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State of Science

Reflections on the history of research on large wood in rivers

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Earth Surface Processes and Landforms

ABSTRACT: Dynamics and functions of large wood have become integral considerations in the science and management of river systems. Study of large wood in rivers took place as monitoring of fish response to wooden structures placed in rivers in the central United States in the early 20th century, but did not begin in earnest until the 1970s. Research has increased in intensity and thematic scope ever since. A wide range of factors has prompted these research efforts, including basic understanding of stream systems, protection and restoration of aquatic ecosystems, and environmental hazards in mountain environments. Research and management have adopted perspectives from ecology, geomorphology, and engineering, using observational, experimental, and modelling approaches. Important advances have been made where practical information needs converge with institutional and science leadership capacities to undertake multi-pronged research programmes. Case studies include ecosystem research to inform regulations for forest management; storage and transport of large wood as a component in global carbon dynamics; and the role of wood transport in environmental hazards in mountain regions, including areas affected by severe landscape disturbances, such as volcanic eruptions. As the field of research has advanced, influences of large wood on river structures and processes have been merged with understanding of streamflow and sediment regimes, so river form and function are now viewed as involving the tripartite system of water, sediment, and wood. A growing community of researchers and river managers is extending understanding of large wood in rivers to climatic, forest, landform, and social contexts not previously investigated. © 2020 John Wiley & Sons, Ltd.

KEYWORDS: environmental hazards; large wood; river; river ecology; river engineering

Introduction

Over recent decades, the dynamics and functions of large wood have become integral considerations in the science and management of river systems. Research on large wood in rivers has grown tremendously over this period, as evident in the growth in number of publications. This interesting development follows a long period when fluvial geomorphologists, stream ecologists, and river engineers essentially ignored large wood. These disciplines had their favoured research questions and study of large wood posed significant challenges – buoyancy and large size complicated channel form and sediment transport studies, slow decomposition rate complicated organic matter studies of ecologists, and, simply, much of this early work was taking place where little to no large wood existed for reasons such as past land use or paucity of forest sources of wood. But, once the issue was raised, attention to the topic rapidly expanded. Signs of maturation can be found in a succession of international conferences held on three continents over the past 20 years, and in major review publications over recent decades emphasizing ecological topics (Harmon *et al.*, 1986; Maser *et al.*, 1988; Maser and Sedell, 1994; Gurnell *et al.*, 2002; Abbe *et al.*, 2003; Gregory, 2003; Reich *et al.*, 2003; Kail *et al.*, 2007; Gurnell, 2013; Le Lay *et al.*, 2013; Roni *et al.*, 2015; Grabowski *et al.*, 2019; Roni, 2019) and recently in articles targeting geophysical research (Ruiz-Villanueva *et al.*, 2016; Wohl, 2017).

The objectives of these reflections on the history of research on large wood in rivers are to briefly outline this history, explore explanations for the trajectory of rapid increase, and offer several case studies giving examples of clusters of research efforts on facets of the topic, leading to a variety of applications. We conclude with some speculations about the future of the field. Important threads through this historical retrospective include the prevalent need for taking an interdisciplinary approach to the research and attention to the social context as a motivator of the research and often a challenge to its application.

Growth of the Field

Research on physical and ecological aspects of large wood in rivers proceeded very slowly over the 20th century until erupting around 1980, followed by an accelerating intensity of work. Studies commenced when and where research motivations aligned with the capacities of individuals and institutions, and these factors determined what disciplines took part and the research approaches used. Through the 20th century until the 1970s, only a few dozen published studies addressed wood in rivers, mainly on the topic of its use in fish habitat restoration (Thompson, 2006). Large wood was used in stream restoration projects throughout the United States, starting during the 1930s as part of the Civilian Conservation Corps in make-work projects intended to help the nation recover from the Great Depression (Needham, 1938; Thompson, 2006). However, agencies and academia had little relevant research capacity in those early years and even monitoring was very limited, so these projects are interpreted to have had variable success (Hunt, 1988; Thompson, 2006; Roni *et al.*, 2015; Roni, 2019). Since the mid-1900s, wood placement in rivers has been widely used in stream restoration programmes (Abbe *et al.*, 2003; Reich *et al.*, 2003; Kail *et al.*, 2007; Grabowski *et al.*, 2019).

In the mid-1970s, an unusual combination of basic and applied research motivations prompted an interdisciplinary team of ecologists and geomorphologists to pursue the topic in the Pacific Northwest of the United States, a region with extensive, massive, native forests; abundant large wood in rivers; socially important fish species in decline; and a need for science as a basis for regulating forest practices. This pulse of work appears to have unleashed bottled-up energy as research communities discovered this intrinsically interesting topic. In some areas with histories of land use, researchers realized the ecosystems they had been studying were missing this critical component – lost as a land-use legacy of stream 'cleaning' and forest conversion to agriculture (Wohl, 2014). The capacity for this type of research grew as teams of researchers spanning forest and stream ecology and earth sciences became more common late in the 20th century. In this context, study of large wood in rivers became a nexus for interdisciplinary science – all perspectives had significant roles in the work.

The surge of research on large wood in rivers over the past 40 years has taken several forms. A basic, descriptive form of study has been the characterization of environments not previously examined, and often related to basic ecosystem research, such as roles of large wood in carbon and nitrogen budgets. A second type of project involves interdisciplinary teams motivated by management-related issues, such as aquatic habitat improvement projects and environmental hazards posed by wood transported in floods in mountain regions of Japan (Ishikawa, 1990; Uchiogi *et al.*, 1996; Braudrick *et al.*, 1997; Sabo Department, 2000) and Europe (Comiti *et al.*, 2012, 2016). A third research emphasis has been to document how both the presence and absence of wood in channels and floodplains can alter river process and form by increasing hydraulic roughness and obstructing flow in a manner that affects sediment dynamics, channel geometry, channel planform, and channel–floodplain connectivity (Massong and Montgomery, 2000; Buffington *et al.*, 2004; Collins *et al.*, 2012). As shown in the case studies below, the balance among geomorphology, ecology, and engineering approaches varies with the topic and the disciplinary culture of participating researchers.

Several analyses of the publication record offer insights on the development of the field of research on large wood in rivers. Bibliographic analysis of this type is complicated because of the differing terminology among disciplines and over time in individual fields, so no single, sharp picture emerges. The keynote address of the first Wood in World Rivers Conference in 2000 described the growth of literature on the physical and ecological relationships of large wood in streams and rivers (Gregory *et al.*, 2003a); based on analysis of 1172 publications on wood in rivers, the rate of growth of the literature on wood increased sharply from 1970 to 2000. Recent bibliographic analysis indicates that the rate of wood-related publications has continued to accelerate in the last two decades. A simple histogram of the numbers of publications annually since 1904 with keywords 'woody debris', 'large wood', 'large organic material', 'instream wood', 'large organic debris', 'river', and 'stream' in the ISI Web of Science (totalling nearly 20 000) reveals dramatic growth in research attention relevant to large wood in rivers beginning in the early 1980s (Ruiz-Villanueva and Stoffel, 2017, fig. 1). Independent bibliographic research by Wohl *et al.* (2017) shows the emergence of this phenomenon beginning in the Pacific Northwest of the United States during the late 1970s and 1980s (e.g. Harmon *et al.*, 1986), and then a proliferation across other parts of North America, Europe, and southeast Australia in the succeeding two decades. In a further bibliographic analysis, limiting the search to published articles in English with the keywords 'wood*' (using the * includes other words like 'woody') and 'river', and excluding papers published in unrelated fields (e.g. agriculture, archaeology, biochemistry, arts, etc.), we updated the analysis to mid-2019, finding 2034 records (ISI Web of Sciences last accessed on 8 August 2019) (Figure 1). The upward trend in the number of publications is significant, with a strong increase in the 2000s (~90% of records). Most of the works were related to the fields of geosciences (37%), environmental sciences and ecology (33%), water resources (14%), and engineering (8%). A further analysis of the keywords used by the authors of these publications revealed two large groups. The first one, mostly related to environmental and geomorphological studies, includes works indexed by words like 'forest, basin', 'ecosystem', 'pattern', 'vegetation', 'water', 'biodiversity', and 'climate'. The second group focused on more applied and engineering aspects, characterized by words like 'management', 'land-use', 'restoration', 'transport', 'habitat', and 'dynamics'.

We speculate that the long period of paucity of research on large wood in rivers in the first three-quarters of the 20th century reflects two main factors: first, lack of interest within the relevant disciplines; second, histories of river management and land use that greatly reduced the presence of large wood in river landscapes of the world where there has long been a significant human presence (Wohl, 2014; Nakamura *et al.*, 2017). Consequently, it was easy to avoid research on large wood in rivers.

