once looked through my own research in Rocky Mountain National Park, Colorado. After working on instream wood in the region for several years, I was astonished at the quantity of wood within river corridors when I started exploring some of the least accessible portions of the national park. Rivers in these areas flow through old-growth forest. I initially thought the enormous quantities of wood in channels and floodplains (Figure 1) reflected some extreme disturbance, such as a blowdown, but I eventually realized that what I was seeing was normal for this dry, cold region where circa 600 years must pass before a large, fallen tree completely decays.[48] The abundant instream wood creates a channel planform with multiple secondary channels[18] and much greater biodiversity and abundance than other portions of the river corridor with younger forest and a history of human alteration.[22]

Similarly, Rocky Mountain National Park now has two active beaver meadows—broad valley bottoms with numerous dams and ponds—but systematic surveys of the river corridors on the eastern side of the park indicate that relict beaver dams extend up to tree line and numerous beaver meadows were once present.[49] Surveying the relict, dry beaver meadows, I try to imagine how the river corridor once looked, with numerous ponds interspersed among dense willow thickets and a maze of secondary channels. Although the relict beaver meadows remain scenic portions of the national park, their process and form have changed substantially from when beavers were present (Figure 2).

A final point that arises from existing knowledge of instream wood is that management of river corridors, including rehabilitation and restoration, can be improved by explicitly incorporating wood and beavers. Incorporation here covers a range of actions, from protecting existing floodplain forests that provide wood to river corridors or protecting existing beaver populations, to actively re-introducing wood to channels in the form of single pieces or engineered logjams[50,51] and re-introducing beavers.[24]

FROM LARGE WOODY DEBRIS TO INSTREAM WOOD

Research on the structure and function of wood within river corridors largely dates to the late 1970s and studies in the Pacific Northwest Region of North America (e.g. Refs 52, 53). Many of these investigations arose from a desire to understand how commercial timber harvest might be affecting salmon populations in the region, which had declined precipitously from 19th-century levels.[54] For more than a decade, the great majority of instream wood research continued to be conducted in this region of the world. Only during the late 1980s and early 1990s did studies start to appear from Europe,[55,56] with papers eventually following from Australia, New Zealand, Japan, and other areas of North America. This trend has accelerated through time and a brief overview of papers

FIGURE 1 | Panoramic downstream view of a portion of the river corridor along North St. Vrain Creek in Rocky Mountain National Park in Colorado, USA. The main channel is to the right. The downed wood in the foreground is from normal, individual tree mortality, rather than mass mortality. (Photograph courtesy of Lina Polvi)