A cursory review of the literature and our own experiences suggest that research on large wood in rivers has progressed through a sequence of stages at the scales of individual investigators, research teams, and the field as a whole. First, there may be a descriptive phase to document the quantity, size distribution of pieces, and arrangement dating from Needham (1938) and more recently Swanson *et al.* (1984), Gurnell *et al.* (2002), Abbe and Montgomery (2003), Comiti *et al.* (2006), and Andreoli *et al.* (2007). This may include natural history observations, such as residence time using dendrochronological and other techniques (Hyatt and Naiman, 2001; Dahlström *et al.*, 2005; Jochner *et al.*, 2015). Physical process studies

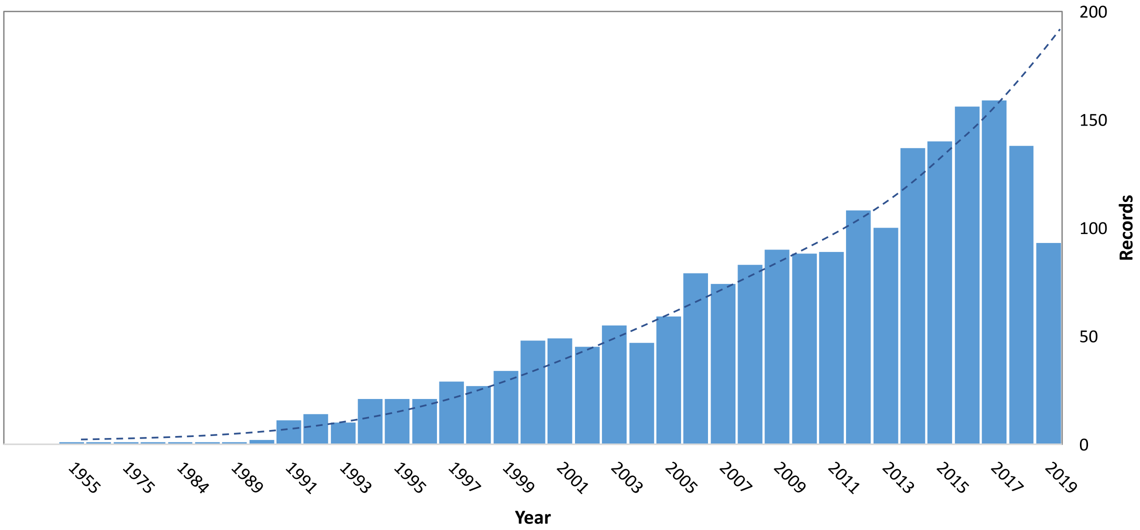

Figure 1. Annual number of articles published in English with the keywords 'wood*' (using the * includes other words such as 'woody') and 'river', and excluding papers published in unrelated fields (e.g. agriculture, archaeology, arts, biochemistry) found in the ISI Web of Sciences (last accessed 8 August 2019) (*n* = 2034). [Colour figure can be viewed at wileyonlinelibrary.com]

may follow, addressing wood recruitment, transport, decay, and storage dynamics (e.g., Martin and Benda, 2001; Benda *et al.*, 2003; Gurnell, 2003; Le Lay *et al.*, 2013). Studies of the geomorphic and ecological functions of large wood may come next (Montgomery *et al.*, 2003). Ultimately, short-term studies may evolve into long-term programmes (e.g., Wohl and Goode, 2008; Iroumé *et al.*, 2015, 2018a, 2018b). Such studies can make important contributions in terms of direct observation of gradual processes and infrequent events, which are an important part of large wood dynamics. New technologies give opportunity to take a fresh look at issues addressed earlier with cruder techniques, as in the case of new applications of tools for monitoring and tracking wood transport and dynamics over time (MacVicar and Piégay, 2012; Kramer and Wohl, 2014; Schenk *et al.*, 2014; Ravazzolo *et al.*, 2015; Sanhueza *et al.*, 2019).

The human dimensions of research on large wood have also evolved over time. It is interesting to note that geomorphology and ecology studies of the 1970s that helped launch a surge of research were motivated in part by information needs in the context of setting forestry regulations. The findings also influenced use of wood in river restoration practices and streamside 'buffer strips' for protection of aquatic ecosystems in landscapes subject to forestry practices. As the basic scientific understanding of wood in rivers grew, land and river managers in North America and Europe became aware of the need to incorporate this emerging science in policy and practices (Swanson *et al.*, 1976; Gurnell *et al.*, 1995). But decades passed before social science research began to address public perceptions of wood (Piégay *et al.*, 2005; Chin *et al.*, 2008). This was prompted by the importance of social licence to modify rivers, which is complicated by substantial country-to-country disparities in social acceptability of wood in rivers, based on cultural experience (Piégay *et al.*, 2005; Le Lay *et al.*, 2008; Chin *et al.*, 2012). Of the nine countries sampled by Piégay *et al.* (2005), only students in Germany and Oregon in the United States considered wood to be ecologically beneficial – not requiring removal or restoration. The other countries considered wood to be dangerous and requiring of intervention. A subsequent study of 196 professional managers found that most American managers considered wood more aesthetically pleasing, less dangerous, and less in need of improvement, in contrast to a study of 376 students in eight states of the United States (Chin *et al.*, 2008). Different types of managers (e.g. forestry, fisheries, recreation, conservation, water) have similar perceptions, indicating that education, training, and subsequent experience change perceptions and incorporate emerging scientific information in land and river management. However, in many regions strong differences of opinion exist between those responsible for public safety and those placing emphasis on ecological values.

The use of simulation modelling as a fundamental tool for integrating empirical results of wood-related research has evolved over the history of this field of research (Gregory *et al.*, 2003a). This review of wood dynamics models for the first Wood in World Rivers Conference described classifications of mathematical models and attributes of different types of models and their requirements. Early models focused on primary processes, such as input and storage at reach scales (Van Sickle and Gregory, 1990; Meleason *et al.*, 2003), and subsequent models included breakage of fallen pieces to more accurately represent wood size upon entry (Sobota *et al.*, 2006) and transport (Braudrick *et al.*, 1997; Ruiz-Villanueva *et al.*, 2014c). Most wood models focus on the reach-scale process, but some models have been developed to represent basin-scale processes and patterns (Benda and Sias, 2003). Research on European rivers has greatly expanded models for transport processes and hazard management during floods and mass failures (Comiti *et al.*, 2012; Ruiz-Villanueva *et al.*, 2014b). Models are abstract representations of physical and biological processes and are limited inherently by the quality of empirical data used to create and parameterize them. But, as such, models serve to integrate understanding of complex relationships, provide quantitative tools for researchers and managers alike, identify gaps in our understanding, and bridge disparate disciplines concerned with the dynamics of wood in stream and river systems.

Several decades into development of the field of large wood in rivers, an international community began to form. One manifestation has been the succession of Wood in World Rivers conferences – in Corvallis, OR (2000); Stirling, Scotland (2006); Padova, Italy (2015); and Valdivia, Chile (2019). Collections of papers have emerged from these conferences (Gregory *et al.*, 2003; Picco *et al.*, 2017; this issue), and in both those and other publications the number of papers with authors from multiple countries has increased. Over the course of these conferences, interest in wood in rivers has spread geographically, but the recent literature shows that a majority of published studies came from Europe (34%) and the United States (35%), while works from Australia, Japan, New Zealand, China, and South America increased. The emergence of this international community of scholars facilitates advancement of the field and collaboration in both biophysical and social sciences.

Links Among Water, Sediment, and Ecological Science

As the science of large wood in rivers has matured over recent decades, it has gradually been incorporated into conceptual frameworks for water and sediment transport and consideration of stream ecosystems. The much-cited publication on the natural flow regime concept has been seminal in both science and river restoration, based on the fundamental notion that river ecology is closely tied to many dimensions of the streamflow regime, including the distributions and timing of peak flows and low flows (Poff *et al.*, 1997). Both climate variability and many human actions, such as extraction of surface or groundwater and direct flow regulation, alter the streamflow regimes – with a wide array of consequences for aquatic ecosystems. Wohl *et al.* (2015) extended this concept to include inorganic sediment – the sediment regime – which is also subject to alteration by a wide range of natural and human-imposed factors, and which has some similarities to large wood in terms of movement and storage (Gurnell, 2007). In the case of sediment, also, aquatic ecosystems can be sensitive to regime shifts. Wohl *et al.* (2019) have extended the regime concept to include wood and how that regime may shift in response to changes in supply, storage, and transport capacity of river systems. They assert that ‘the natural wood regime forms the third leg of a tripod that supports river science and management, along with the natural flow and sediment regimes’.