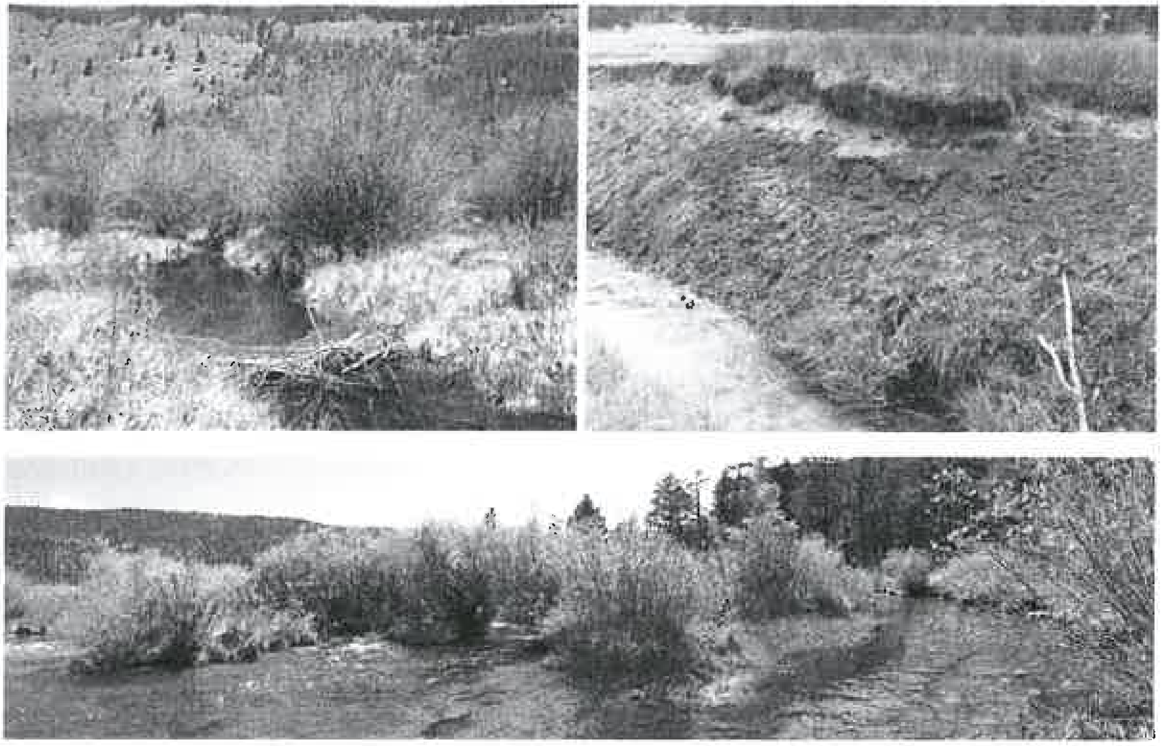

FIGURE 2 | Photographs illustrating alternate stable states of beaver meadow (extensive floodplain wetlands when beaver dams are present; upper left and bottom photo) and elk grasslands (drier floodplain grasslands with single incised channels when beaver dams are absent; upper right).

published during 2014 indicates that, of 37 papers describing field-based case studies, 10 are from the Pacific Northwest, 11 from other portions of North America, 9 from Europe, 3 from Australia, and 4 from Central and South America.

Despite the geographic expansion of wood studies, most of the conceptual models and numerical simulations of wood processes continue to rely heavily on knowledge of wood dynamics drawn largely from the Pacific Northwest. Early studies from this region introduced the phrase 'large woody debris', which was quickly abbreviated to LWD or CWD (coarse woody debris). Use of the word 'debris' derives from timber harvest: when the commercially worthless slash or residue of cut trees is called debris and commonly left in channels. A rose is a rose, but language matters.

'Debris' has negative connotations, prompting the use of alternate phrases such as instream wood or simply large wood. Regardless of the words used, the consensus of the river science community is that wood is beneficial to river structure and function.

Leave It to Beavers

Although 19th century scholars recognized the beneficial effects of beavers on river corridors (e.g. Ref 57), scientific research on beavers largely dates to the work of Robert Naiman starting in the 1980s (e.g. Refs 6, 38, 58). As with instream wood, the number of investigators, geographic locations of field studies, and physical and ecological effects being investigated has subsequently expanded greatly. There was a period of time during which North American fisheries managers sometimes removed beaver dams under the mistaken perception that these dams impeded fish passage, but the river scientific community has largely always regarded the physical and ecological effects associated with beaver populations as beneficial to river corridors.

A PERCEPTION GAP

Just as scientists from the Pacific Northwest pioneered study of the structure and function of wood within river corridors, so resource managers and practitioners of river restoration in the Pacific Northwest now appear to be leading a growing tendency to actively retain or restore wood in channels and floodplains. I base this impression on what is being published and on presentations at river restoration conferences across the United States (e.g. Southwest Stream Restoration Conference, http://southweststream.org/, Mid-Atlantic Stream Restoration Conference, http://www.resourceinstituteinc.org/MASRC.html). During the past decade, presentations at these conferences indicate a gradual shift away from restoration focused almost solely on channel form toward restoration that includes processes such as channel-floodplain connectivity and hyporheic exchange. Only at River Restoration Northwest (http://www.rrnw.org/Home), however, the annual river restoration conference held in the Pacific Northwest, have I heard much discussion of restoring instream and floodplain wood. Similarly, the case studies of river restoration described on the UK's River Restoration Centre (http://www.therrc.co.uk/index.php) website include few examples of actively incorporating instream wood, and the European River Restoration Conference (http://www.errc2014.eu/) and the website for the Australian River Restoration Centre (http://australianriverrestorationcentre.com.au/) do not mention wood.

The lack of attention to wood as part of river restoration in regions outside the Pacific Northwest likely mirrors the widespread perception outside the river science community of wood within river corridors as unnatural, unattractive, and hazardous—in other words, as an entity that needs to be actively removed rather than protected or restored. The first study to systematically survey this divergence in perceptions of wood involved a survey of undergraduate university students in physical geography or environmental geology courses in eight states within the United States. Shown a series of photographs of rivers and asked to numerically rank each view with respect to four categories (esthetically pleasing, naturalness, perception of danger, need for improvement), students consistently ranked views of rivers containing wood as being less pleasing and more in need of improvement than rivers without wood.[59] The only exceptions were students from Oregon, who recognized that wood is beneficial to stream habitat and fish. This may reflect the emphasis on watershed protection in connection with attempts to restore populations of different species of salmon. Salmon have become the charismatic megafauna of the Pacific Northwest and representations of salmon in art, on clothing, and in regional writing are ubiquitous.

A subsequent study of wood perceptions among resource managers in seven US states indicated that diverse types of managers (conservation, fisheries, forestry, recreation) perceived rivers with wood as significantly more esthetically pleasing, less dangerous, and less in need of improvement than rivers without wood.[60]

The divergent result from these two sets of surveys suggest a striking gap in the way scientists and resource managers perceive wood in river corridors and the manner in which the public and many of those engaged in river restoration perceive wood. My recent experience during the September 2013 flood in the Colorado Front Range supports the idea that public perception of wood remains largely negative. Following intensive and widespread flooding, local news stories featured efforts to 'clean up' rivers and to 'put the rivers back' into their places. Cleaning up in this context meant removing debris, some of which was mangled pieces of houses, cars, and urban infrastructure, but a good deal of which was wood recruited into the channels during the flood. Putting the rivers back meant physically moving channels that had avulsed across the historical floodplain. The net effect was a rapid removal of flood-recruited wood and re-homogenization of channels that had become more physically diverse when the flood formed secondary channels, introduced wood, and created new erosional and depositional features. This tendency to restore simplified, homogenized, controlled river channels, and floodplains following floods is common across the United States (Figure 3).

FIGURE 3 | Sign outside a small café and general store in the village of Elk Creek, Pennsylvania following severe flooding in 2012. The village is along Upper Fishing Creek in the Susquehanna River Basin. Photograph courtesy of R. Craig Kochel, who described this scenario as 'bring your own bulldozer' in recognition of the magnitude of wood removal being undertaken by individuals and small communities in this rural area.

Negative perceptions of wood also result from the possibility that wood moving during high flows, particularly during extreme floods, can strike bridges or other structures with sufficient force to damage the structure. Wood can accumulate against a structure and exacerbate overbank flooding, bed aggradation, or local scour during a flood.[61,62] The potential for wood-related damage during floods implies that wood management is necessary along river corridors that include infrastructure or urban development. Management options include selective removal of pieces likely to become mobile and construction of retention structures to trap wood upstream from portions of the river corridor vulnerable to damage during floods.[63] The need to manage mobile wood pieces along vulnerable portions of a river corridor does not, however, mean that all wood must be automatically removed from river corridors with infrastructure. Mobile wood pieces on forested floodplains, for example, may be effectively trapped by closely spaced trunks of living trees.[64]

Negative public perceptions of wood in river corridors have important implications for river management, not least because the greatest number of river restoration projects are small scale projects targeting a single channel segment, typically less than 1 km long, that are initiated by local stakeholders such as cities or private landowners.[65] If these people, who so strongly influence local-scale river management, continue to perceive all wood negatively, then wood will continue to be completely removed from river corridors.

Public perceptions of beavers provide an interesting contrast to perceptions of other forms of instream wood. These perceptions appear to be bipolar. There are people who adore beavers, and I use the word adore deliberately. Once you start looking, it is easy to find beaver hand puppets and children's toys, beaver stationery, beaver calendars, and other beaver-themed gifts. Non-governmental organizations dedicated to protecting individual beaver colonies exist (e.g. Worth a Dam, http://www.martinezbeavers.org/wordpress/) and annual meetings are held that address all things related to beavers (e.g. The State of the Beaver 2015 Conference, http://www.surcp.org/beavers/agenda.html). The scientific papers I have published that include anything related to beavers have generated far more public and media attention than any of my other papers.