Understanding and terminology of processes that transport inorganic sediment in water–sediment mixtures has also advanced greatly over recent decades (e.g. Carter, 1975; Pierson, 1987; Iverson, 1997; Hungr *et al.*, 2014; Takahaski, 2014), but only recently has wood transport been well integrated into a water–sediment–wood system. This work has been advanced by physical experiments in flumes (Braudrick *et al.*, 1997; Bocchiola *et al.*, 2013; Crosato *et al.*, 2013; Bertoldi *et al.*, 2015). In an innovative, international effort, Ruiz-Villanueva *et al.* (2019) use an unlikely combination of analysis of home videos of wood-laden flows with physics-based modelling of such flows containing only a small fraction of inorganic sediment. This work adds ‘hypercongested’ wood-laden flows to the terminology of ‘uncongested’ and ‘congested’ flow states of wood transport by streamflow developed by Braudrick *et al.* (1997), and unifies depiction of the water–sediment–wood system. These distinctions within the water–wood system are important in terms of potential hazards to ecosystems, infrastructure, and human lives.

The frequently cited River Continuum Concept provides an important conceptual framework for viewing longitudinal variation in the structure, composition, and function of river ecosystems (Vannote *et al.*, 1980). Among the four initial Continuum sites of intensive field study in first-, third-, fifth-, and seventh-order river reaches flowing through forested landscapes, the site in Oregon pursued large wood studies because large wood was an integral part of the ecosystem (Triska and Cromack, 1980; Harmon *et al.*, 1986). Large wood was not a major feature at the other sites, in part because of land use histories. Researchers at the Oregon site documented that large wood quantity (volume per unit area) decreases with increasing stream size and found that large wood strongly influences channel form in headwater streams, but its arrangement and geomorphic roles transform in the downstream direction to being increasingly controlled by channel form in larger rivers, which have the capacity to transport big wood (Keller and Swanson, 1979).

An additional conceptual framework that originally developed in ecology (Poole, 2002) and has been adapted by geomorphologists (Montgomery, 1999) emphasizes longitudinal discontinuities in river corridors. Many mountainous river networks, in particular, have substantial and relatively abrupt downstream changes in gradient and lateral extent of the valley bottom (Wohl, 2010). Several studies demonstrate that large wood is preferentially stored in discrete segments with higher trapping capacity (e.g. Wohl and Cadol, 2011; Ruiz-Villanueva *et al.*, 2016).

Another aspect of the maturation of the science of large wood in rivers has been the adoption of conceptual frameworks from allied fields of inquiry. Wood budgeting and routing (Benda *et al.*, 2003), for example, adapted the systems perspective used in sediment budgets and routing publications beginning in the late 1970s (Dietrich and Dunne, 1978; Swanson *et al.*, 1982). In both the case of soil/sediment and large wood routing, storage compartments and transfer processes are quantified, and breakdown of particles in storage and while in transport is interpreted to assess system dynamics. In another example of enlisting analytical approaches from allied fields of inquiry, Latterell and Naiman (2007) adapted the ‘spiralling’ concept used to characterize nutrient cycling along downstream flowpaths in stream ecosystems (Webster and Patten, 1979) to examine storage and transport of large wood in the near-natural Queets River along the Pacific Northwest coast of the United States.

Case Studies

The following case studies of clusters of research activities on large wood in rivers reveal the variety of motivations; capacities of individuals, teams, and institutions; research approaches; and potential applications of the knowledge to real-world issues. We feature cases that collectively span much of the period of major interest in large wood in rivers and regions which hosted Wood in World River conferences from 2000 to 2019.

River ecology and forest management – early work in the Pacific Northwest United States

The major surge of interest in the study of large wood in rivers took off in the 1970s with dual motivations. A team of forest and stream ecologists and geomorphologists based in the H. J. Andrews Experimental Forest, Oregon, USA, and associated with Oregon State University and the US Forest Service, were conducting basic ecosystem research in the National Science Foundation-sponsored International Biological Programme. Part of the science mission was to construct budgets and systems models of stocks and flows of carbon, nitrogen, and other forest and stream system components. Stream ecologists were familiar with processing of the small, fast-turnover pools of fine litter (e.g. leaves, needles), but the big, slow pools of large wood proved to be a challenge.

In its basic science programme, the Andrews Forest research team investigated many facets of large wood in streams, including geomorphic and ecological effects, decomposition, and relation to forest history spanning 500 years (Swanson *et al.*, 1976; Triska and Cromack, 1980; Harmon *et al.*, 1986). This work revealed the critical role of large wood in stream ecosystems and in forest management, including issues such as managing stream-side forest as a future source of large wood (Harmon *et al.*, 1986; Gregory *et al.*, 1991; Gregory, 1996). The study approaches included natural history observations, field experiments, restoration projects, long-term monitoring, and ecological investigations of riparian forest dynamics (Acker *et al.*, 2003). Study components touched on wood inputs (Ward and Aumen, 1986; McDade *et al.*, 1990; Van Sickle and Gregory, 1990), decomposition (Triska *et al.*, 1982; Aumen *et al.*, 1983), algae (Sabater *et al.*, 1998), nutrient uptake (Aumen *et al.*, 1990), macroinvertebrates (Anderson *et al.*, 1978, 1984), fish, simulation modelling (Meleason *et al.*, 2003; Gregory *et al.*, 2003b), and outreach to forest managers and the public (Maser and Sedell, 1994). This work started in the mid-1970s, and ultimately found an important place in the formulation of a major forest and river conservation plan (Swanson and Gregory, 2018).

As the basic science programme concerning forest–stream interactions developed at the Andrews Forest in the mid-1970s, management of large wood in streams became a pressing, practical issue – what should the State of Oregon's new forest practice rules say about management of wood in streams flowing through logging sites? Historical perspectives of wood in streams at logging sites were directly opposite to the emerging new information on the geomorphic and ecological importance of wood in streams (Gregory, 1996). During the 1960s and early 1970s, wood was 'cleaned' from streams after logging. Studies of the effects of clearcutting in the 1960s documented negative effects of logging debris on dissolved oxygen, temperature, and siltation. Forest practice guidelines were developed to prevent these impacts of the early clearcutting practices and their exacerbated effects when floods transported wood, blocking culverts and bridges. Fisheries agencies developed guidelines to require logging debris to be removed after logging operations, but these guidelines also required pre-existing wood to be retained. The public and operators often misunderstood, and commonly all wood was removed during stream cleanup. When scientists called for retention of natural wood in channels and protection of riparian areas to provide large wood to streams and restored streams by adding large wood, many non-scientists were confused. Scientists worked with land management agencies to develop new approaches for riparian management to provide multiple benefits beyond large wood, including shade protection to reduce warming of stream water and limit erosion and sedimentation, while benefitting wildlife habitat and channel stability (Gregory and Ashkenas, 1990).

This surge of work on large wood in rivers arose from a fortuitous confluence of circumstances – of place, people, science framing, and societal issues. Essential ingredients included the presence of a highly interdisciplinary research team with a suitable portfolio of skills, an adventuresome spirit, a strong partnership with land managers, and freedom for open inquiry located in forests of the Pacific Northwest where large wood and big, old, native forest are still present. 'Wild science' funding from the National Science Foundation was free of the confines of mission-oriented, 'domesticated science' common to a college of forestry or an agency (science-type terminology personal communication from J. Franklin). The combination of basic science, applied studies, and long-term monitoring (Swanson and Jones, 2002; Dodds *et al.*, 2012) enriched the early perspectives, but the pace of research on large wood in rivers has fallen off as funding emphasis has shifted to other topics.

Organic carbon dynamics

Growing concern with global environmental change and increased carbon loading in the atmosphere has spurred research on storage and flux of large wood in rivers from the perspective of organic carbon dynamics. Studies on this topic along river corridors began after a few papers by European investigators noted that floodplain soils can store significant organic carbon stocks (Hoffmann *et al.*, 2009; Cierjacks *et al.*, 2010). Subsequent research indicates that river corridors – channels and floodplains – can contain disproportionately large organic carbon stocks in the form of downed, dead wood and floodplain soils (Wohl *et al.*, 2012, 2017; Sutfin *et al.*, 2016; Scott and Wohl, 2018b; Lininger *et al.*, 2019). The relative importance of downed wood versus soil organic carbon varies between sites. Decomposition rates of coarse particulate organic matter and downed wood in the floodplains can be significantly higher than adjacent uplands (Neatrour *et al.*, 2004; Barbosa *et al.*, 2017), but much of the organic carbon released through breakdown and decomposition is added to floodplain soils in which anoxic conditions limit microbial respiration and release of carbon to the atmosphere. The large carbon stocks in rivers reflect high primary productivity in many floodplain and riparian forests relative to adjacent uplands (Naiman and Décamps, 1997), as well as continually moist or saturated floodplain and delta soils that retain organic carbon in a reduced state (Sutfin *et al.*, 2016; Scott and Wohl, 2017, 2018a).