On the other hand, many people regard beavers as nuisance rodents that are to be trapped and removed wherever they are present. This attitude stems from perceptions that beavers are a detriment to fishing, or that wood pieces will come loose from beaver dams and clog downstream structures such as culverts or irrigation intakes. Some people prefer to have free-flowing rather than dammed streams, or resent the removal of riparian trees by beavers. Beaver ponds can submerge roads or property. Some individuals also believe that beaver ponds decrease stream flow. During a severe drought in 2003, the State Engineer of Colorado sent an email to water managers across the state suggesting that they remove beaver dams to increase stream flow. Whatever the reason, beavers and their dams continue to be aggressively removed along many streams.

BRIDGING THE PERCEPTION GAP

The more I learn about historical wood loads and beaver populations in diverse forested river corridors and the more I realize how fundamentally different most of these corridors appeared and operated, the more disturbed I am by the perception gap regarding instream wood and beavers. However, the perception gap also creates the opportunity to put our science to work by acting on our knowledge.

A decade ago, few people practicing river restoration focused on process. The emphasis was on restoring form, often a ludicrously static form such as heavily stabilized meander bends that could not actually migrate through time and thus create the processes that maintain fish habitat and productivity. With time, the hard-engineering approach to river restoration has given way to more flexible and self-sustaining approaches that explicitly recognize the importance of river processes, such as hyporheic exchange, bed and bank scour and deposition, and overbank flows, to sustaining ecosystem services including clean water and fisheries. This change has come about because of the sustained efforts of river scientists working to bridge the gap between scientific and societal perceptions of rivers. This gap has arguably been more effectively bridged in some geographic regions, such as the Pacific Northwest.

As noted above, I think that the presence of a widely publicized, charismatic river megafauna in the Pacific Northwest—diverse species of salmon—has substantially helped to engage public attention in the importance of healthy river corridors. But the perception of what contributes to river health, including functioning watersheds, forests, and instream wood, relies on a sustained educational and outreach campaign that ranges from curriculum in K-12 schools to artwork on t-shirts and other souvenirs. The challenge for river scientists in other regions of the world is not only to communicate the physical and ecological importance of wood and beavers in river corridors, but to tie that importance to some metaphor, image, or plant or animal species that can emotionally engage a broad segment of the public. Many people can emotionally engage with rivers: they fish, paddle, watch birds, or simply enjoy being along a stream of flowing, sparkling water. If river scientists can take the next step and help people to perceive rivers as ecosystems that rely on connections to the greater landscape—including inputs of wood and the presence of beaver colonies in forested regions—then we can build a constituency that will work for retaining wood in rivers. We can move beyond 'cleaning up' rivers to diversifying, and thereby strengthening, rivers.