Large wood influences carbon storage both directly and indirectly. Most dead wood is approximately 50% organic carbon, so the direct influence comes from the mass of wood stored in a river corridor and the rate at which that wood decays or is transported downstream. Large wood buried in floodplains can persist for thousands of years (Guyette *et al.*, 2008), creating a long-term carbon sink on management timescales. Indirect influences of large wood on carbon dynamics result from the manner in which wood influences floodplain soil. These influences include the potential for greater soil moisture and nutrient content under decaying wood (Zalamea *et al.*, 2007). Logjams within the active channel can facilitate overbank flooding and associated deposition of organic matter and mineral sediment (e.g. Sear *et al.*, 2010), thus promoting high riparian water tables and burial of organic carbon within floodplain sediments (Wohl, 2013a). Logjams within the channel can also facilitate channel avulsion (Collins *et al.*, 2012), creating secondary or abandoned channels that can fill with wood, provide sites for beaver dams and ponds that also disproportionately store carbon (Wohl, 2013b; Johnston, 2014; Laurel and Wohl, 2019), and leave abandoned logjams that are buried or laterally accreted to the floodplain (Collins *et al.*, 2012; Lininger and Wohl, 2019).

One of the implications of this recognition of the importance of river corridors in sequestering organic carbon at timespans of 10^2–10^3 years is that management designed to foster carbon sequestration, which currently focuses primarily on upland reforestation (e.g. Cerbu *et al.*, 2011), can also focus on restoring spatial heterogeneity, large wood retention, and floodplain wetlands (Wohl *et al.*, 2018a).

Important gaps remain in our knowledge of the influence of large wood on organic carbon dynamics. Among these gaps are how floodplain carbon stocks differ within a river network and among river networks, although recent studies have examined patterns in spatial variability within at least some river networks (Lininger *et al.*, 2018, 2019; Scott and Wohl, 2018a, 2018b; Sutfin and Wohl, 2019). The tropics represent a significant unknown in this respect. Existing studies have primarily focused on carbon export in the form of large wood transported during extreme storms (West *et al.*, 2011; Wohl and Ogden, 2013), but limited studies of tropical floodplain lakes and wetlands suggest that river corridors in the tropics may also store significant amounts of organic carbon (Moreira-Turcq *et al.*, 2004; Dommain *et al.*, 2014). The rate at which wood decays in floodplains is also relatively unknown; much of the literature comes from forest ecology and may represent general rates for uplands rather than rates specific to floodplains. Remarkably little has been published on floodplain wood loads (Piégay, 1993; Lininger *et al.*, 2017; Wohl *et al.*, 2018b; Gregory *et al.*, 2019) – as distinguished from wood loads within channels – which further limits our ability to estimate carbon stocks in the form of large wood.

Large wood and environmental hazards in European mountains

Mountain regions of Europe with long histories of human occupation and river engineering – tailored in part to deal with hazards from landslides, debris flows, and floods – have become a focal point for intensive study and modelling of large wood in river networks (Comiti *et al.*, 2016). In these environments, large wood is often perceived as a dangerous and problematic element, especially when interacting with infrastructure like bridges (Diehl, 1997). During infrequent, high-magnitude events, floods and debris flows may transport and deposit large quantities of large wood, enhancing the potential for damage to populations and infrastructure (Ruiz-Villanueva *et al.*, 2014b, 2018; Lucía *et al.*, 2015; Steeb *et al.*, 2017). At narrow sections of river valleys, or bridges, weirs, and dams that have not been properly designed to allow the wood to pass (Lassettre and Kondolf, 2012), the deposition of large wood may cause a significant reduction in channel cross-sectional area, causing backwater flooding (Ruiz-Villanueva *et al.*, 2017), local scour and erosion (Pagliara and Carnacina, 2011; Schalko *et al.*, 2019), sediment deposition, and bed aggradation or channel avulsion. Therefore, it is not surprising that large wood studies in these regions have focused on wood recruitment, transport, and deposition at short timescales (i.e. during single large events), with special attention paid to associated hazards and risks at the local scale, impacts to infrastructure, and large wood management.

Interaction between large wood and infrastructure and the need to mitigate potential hazards in downstream areas have resulted in increasing interest among engineers, managers, and scientists. Based on direct observation and flume experiments, researchers have seen that the shape of the wood accumulation against bridge piers increases the potential for scour (Lagasse *et al.*, 2010). Flow conditions leading up to obstructions drive the probability of large wood accumulation (e.g. Schalko, 2018; Schalko *et al.*, 2019). The design of the structure in terms of bridge deck and pier shape may influence the magnitude of wood blockage (Schmocker and Hager, 2011; Comiti et al., 2012; Gschnitzer *et al.*, 2017). Many of these works aimed at designing engineering mitigation measures, such as deflectors or retention structures, are similar to check dams designed to retain bedload (Piton and Recking, 2015). Many examples of such structures can be found in the Austrian, Italian, Japanese, and Swiss Alps (e.g. Schmocker and Hager, 2011). The challenge is to find a proper design that can retain the wood where necessary, but also allow continuity of sediment transport. In the case of sediment retention structures, these must be designed to work properly also in the presence of wood. However, this topic has not yet been intensively investigated (Schalko, 2018).

Diverse models, based on empirical equations using deterministic and probabilistic approaches, have been proposed to predict and estimate the amount of wood that can be delivered during large events (Takahashi, 2014; Rickenmann, 1997; Mazzorana *et al.*, 2009; Ruiz-Villanueva *et al.*, 2014c; Comiti *et al.*, 2016; Cislaghi and Bischetti, 2019). Most of these models use available information (e.g. hazard maps) for areas susceptible to recruitment processes (e.g. landslides, debris flows, bank erosion) or expert-based delineation of buffer zones, and do not attempt to actually model the processes. In fact, modelling these geomorphic processes is a considerable challenge. Although important progress has been achieved in recent years, the parameterization and validation of existing models remain challenging because of the lack of field observations.

Numerical models have also been applied and developed to analyse wood transport and its interactions with infrastructure (Lagasse *et al.*, 2010; Comiti *et al.*, 2012; Ruiz-Villanueva *et al.*, 2014a, 2017). One- or two-dimensional computational fluid dynamics modelling was initially used to obtain the relevant hydraulic variables to calculate wood mobilization (Merten *et al.*, 2010; Mazzorana *et al.*, 2011; Ruiz-Villanueva *et al.*, 2013; Zischg *et al.*, 2018). In recent years, models have been enhanced to explicitly simulate wood transport (e.g. Persi *et al.*, 2018), although only a few fully couple wood transport to hydrodynamics (Ruiz-Villanueva *et al.*, 2014a; Kang and Kimura, 2018).

Understanding large wood recruitment and the factors controlling large wood deposition is crucial for the proper management of river basins and flood hazard mitigation (Piégay *et al.*, 2005; Comiti *et al.*, 2012, 2016). Still, our knowledge is limited and few studies of transport and deposition of large wood after large events exist (Lucía *et al.*, 2015; Steeb *et al.*, 2017; Ruiz-Villanueva *et al.*, 2018). These post-event surveys are invaluable when it comes to improving insights on large wood-related processes, to provide the required information for the planning of appropriate mitigation measures and to make spatially explicit assessments of hazards related to large wood (Steeb *et al.*, 2017).

Effects of volcanic eruptions on large wood in rivers

Major landscape disturbances in forested areas present important opportunities for study of large wood in rivers, and this is especially true for volcanic eruptions. The orographic effect of major volcanic mountain chains, such as the Andes and Cascades of the Americas, adds to the wetness of surrounding areas, increasing the potential for volcanoes to be located in forest biomes with extensive river networks (Crisafulli *et al.*, 2015). Volcanic processes can have widely varying influences on wood in rivers: for example, lateral volcanic blasts and massive debris avalanches can greatly increase wood delivery to rivers, but burial of forests beneath lava flows may sequester large wood and impede development of forests to serve as future wood sources. The 1980 eruption of Mount St. Helens (Washington State), for example, involved several volcanic processes that greatly modified large wood in rivers (Lipman and Mullineaux, 1981). However, except for the work carried out by Lisle (1995), little study focused directly on large wood in rivers. This may have been a consequence of this field of research just gaining attention at that time, and the eruption presented so many other geomorphology and ecology research topics that commanded the attention of the large community of scientists engaging with the landscape. Lisle (1995) highlighted the large piece size and total volume of old-growth forest that the lateral blast toppled into reaches of Clearwater Creek, and the effects of experimental manipulations of this LW (i.e. retention and removal) on channel morphology and stream habitat complexity.