REFERENCES

1. Wohl E. A legacy of absence: wood removal in US rivers. *Prog Phys Geogr* 2014, 38:637–663.
2. Triska FJ. Role of wood debris in modifying channel geomorphology and riparian areas of a large lowland river under pristine conditions: a historical case study. *Verhand Inter Verein Limnol* 1984, 22:1876–1892.
3. Morrison CA. *Running the River: Poleboats, Steamboats and Timber Rafts on the Altamaha, Ocmulgee, Oconee and Ohoopee*. St. Simons Island, GA: Saltmarsh Press; 2003, 57.
4. Comiti F. How natural are Alpine mountain rivers? Evidence from the Italian Alps. *Earth Surf Proc Land* 2012, 37:693–707.
5. Schama S. *Landscape and Memory*. New York, NY: Alfred A. Knopf; 1995.
6. Naiman RJ, Johnston CA, Kelley JC. Alteration of North American streams by beaver. *BioScience* 1988, 38:753–762.
7. Hartman G. Habitat selection by European beaver (*Castor fiber*) colonizing a boreal landscape. *J Zoolo Lon* 1996, 240:317–325.
8. Rosell F, Bozser O, Collen P, Parker H. Ecological impact of beavers *Castor fiber* and *C. canadensis* and their ability to modify ecosystems. *Mammal Rev* 2005, 35:248–276.
9. Brooks AP, Brierley GJ, Millar RG. The long-term control of vegetation and woody debris on channel and flood-plain evolution: insights from a paired catchment study in southeastern Australia. *Geomorphology* 2003, 51:7–29.
10. Mackay D. *Working the Kauri*. Auckland, New Zealand: Random Century; 1991.
11. Herget J. Holocene development of the River Lippe valley, Germany: a case study of anthropogenic influence. *Earth Surf Proc Land* 2000, 25:293–305.
12. Curran JH, Wohl EE. Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. *Geomorphology* 2003, 51:141–157.
13. Buffington JM, Lisle TE, Woodsmith RD, Hilton S. Controls on the size and occurrence of pools in coarse-grained forest rivers. *River Res Appl* 2002, 18:507–531.
14. Bilby RE, Likens GE. Importance of organic debris dams in the structure and function of stream ecosystems. *Ecology* 1980, 61:1107–1113.
15. MacFarlane WA, Wohl E. Influence of step composition on step geometry and flow resistance in step-pool streams of the Washington Cascades. *Water Resour Res* 2003, 39:1037.
16. Montgomery DR, Abbe TB, Petersen NP, Buffington JM, Schmidt K, Stock JD. Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature* 1996, 381:587–589.
17. Collins BD, Montgomery DR. Forest development, wood jams, and restoration of floodplain rivers in the Puget Lowland, Washington. *Restor Ecol* 2002, 10:237–247.
18. Wohl E. Threshold-induced complex behavior of wood in mountain streams. *Geology* 2011, 39:587–590.
19. Nagayama S, Nakamura F, Kawaguchi Y, Nakano D. Effects of configuration of instream wood on autumn and winter habitat use by fish in a large remeandering reach. *Hydrobiologia* 2012, 680:159–170.
20. Sawyer AH, Cardenas MB, Buttles J. Hyporheic temperature dynamics and heat exchange near channel-spanning logs. *Water Resour Res* 2012, 48:W01529. doi:10.1029/2011WR011200.
21. Buckley BM, Triska FJ. Presence and ecological role of nitrogen fixing bacteria associated with wood decay in streams. *Verhand Inter Verein Theor Angewan Limnol* 1978, 20:1333–1339.
22. Beckman ND, Wohl E. Carbon storage in mountainous headwater streams: the role of old-growth forest and logjams. *Water Resour Res* 2014, 50:2376–2393.
23. Benke AC, Wallace JB. Influence of wood on invertebrate communities in streams and rivers. In: Gregory SV, Boyer K, Gurnell AM, eds. *The Ecology and Management of Wood in World Rivers*, vol. 37. Bethesda, MD: American Fisheries Society Symposium; 2003, 149–177.
24. Pollock MM, Beechie TJ, Wheaton JM, Jordan CE, Bouwes N, Weber N, Volk C. Using beaver dams to restore incised stream ecosystems. *BioScience* 2014, 64:279–290.
25. Marston RA. River entrenchment in small mountain valleys of the western USA: influence of beaver, grazing and clearcut logging. *Revue Geograp Lyon* 1994, 69:11–15.
26. Green KC, Westbrook CJ. Changes in riparian area structure, channel hydraulics, and sediment yield following loss of beaver dams. *BC J Ecosyst Manag* 2009, 10:68–79.
27. Butler DR, Malanson GP. Sedimentation rates and patterns in beaver ponds in a mountain environment. *Geomorphology* 1995, 13:255–269.

28. Pollock MM, Beechie TJ, Jordan CE. Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. *Earth Surf Proc Land* 2007, 32:1174–1185.

29. Correll DL, Jordan TE, Weller DE. Beaver pond biogeochemical effects in the Maryland Coastal Plain. *Biogeochemistry* 2000, 49:217–239.

30. Briggs MA, Lautz LK, McKenzie JM, Gordon RP, Hare DK. Using high-resolution distributed temperature sensing to quantify spatial and temporal variability in vertical hyporheic flux. *Water Resour Res* 2012, 48:W02527. doi:10.1029/2011WR011227.

31. Levine R, Meyer GA. Beaver dams and channel sediment dynamics on Odell Creek, Centennial Valley, Montana, USA. *Geomorphology* 2014, 205:51–64.

32. Pollock MM, Heim M, Werner D. Hydrologic and geomorphic effects of beaver dams and their influence on fishes. In: Gregory SV, Boyer K, Gurnell A, eds. *The Ecology and Management of Wood in World Rivers*, vol. 37. Bethesda, MD: American Fisheries Society Symposium; 2003, 213–233.

33. Westbrook CJ, Cooper DJ, Baker BW. Beaver dams and overbank floods influence groundwater-surface water interactions of a Rocky Mountain riparian area. *Water Resour Res* 2006, 42:W06404.

34. Jeffries R, Darby SE, Sear DA. The influence of vegetation and organic debris on flood-plain sediment dynamics: case study of a low-order stream in the New Forest, England. *Geomorphology* 2003, 51:61–80.

35. Collins BD, Montgomery DR, Fetherston KL, Abbe TB. The floodplain large wood cycle hypothesis: a mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal eco-region. *Geomorphology* 2012, 139–140:460–470.

36. Sedell JR, Bisson PA, Swanson FJ, Gregory SV. What we know about large trees that fall into streams and rivers. In Maser C, Tarrant RF, Trappe JM, Franklin JF, eds. *From the Forest to the Sea: A Story of Fallen Trees*. USDA Forest Service General Technical Report PNW-GTR-229, 1998.

37. Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, et al. Ecology of coarse woody debris in temperate ecosystems. *Adv Ecol Res* 1986, 15:133–302.

38. Naiman RJ, Melillo JM, Hobbie JE. Ecosystem alteration of boreal forest streams by beaver (*Castor canadensis*). *Ecology* 1986, 67:1254–1269.

39. Wright JP, Jones CG, Flecker AS. An ecosystem engineer, the beaver, increases species richness at the landscape scale. *Oecologia* 2002, 132:96–101.

40. Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, Seitzinger SP, Asner GP, Cleveland CC, Green PA, Holland EA, et al. Nitrogen cycles: past, present, and future. *Biogeochemistry* 2004, 70:153–226.

41. Mitsch WJ, Day JW, Gilliam JW, Groffman PM, Hey DL, Randall GW, Wang N. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River basin: strategies to counter a persistent ecological problem. *BioScience* 2001, 51:373–388.

42. Cole JJ, Prairie YT, Caraco NF, McDowell WH, Tranvik LJ, Striegl RG, Duarte CM, Kortelainen P, Downing JA, Middelburg JJ, et al. Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. *Ecosystems* 2007, 10:171–184.

43. Hoffmann T, Glatzel S, Dikau R. A carbon storage perspective on alluvial sediment storage in the Rhine catchment. *Geomorphology* 2009, 108:127–137.

44. Wohl E, Dwire K, Sutfin N, Polvi L, Bazan R. Mechanisms of carbon storage in mountainous headwater rivers. *Nat Commun* 2012, 3:1263. doi:10.1038/ncomms2274.

45. Aufdenkampe AK, Mayorga E, Raymond PA, Melack JM, Doney SC, Alin SR, Aalto RE, Yoo K. Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Front Ecol Environ* 2011, 9:53–60.

46. McMahon PB. Some bacteria are beneficial! U.S. Geological Survey Fact Sheet 1995, FS-102-95, Denver, CO.

47. Reuss M. *Designing the Bayous: the Control of Water in the Atchafalaya Basin, 1800–1885*. College Station, TX: Texas A&M University Press; 2004.

48. Kueppers LM, Southon J, Baer P, Harte J. Dead wood biomass and turnover time, measured by radiocarbon, along a subalpine elevation gradient. *Oecologia* 2004, 141:641–651.

49. Wohl E. Landscape-scale carbon storage associated with beaver dams. *Geophys Res Lett* 2013, 40:1–6.

50. Abbe T, Brooks A. Geomorphic, engineering, and ecological considerations when using wood in river restoration. In: Simon A, Bennett SJ, Castro JM, eds. *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. Washington, DC: American Geophysical Union; 2011, 419–451.

51. Gallisdorfer MS, Bennett SJ, Atkinson JF, Ghaneeizad SM, Brooks AP, Simon A, Langendoen EJ. Physical-scale model designs for engineered log jams in rivers. *J Hydroenviron Res* 2014, 8:115–128.

52. Swanson FJ, Lienkaemper GW, Sedell JR. History, physical effects, and management implications of large organic debris in western Oregon streams. USDA Forest Service General Technical Report PNW-56 1976.

53. Keller EA, Swanson FJ. Effects of large organic material on channel form and fluvial processes. *Earth Surf Proc* 1979, 4:361–380.

54. Montgomery DR. *King of Fish: the Thousand-Year Run of Salmon*. Boulder, CO: Westview Press; 2003.

55. Gregory KJ, Gurnell AM, Hill CT. The permanence of debris dams related to river channel processes. *Hydrol Sci J* 1985, 30:371–381.