By the 21st century, however, research on large wood in rivers and the ecology of disturbed landscapes had matured to the point that the eruptions of Chilean volcanoes (Chaiten in 2008 and Calbuco in 2015) prompted intensive research on large wood. This work by an international cadre of scientists has concentrated on channel segments of the Blanco (also known as Chaitén) and Rayas rivers in the Chaitén area, and the Blanco-Este River which drains the northeastern flanks of Calbuco volcano (Umazano *et al.*, 2014; Valdebenito *et al.*, 2015; Ulloa *et al.*, 2015a, 2015b; Mohr *et al.*, 2017; Tonon *et al.*, 2017; Sanhueza *et al.*, 2019). The studies address a variety of questions concerning sources and fates of large wood affected by pyroclastic density currents (PDC), tephra fall, and post-eruption runoff processes in rivers draining from these volcanoes. A long-term aim of the research is to understand and assess volcanic hazards, especially in the case of Chaitén where the volcano stands only 10 km from the town.

Research has focused on understanding the post-eruption role of logjams in the fluvial responses (Umazano *et al.*, 2014), the fluctuations in large wood abundance and dynamics of individual wood pieces and logjams (Ulloa *et al.*, 2015a; Tonon *et al.*, 2017; Sanhueza *et al.*, 2019), and estimating pulsed release of organic carbon, mainly in the form of large wood, into river channels and Patagonian fjords (Ulloa *et al.*, 2015b; Mohr *et al.*, 2017).

Testing of ground- and aerial-based remote-sensing techniques for research on large wood in rivers is highly suited to work in severely disturbed landscapes because of the absence of forest cover which might limit detection of wood pieces and the flight of aircraft. This has made the Chilean volcanic landscape ideal for exploring the use of technological tools for remotely sensing large wood, such as identifying wood pieces buried in the volcanic deposits using non-invasive methods (Valdebenito *et al.*, 2015) and testing the potential of using high-resolution unmanned aerial vehicle (UAV)-derived imagery and Structure from Motion (SfM) photogrammetry to map single pieces and logjams and calculate the wood load (Sanhueza *et al.*, 2019).

Key findings from these studies of recent eruptions of volcanoes in Chile address both landscape processes and suitable study methods in such landscapes. Explosive volcanic eruptions can greatly modify landscapes, resulting in complicated, rapidly changing systems of sediment and larger wood storage and transport (Iroumé *et al.*, 2018a, 2018b), including slope-to-channel connectivity (Martini *et al.*, 2019). Geophysical processes propagate over time and down gravitational flowpaths, unfolding over years and decades following landscape disturbance by eruptions (Korup *et al.*, 2019; Mazzorana *et al.*, 2019). These primary and secondary geophysical processes have a wide range of impacts on wood in rivers, ranging from greatly increasing its availability and opportunity for transport (e.g. in the case of lateral blasts and extreme sediment discharge following tephra fall) to removal of large wood from influencing river systems by burial (e.g. in PDC deposits) and destruction of wood (e.g. combustion and charcoal formation in PDC deposits) (Pierson *et al.*, 2013; Swanson *et al.*, 2013).

Given this complexity, it is not surprising that rivers draining Chaiten and Calbuco volcanoes have differed substantially in abundance and flux of large wood, and both landscapes remain very dynamic even 10 years after eruption. Eruptions can account for large fluxes of carbon from terrestrial to river to estuarine environments (Ulloa *et al.*, 2015b; Mohr *et al.*, 2017). The carbon footprint of the 2008 Chaitén eruption on the Rayas River was more significant than the measured geomorphic impacts on channel geometry for the first 5 years following disturbance; a modest post-eruptive geomorphic response in this river has been a poor indicator of its biogeochemical response (Ulloa *et al.*, 2015b). In terms of hazard and risk management, protracted high levels of sediment and wood delivery to and through river networks are likely to follow eruptions, and type of eruption processes and other factors can be used to predict magnitude and duration of elevated levels. For example, Basso *et al.* (2020) used the 2D IBER® hydrodynamic model and found that, even without a new volcanic eruption as a hazard trigger, an extensive area within the city of Chaitén is still exposed to flooding, especially if large wood is involved. In such assessments, it is important to note possible synergistic effects of high discharge of both wood and sediment.

A critical knowledge gap for work in severely disturbed landscapes is sustained observations over decades or even centuries, because this is the timescale of major change in landscape configuration and hydrogeomorphic processes. The pace of sediment and large wood yield and vegetation development plays out on such scales, and the impact of major storm events depends on the stage of landscape response at the time of the hydrological events.

Knowledge Gaps and Future Work

Based on a comprehensive review of the literature, Wohl *et al.* (2017) identifies many gaps in knowledge of large wood in rivers – mainly in geographic, physical process, and social terms. From a geographic perspective, research to date has emphasized small and intermediate-sized rivers (big rivers are logistically very difficult), and has focused on several regions of the globe, notably the temperate conifer forests of the Pacific Northwest of North America. This geographic imbalance means that many important climatic, forest types, and flow regimes of the world are poorly represented in the current literature. Knowledge is also uneven among components of wood regimes, with important gaps in wood recruitment by mass mortality processes, transport distances, storage duration and exhumation of buried wood, and channel–floodplain interactions involving large wood. As with many natural resource issues, social dimensions of management of large wood in rivers, especially in the case of river restoration, are exceptionally challenging, but have received little research attention. The few social science studies reveal strong differences among cultures and countries in public perceptions of aesthetic and biophysical aspects of large wood in rivers (Piégay *et al.*, 2005), which complicate efforts to restore wood in rivers where land and river management has rendered it absent for many generations.

Many of the gaps identified for geomorphic disciplines apply to ecological sciences as well, especially geographic imbalances and cultural biases. There is a great disparity in our ecological understanding of relationships of large wood with different components of aquatic communities. Research on the influences of large wood on fish communities far exceeds the studies of other aquatic communities and trophic levels. Studies of macroinvertebrate associations with large wood and decomposition processes are growing, and the lower trophic levels, such as benthic algae and primary production, are far more limited. For all trophic levels, links between physical structure and food availability are needed. Factors that determine responses to wood availability or restoration require additional research. The abundance of fish may be determined by factors and other stages in their life history, or other locations in their distribution. In particular, researchers need to consider density dependence in fish populations and the causes of density dependence, such as food availability, habitat quality, flood refuge, drought refuge, and thermal refuge. Also, far more studies have examined the ecological and geomorphic influences of large wood, but the relationships with small wood (<1 m length and 10 cm diameter) have received far less attention (Ward and Aumen, 1986; Enefalk and Bergman, 2016; Galia *et al.*, 2018). Addressing other gaps in large wood research, such as attention to dynamics and roles of wood on floodplains, can be complicated by the need for cross-discipline collaboration, such as between terrestrial and stream ecologists. Just as the types of wood, rivers, regions, and cultures are globally diverse, scientists and the public should expect the ecological relationships of wood to vary widely as well.

Given the documented differences in large wood dynamics across different portions of a river network and between networks in diverse geographic regions, our understanding of large wood in rivers would benefit greatly from coordinated, long-term field studies in multiple field sites that focus on a few key questions. This type of research programme could foster direct comparisons among sites.

Climate change has the potential to modify all elements of systems influencing large wood in rivers – the forest sources of large wood, wood transport processes, losses of wood through decomposition and other processes, and human influences. Climate strongly influences many forest disturbance processes, such as wildfire, landslides, wind and canopy-icing storms, insect attacks, and diseases, which, in turn, regulate the timing and magnitude of large wood delivery to rivers. Similarly, climate-sensitive processes, such as melting of seasonal snowpacks and rain-on-snow flooding, may have a strong influence on transport of large wood. Decomposition of large wood in channels and on floodplains is regulated in part by water content – too much or too little water may impede the breakdown processes. Warming and change in precipitation may alter these conditions. Human actions in response to – or anticipation of – climate change impacts on forests and rivers may take many forms. Given these complexities, it is prudent to give careful attention to local conditions when assessing potential climate change impacts.

The overall challenge is to find sustainable conditions that can maintain the natural (or a target) wood regime and the desired ecological status of rivers, while minimizing the potential hazards (Mao *et al.*, 2013; Wohl *et al.*, 2016; Mazzorana *et al.*, 2018a, 2018b). Inherent in achieving sustainable conditions are (i) practicing watershed thinking, or explicitly managing rivers in a watershed context, and (ii) helping people outside the river research community to understand the benefits of large wood and thus accept the presence of wood in rivers. A sound management strategy should be holistic and catchment-based, and should include non-structural measures (Lane, 2017; Gurnell *et al.*, 2018). But finding the optimal balance, whether it emphasizes hazard mitigation or conservation, is founded on sustained, long-term, interdisciplinary monitoring and research, which are rare.

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Data Availability statement

No research data were used in this historical review.

Conflict of Interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the findings reported.

References

Abbe TB, Montgomery DR. 2003. Patterns and processes of wood debris accumulation in the Queets River Basin, Washington. *Geomorphology* **51**: 81–107.

Abbe TB, Brooks AP, Montgomery DR. 2003. Wood in river rehabilitation and management. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer KL, Gurnell AM (eds), Symposium 37. American Fisheries Society: Bethesda, MD; 407–420.

Acker SA, Gregory SV, Lienkaemper G, McKee WA, Swanson FJ, Miller SD. 2003. Composition, complexity, and tree mortality in riparian forests in the central western Cascades of Oregon. *Forest Ecology and Management* **173**: 293–308.

Anderson NH, Sedell JR, Roberts LM, Triska FJ. 1978. The role of aquatic invertebrates in processing of wood debris in coniferous forest streams. *American Midland Naturalist* **100**: 64–82.

Anderson NH, Steedman RJ, Dudley T. 1984. Patterns of exploitation by stream invertebrates of wood debris (xylophagy). *Internationale Vereinigung fiir Theoretische und Angewandte Limnologie* **22**: 1847–1852.

Andreoli A, Comiti F, Lenzi MA. 2007. Characteristics, distribution and geomorphic role of large woody debris in a mountain stream of the Chilean Andes. *Earth Surface Processes and Landforms* **1692**: 1675–1692.

Aumen NG, Bottomley PJ, Ward GM, Gregory SV. 1983. Microbial decomposition of wood in streams: distribution of microflora and factors affecting (C-14) lignocellulose mineralization. *Applied and Environmental Microbiology* **46**: 1409–1416.

Aumen NG, Hawkins CP, Gregory SV. 1990. Influence of woody debris on nutrient retention in catastrophically disturbed streams. *Hydrobiologia* **190**: 183–192.

Barbosa RI, Volkmer de Castilho C, de Oliveira PR, Damasco G, Rodrigues R, Fearnside PM. 2017. Decomposition rates of coarse woody debris in undisturbed Amazonian seasonally flooded and unflooded forests in the Rio Negro–Rio Branco Basin in Roraima, Brazil. *Forest Ecology and Management* **397**: 1–9.

Basso S, Mazzorana B, Ulloa H, Bahamondes D, Ruiz-Villanueva V, Iroumé A, Picco L. 2020. Unravelling the impacts to the built environment caused by floods in a river heavily perturbed by a volcanic eruption. *Journal of South American Earth Sciences*.

Benda LE, Sias JC. 2003. A quantitative framework for evaluating the wood budget. *Forest Ecology and Management* **172**: 1–16.

Benda L, Miller D, Sias J, Martin D, Bilby R, Veldhuisen C, Dunne T. 2003. Wood recruitment processes and wood budgeting. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer KL, Gurnell AM (eds). Symposium 37. American Fisheries Society: Bethesda, MD; 49–73.

Bertoldi W, Welber AM, Gurnell AM, Mao L, Comiti F, Tal M. 2015. Physical modelling of the combined effect of vegetation and wood in river morphology. *Geomorphology* **246**: 178–187.

Bocchiola D, Rulli MC, Rosso R. 2013. Flume experiments on wood entrainment in rivers. *Advances in Water Resources* **29**: 1182–1195.

Braudrick CA, Grant GE, Ishikawa Y, Ikeda H. 1997. Dynamics of wood transport in streams: a flume experiment. *Earth Surface Processes and Landforms* **22**: 669–683.

Buffington JM, Montgomery DR, Greenberg HM. 2004. Basin-scale availability of salmonid spawning gravel as influenced by channel type and hydraulic roughness in mountain catchments. *Canadian Journal of Fisheries and Aquatic Sciences* **61**: 2085–2096.

Carter RM. 1975. A discussion and classification of subaqueous mass-transport with particular application to grain-flow, slurry-flow, and fluxoturbidites. *Earth Science Reviews* **11**: 145–177.

Cerbu GA, Swallow BM, Thompson DY. 2011. Locating REDD: a global survey and analysis of REDD readiness and demonstration activities. *Environmental Science and Policy* **14**: 168–180.

Chin A, Daniels MD, Urban MA, Piégay H, Gregory KJ, Bigler W, Butt AZ, Grable JL, Gregory SV, Lafrenz M, Laurencio LR, Wohl E. 2008. Perceptions of wood in rivers and challenges for stream restoration in the United States. *Environmental Management* **41**: 893–903.

Chin A, Laurencio LR, Daniels MD, Wohl EE, Urban MA, Boyer KL, Butt A, Piégay H, Gregory KJ. 2012. The significance of perceptions and feedbacks for effectively managing wood in rivers. *River Research and Applications* **30**: 98–111.

Cierjacks A, Kleinschmit B, Babinsky M, Kleinschroth F, Markert A, Menzel M, Ziechmann U, Schiller T, Graf M, Lang F. 2010. Carbon stocks of soil and vegetation on Danubian floodplains. *Journal of Plant Nutrition and Soil Science* **173**: 644–653.

Cislaghi A, Bischetti GB. 2019. Source areas, connectivity, and delivery rate of sediments in mountainous-forested hillslopes: a probabilistic approach. *Science of the Total Environment* **652**: 1168–1186.

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

Comiti F, Andreoli M, Lenzi MA, Mao L. 2006. Spatial density and characteristics of woody debris in five mountain rivers of the Dolomites (Italian Alps). *Geomorphology* **78**: 44–63.

Comiti F, D'Agostino VD, Moser M, Lenzi MA, Bettella F, Agnese AD, Rigon E, Gius S, Mazzorana B. 2012. Preventing wood-related hazards in mountain basins: from wood load estimate to designing retention structures. In *12th Congress INTERPRAEVENT 2012*. Grenoble, France; 651–662.

Comiti F, Lucía A, Rickenmann D. 2016. Large wood recruitment and transport during large floods: a review. *Geomorphology* **269**: 23–35.

Crisafulli CM, Swanson FJ, Halvorson JJ, Clarkson RD. 2015. Volcano ecology: disturbance characteristics and assembly of biological communities. In *Encyclopedia of Volcanoes*, 2nd edn, Sigurdsson H, Houghton B, McNutt SR, Rymer H, Stix J (eds). Elsevier: New York; 1265–1284).

Crosato A, Rajbhandari N, Comiti F, Cherradi X, Uijttewaal W. 2013. Flume experiments on entrainment of large wood in low-land rivers. *Journal of Hydraulic Research* **51**: 581–588.

Dahlström N, Jönsson K, Nilsson C. 2005. Long-term dynamics of large woody debris in a managed boreal forest stream. *Forest Ecology and Management* **210**: 363–373.

Diehl TH. 1997. *Predicting drift accumulation at bridges. Publication No. FHWA-RD-97-028*. US Department of Transportation: McLean, VA.

Dietrich WE, Dunne T. 1978. Sediment budget for a small catchment in mountainous terrain. *Zietschrift fur Geomorphologie* **29**: 191–206.

Dodds WK, Robinson CT, Gaiser EE, Hansen GJA, Powell H, Smith JM, Morse NB, Johnson SL, Gregory SV, Bell T, Kratz TK, McDowell WH. 2012. Surprises and insights from long-term aquatic data sets and experiments. *Bioscience* **62**: 709–721.

Dommain R, Couwenberg J, Glaser PH, Joosten H, Suryadiputra NN. 2014. Carbon storage and release in Indonesian peatlands since the last deglaciation. *Quaternary Science Reviews* **97**: 1–32.

Enefalk **Å**, Bergman E. 2016. Effects of fine wood on macroinvertebrate drift in four boreal forest streams. *Hydrobiologia* **765**: 317–327.

Galia T, Ruiz-Villanueva V, Tichavský R, Šilhán K, Horáček M, Stoffel M. 2018. Characteristics and abundance of large and small instream wood in a Carpathian mixed-forest headwater basin. *Forest Ecology and Management* **424**: 468–482.

Grabowski RC, Gurnell AM, Burgess-Gamble L, England J, Holland D, Klaar MJ, Morrissey I, Uttley C, Wharton G. 2019. The current state of the use of large wood in river restoration and management. *Water Environment Journal* **33**: 366–377.

Gregory SV. 1996. History of management of large woody debris in the Pacific Northwest. In *The Northwest Salmon Crisis: A Documentary History*, Cone J, Ridlington S (eds). Oregon State University Press: Corvallis, OR; 148–160.

Gregory K. 2003. The limits of wood in world rivers: present, past, and future. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer KL, Gurnell AM (eds). Symposium 37. American Fisheries Society: Bethesda, MD; 1–20.

Gregory SV, Ashkenas LR. 1990. Riparian Management Guidelines for the Willamette National Forest. In *US Forest Service Technical Report*. US Forest Service: Willamette National Forest.

Gregory SV, Swanson FJ, McKee WA, Cummins KW. 1991. An ecosystem perspective of riparian zones: focus on links between land and water. *Bioscience* **41**: 540–551.