56. Piegay H. Nature, mass and preferential sites of coarse woody debris deposits in the lower Ain Valley (Mollon Reach), France. *Regul Rivers Res Manag* 1993, 8:359–372.

57. Morgan LH. *The American Beaver and his Works*. Philadelphia, PA: J.B. Lippincott & Co.; 1868.

58. Naiman RJ, Melillo JM. Nitrogen budget of a subarctic stream altered by beaver (Castor canadensis). *Oecologia* 1984, 62:150–155.

59. Chin A, Daniels MD, Urban MA, Piegay H, Gregory KJ, Bigler W, Butt AZ, Grable JL, Gregory SV, Lafrenz M, et al. Perceptions of wood in rivers and challenges for stream restoration in the United States. *Environ Manage* 2008, 41:893–903.

60. Chin A, Laurencio LR, Daniels MD, Wohl E, Urban MA, Boyer KL, Butt A, Piegay H, Gregory KJ. The significance of perceptions and feedbacks for effectively managing wood in rivers. *River Res Appl* 2014, 30:98–111.

61. Ruiz-Villanueva V, Bodoque JM, Diez-Herrero A, Bladé E. Large wood transport as significant influence on flood risk in a mountain village. *Nat Hazards* 2014, 74:967–987. doi:10.1007/s11069-014-122-4.

62. Mazzorana B, Hübl J, Zischg A, Largiader A. Modelling woody material transport and deposition in alpine rivers. *Nat Hazards* 2011, 56:425–449.

63. Mao L, Andreoli A, Iroumé A, Comiti F, Lenzi MA. Dynamics and management alternatives of in-channel large wood in mountain basins of the southern Andes. *Bosque* 2013, 34:319–330.

64. Wohl E, Polvi LE, Cadol D. Wood distribution along streams draining old-growth floodplain forests in Congaree National Park, South Carolina, USA. *Geomorphology* 2011, 126:108–120.

65. Bernhardt ES, Palmer MA, Allan JD, Alexander G, Barnas K, Brooks S, Carr J, Clayton S, Dahm C, Follstad-Shah J, et al. Synthesizing U.S. river restoration efforts. *Science* 2005, 308:636–637.

FURTHER READING/RESOURCES

Bartel RA, Haddad NM, Wright JP. Ecosystem engineers maintain a new species of butterfly and increase plant diversity. *Oikos* 2010, 119:883–890.

Fausch KD. Experimental analysis of microhabitat selection by juvenile steelhead (Oncorhynchus mykiss) and coho salmon (*O. kisutch*) in a British Columbia stream. *Can J Fish Aquat Sci* 1993, 50:1198–1207.

Florsheim JL, Mount JF. Restoration of floodplain topography by sand-splay complex formation in response to intentional levee breaches, lower Cosumnes River, California. *Geomorphology* 2002, 44:67–94.

Gowan C, Fausch KD. Long-term demographic responses of trout populations to habitat manipulation in six Colorado streams. *Ecol Appl* 1996, 6:931–946.

Harwood K, Brown AG. Fluvial processes in a forested anastomosing river: flood partitioning and changing flow patterns. *Earth Surf Proc Land* 1993, 18:741–748.

Hood GA, Larson DG. Beaver-created habitat heterogeneity influences aquatic invertebrate assemblages in boreal Canada. *Wetlands* 2014, 34:19–29.

John S, Klein A. Hydrogeomorphic effects of beaver dams on floodplain morphology: avulsion processes and sediment fluxes in upland valley floors (Spessart, Germany). *Quaternaire* 2004, 15:219–231.

O'Connor JE, Jones MA, Haluska TL. Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA. *Geomorphology* 2003, 51:31–59.

Pettit NE, Naiman RJ. Flood-deposited wood creates regeneration niches for riparian vegetation on a semi-arid South African river. *J Veg Sci* 2006, 17:615–624.

Richmond AD, Fausch KD. Characteristics and function of large woody debris in subalpine Rocky Mountain streams in northern Colorado. *Can J Fish Aquat Sci* 1995, 52:1789–1802.

Rolauffs P, Hering D, Lohse S. Composition, invertebrate community and productivity of a beaver dam in comparison to other stream habitat types. *Hydrobiologia* 2001, 459:201–212.

Sear DA, Millington CE, Kitts DR, Jeffries R. Logjam controls on channel: floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns. *Geomorphology* 2010, 116:305–319.