Gregory SV, Boyer KL, Gurnell AM (eds). 2003a. The Ecology and Management of Wood in World Rivers. In *Symposium 37*. Bethesda, MD: American Fisheries Society.

Gregory SV, Meleason M, Sobota DJ. 2003b. Modeling the dynamics of wood in streams and rivers. In *The Ecology and Management of Wood in World Rivers*, Symposium 37, Gregory SV, Boyer KL, Gurnell AM (eds). American Fisheries Society: Bethesda, MD; 315–336.

Gregory S, Wildman R, Hulse D, Ashkenas L, Boyer K. 2019. Historical changes in hydrology, geomorphology, and floodplain vegetation of the Willamette River, Oregon. *River Research and Applications* **35**: 1279–1290.

Gschnitzer T, Gems B, Mazzorana B, Aufleger M. 2017. Towards a robust assessment of bridge clogging processes in flood risk management. *Geomorphology* **279**: 128–140.

Gurnell AM. 2003. Wood storage and mobility. In *The Ecology and Management of Wood in World Rivers*. In *Symposium 37*, Gregory SV, Boyer KL, Gurnell AM (eds). American Fisheries Society: Bethesda, MD; 75–91.

Gurnell AM. 2007. Analogies between mineral sediment and vegetative particle dynamics in fluvial systems. *Geomorphology* **89**: 9–22.

Gurnell AM. 2013. Wood in fluvial systems. In *Treatise on Geomorphology*, Shroder J (ed). Academic Press: San Diego, CA; 163–188.

Gurnell AM, Gregory KJ, Petts GE. 1995. The role of coarse woody debris in forest aquatic habitats: implications for management. *Aquatic Conservation* **5**: 143–166.

Gurnell AM, Piégay H, Swanson FJ, Gregory SV. 2002. Large wood and fluvial processes. *Freshwater Biology* **47**: 601–619.

Gurnell A, Bledsoe BP, Fausch KD, Kramer N, Bestgen L. 2018. Trees and wood: working with natural river processes. *Water Environment Journal* **33**: 342–352.

Guyette RP, Dey CD, Stambaugh MC. 2008. The temporal distribution and carbon storage of large oak wood in streams and floodplain deposits. *Ecosystems* **11**: 643–653.

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K, Jr, Cummins KW. 1986. Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research* **15**: 133–302.

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

Hungr O, Leroueil S, Picarelli L. 2014. The Varnes classification of landslide types, an update. *Landslides* **11**: 167–194.

Hunt RL. 1988. A compendium of 45 trout stream habitat development evaluations in Wisconsin during 1953–1985. In *Technical Bulletin 162*. Madison, WI: Wisconsin Department of Natural Resources.

Hyatt TL, Naiman RJ. 2001. The residence time of large woody debris in the Queets River, Washington, USA. *Ecological Applications* **11**: 191–202.

Iroumé A, Mao L, Andreoli A, Ulloa H, Ardiles MP. 2015. Large wood mobility processes in low-order Chilean river channels. *Geomorphology* **228**: 681–693.

Iroumé A, Ruiz-Villanueva V, Mao L, Barrientos G, Stoffel M, Vergara G. 2018a. Geomorphic and stream flow influences on large wood dynamics and displacement lengths in high gradient mountain streams (Chile). *Hydrological Processes* **32**: 2636–2653.

Iroumé A, Wohl E, Mazzorana B, Picco L. 2018b. Evaluating large wood balance in highly disturbed stream channels. In *Proceedings of the 5th IAHR Europe Congress – New Challenges in Hydraulic Research and Engineering*, Armanini A, Nucci E (eds). Trento, Italy: 5th IAHR Europe Congress Organizers. 559–560. https://doi.org/10.3850/978-981-11-2731-1_065-cd

Ishikawa Y. 1990. *Studies on Disaster Caused by Debris Flow Carrying Floating Logs down Mountain Streams*. SABO Department, Public Works Research Institute: Tsukuba, Japan.

Iverson RM. 1997. The physics of debris flows. *Reviews in Geophysics* **35**: 245–296.

Jochner M, Turowski JM, Badoux A, Stoffel M, Rickli C. 2015. The role of log jams and exceptional flood events in mobilizing coarse particulate organic matter in a steep headwater stream. *Earth Surface Processes and Dynamics* **3**: 173–196.

Johnston CA. 2014. Beaver pond effects on carbon storage in soils. *Geoderma* **213**: 371–378.

Kail J, Hering D, Muhar S, Gerhard M, Preis S. 2007. The use of large wood in stream restoration: experiences from 50 projects in Germany and Austria. *Journal of Applied Ecology* **44**: 1145–1155.

Kang T, Kimura I. 2018. Computational modeling for large wood dynamics with root wad and anisotropic bed friction in shallow flows. *Advances in Water Resources* **121**: 419–431.

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

Korup O, Seidemann J, Mohr CH. 2019. Increased landslide activity on forested hillslopes following two recent volcanic eruptions in Chile. *Nature Geoscience* **12**: 284–289.

Kramer N, Wohl E. 2014. Estimating large wood discharge using time-lapse photography with varying sampling intervals. *Earth Surface Processes and Landforms* **39**: 844–852.

Lagasse PF, Clopper PE, Zevenberger LW, Spitz WJ, Girard LG. 2010. Effects of debris on bridge pier scour. National Cooperative Highway Research Program. NCHRP Report 653. Washington, DC: Transportation Research Board.

Lane SN. 2017. Natural flood management. *WIREs Water* **4**: 1–14.

Lassettre NS, Kondolf GM. 2012. Large woody debris in urban stream channels: redefining the problem. *River Research and Applications* **28**: 1477–1487.

Latterell JJ, Naiman RJ. 2007. Sources and dynamics of large logs in a temperate floodplain river. *Ecological Applications* **17**: 1127–1141.

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**: 342–353.

Le Lay YF, Piégay H, Gregory K, Chin A, Dolodec S, Mutz M, Wyzga B, Zawiejska J. 2008. Variations in cross-cultural perception of riverscapes in relation to in-channel wood. *Transactions of the Institute of British Geographers* **33**: 268–287.

Le Lay YF, Piégay H, Moulin B. 2013. Wood entrance, deposition, transfer and effects on fluvial forms and processes, problem statements and challenging issues. In *Treatise on Geomorphology*, vol. 12, Shroder JF (ed.). Academic Press: San Diego, CA; 20–36.

Lininger KB, Wohl E. 2019. Floodplain dynamics in North American permafrost regions under a warming climate and implications for organic carbon stocks: a review and synthesis. *Earth-Science Reviews* **193**: 24–44.

Lininger KB, Wohl E, Sutfin NA, Rose J. 2017. Floodplain downed wood volumes: a comparison across three biomes. *Earth Surface Processes and Landforms* **42**: 1248–1261.

Lininger KB, Wohl E, Rose JR. 2018. Geomorphic controls on floodplain soil organic carbon in the Yukon Flats, interior Alaska, from reach to river basin scales. *Water Resources Research* **54**: 1934–1951.

Lininger KB, Wohl E, Rose JR, Leisz SJ. 2019. Significant floodplain soil organic carbon storage along a large high-latitude river and its tributaries. *Geophysical Research Letters* **46**: 2121–2129.

Lipman PW, Mullineaux DR (eds). 1981. The 1980 eruptions of Mount St. Helens, Washington. In *US Geological Survey Professional Paper 1250*. US Government Printing Office: Washington, D.C.

Lisle TE. 1995. Effects of coarse woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helens, Washington. *Water Resources Research* **31**: 1797–1808.

Lucía A, Comiti F, Borga M, Cavalli M, Marchi L. 2015. Dynamics of large wood during a flash flood in two mountain catchments. *Natural Hazards and Earth System Sciences Discussions* **3**: 1643–1680.

MacVicar B, Piégay H. 2012. Implementation and validation of video monitoring for wood budgeting in a wandering piedmont river, the Ain River (France). *Earth Surface Processes and Landforms* **37**: 1272–1289.

Mao L, Andreoli A, Iroumé A, Comiti F, Lenzi MA. 2013. Dynamics and management alternatives of in-channel large wood in mountain basins of the southern Andes. *Bosque (Valdivia)* **34**: 15–16.

Martin DJ, Benda LE. 2001. Patterns of instream wood and recruitment at the watershed scale. *Transactions of the American Fisheries Society* **130**: 940–958.

Martini L, Picco L, Iroumé A, Cavalli M. 2019. Sediment connectivity changes in an Andean catchment affected by volcanic eruption. *Science of the Total Environment* **692**: 1209–1222.

Maser C, Sedell JR. 1994. *From the Forest to the Sea: The ecology of wood in streams, rivers, estuaries, and oceans*. St. Lucie Press: Delray Beach, FL.

Maser C, Tarrant RF, Trappe JM, Franklin JF (tech. eds). 1988. From the forest to the sea: a story of fallen trees. General Technical Report PNW-GTR-229. *US Department of Agriculture, Forest Service, Pacific Northwest Research Station/US Department of the Interior*, Bureau of Land Management: Portland, OR.

Massong TM, Montgomery DR. 2000. Influence of sediment supply, lithology, and wood debris on the distribution of bedrock and alluvial channels. *Geological Society of America Bulletin* **112**: 591–599.

Mazzorana B, Hubl J, Fuchs S. 2009. Improving risk assessment by defining consistent and reliable systems scenarios. *Natural Hazards and Earth System Sciences* **9**: 145–159.

Mazzorana B, Hubl J, Zischg A, Largiader A. 2011. Modeling woody material transport and deposition in alpine rivers. *Natural Hazards* **56**: 425–449.

Mazzorana B, Nardini A, Comiti F, Vignoli G, Cook E, Ulloa H, Iroumé A. 2018a. Toward participatory decision-making in river corridor management: two case studies from the European Alps. *Journal of Environmental Planning and Management* **61**: 1250–1270.

Mazzorana B, Ruiz-Villanueva V, Marchi L, Cavalli M, Gems B, Gschnitzer T, Mao L, Iroumé A, Valdebenito G. 2018b. Assessing and mitigating large wood-related hazards in mountain streams: recent approaches. *Journal of Flood Risk Management* **11**(2): 207–222. https://doi.org/10.1111/jfr3.12316.

Mazzorana B, Picco L, Rainato R, Iroumé A, Ruiz-Villanueva V, Rojas C, Valdebenito G, Iribarren-Anacona P, Melnick D. 2019. Cascading processes in a changing environment: disturbances on fluvial ecosystems in Chile and implications for hazard and risk management. *The Science of the Total Environment* **655**: 1089–1103.

McDade MH, Swanson FJ, McKee WA, Franklin JF, Van Sickle J. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. *Canadian Journal of Forest Research* **20**: 326–330.

Meleason MA, Gregory SV, Bolte J. 2003. Implications of selected riparian management strategies on wood in streams of the Pacific Northwest. *Ecological Applications* **13**: 1212–1221.

Merten E, Finlay J, Johnson L, Newman R, Stefan H, Vondracek B. 2010. Factors influencing wood mobilization in streams. *Water Resources Research* **46**. https://doi.org/10.1029/2009WR008772.

Mohr CH, Korup O, Ulloa H, Iroumé A. 2017. Pyroclastic eruption boosts organic carbon fluxes into Patagonian fjords. *Global Biogeochemical Cycles* **31**: 1626–1638.

Montgomery DR. 1999. Process domains and the river continuum. *Journal of the American Water Resources Association* **35**: 397–410.

Montgomery DR, Collins BD, Buffington JM, Abbe TB. 2003. Geomorphic effects of wood in rivers. In *The Ecology and Management of Wood in World Rivers*. In *Symposium 37*, Gregory SV, Boyer KL, Gurnell AM (eds). American Fisheries Society: Bethesda, MD; 21–47.

Moreira-Turcq P, Jouanneau JM, Turcq B, Seyler P, Weber O, Guyot JL. 2004. Carbon sedimentation at Lago Grande de Curuai, a floodplain lake in the low Amazon region: insights into sedimentation rates. *Palaeogeography, Palaeoclimatology, Palaeoecology* **214**: 27–40.

Naiman RJ, Décamps H. 1997. The ecology of interfaces: riparian zones. *Annual Review of Ecology and Systematics* **28**: 621–658.

Nakamura F, Seo JI, Akasaka T, Swanson FJ. 2017. Large wood, sediment, and flow regimes: their interactions and temporal changes caused by human activities in Japan. *Geomorphology* **279**: 176–187.

Neatrour MA, Webster JR, Benfield E. 2004. The role of floods in particulate organic matter dynamics of a southern Appalachian river–floodplain ecosystem. *Journal of the North American Benthological Society* **23**: 198–213.

Needham PR. 1938. *Trout Streams: Conditions that determine their productivity and suggestions for stream and lake management.* Comstock Publishing: Ithaca, NY.

Pagliara S, Carnacina I. 2011. Influence of wood debris accumulation on bridge pier scour. *Journal of Hydraulic Engineering* **137**: 254–261.

Persi E, Petaccia G, Sibilla S. 2018. Woody debris transport modelling by a coupled DE–SW approach. *Natural Hazards* **91**: 59–74.

Picco L, Bertoldi W, Comiti F. 2017. Dynamics and ecology of wood in world rivers. *Geomorphology* **279**: 10–11.

Piégay H. 1993. Nature, mass and preferential sites of coarse woody debris deposits in the lower ain valley (Mollon reach), France. *Regulated Rivers* **8**: 359–372.

Piégay H, Gregory KJ, Bondarev V, Chin A, Dahlstrom N, Elosegi A, Gregory SV, Joshi V, Mutz M, Rinaldi M, Wyzga B, Zawiejska J. 2005. Public perception as a barrier to introducing wood in rivers for restoration purposes. *Environmental Management* **36**: 665–674.

Pierson TC, Costa JE. 1987. A rheological classification of subaerial sediment–water flows. In *Reviews in Engineering Geology Debris Flows/Avalanches, vol. VII*, Costa JE, Wieczorek GF (eds). Geological Society of America: Boulder, CO; 1–12.

Pierson TC, Major JJ, Amigo A, Moreno H. 2013. Acute sedimentation response to rainfall following the explosive phase of the 2008–2009 eruption of Chaitén volcano, Chile. *Bulletin of Volcanology* **75**: 723-740.

Piton G, Recking A. 2015. Design of sediment traps with open check dams. II: woody debris. *Journal of Hydraulic Engineering* **142**: 1–13.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. *Bioscience* **47**: 769–784.

Poole GC. 2002. Fluvial landscape ecology: addressing uniqueness within the river discontinuum. *Freshwater Biology* **47**: 641–660.

Ravazzolo D, Mao L, Picco L, Lenzi ML. 2015. Tracking log displacement during floods in the Tagliamento River using RFID and GPS tracker devices. *Geomorphology* **228**: 226–233.

Reich M, Kershner JL, Wildman RC. 2003. Restoring streams with large wood: a synthesis. In *The Ecology and Management of Wood in World Rivers*, Symposium 37, Gregory SV, Boyer KL, Gurnell AM (eds). American Fisheries Society: Bethesda, MD; 355–366.

Rickenmann D. 1997. Schwemmholz und Hochwasser. *Wasse, Energie, Luft* **89**: 115–119.

Roni P. 2019. Does river restoration increase fish abundance and survival or concentrate fish? The effects of project scale, location, and fish life history. *Fisheries* **44**: 7–19.

Roni P, Beechie T, Pess G, Hanson K. 2015. Wood placement in river restoration: fact, fiction, and future direction. *Canadian Journal of Fisheries and Aquatic Sciences* **72**: 466–478.

Ruiz-Villanueva V, Stoffel M. 2017. Frederick J. Swanson's papers on the effects of instream wood on fluvial processes and instream wood management. *Progress in Physical Geography* **41**: 124–133.

Ruiz-Villanueva V, Bodoque JM, Díez-Herrero A, Eguibar MA, Pardo-Igúzquiza E. 2013. Reconstruction of a flash flood with large wood transport and its influence on hazard patterns in an ungauged mountain basin. *Hydrological Processes* **27**: 3424–3437.

Ruiz-Villanueva V, Bladé E, Sánchez-Juny M, Marti-Cardona B, Díez-Herrero A, Bodoque JM. 2014a. Two-dimensional numerical modeling of wood transport. *Journal of Hydroinformatics* **16**: 1077–1096.

Ruiz-Villanueva V, Bodoque JM, Díez-Herrero A, Bladé E. 2014b. Large wood transport as significant influence on flood risk in a mountain village. *Natural Hazards* **74**: 967–987.

Ruiz-Villanueva V, Díez-Herrero A, Ballesteros-Canovas JA, Bodoque JM. 2014c. Potential large woody debris recruitment due to landslides, bank erosion and floods in mountain basins: a quantitative estimation approach. *River Research and Applications* **30**: 81–97.

Ruiz-Villanueva V, Wyzga B, Hajdukiewicz H, Stoffel M. 2016. Exploring large wood retention and deposition in contrasting river morphologies linking numerical modeling and field observation. *Earth Surface Processes and Landforms* **41**: 446–459.

Ruiz-Villanueva V, Wyżga B, Mikuś P, Hajdukiewicz M, Stoffel M. 2017. Large wood clogging during floods in a gravel-bed river: the Długopole bridge in the Czarny Dunajec River, Poland. *Earth Surface Processes and Landforms* **42**: 516–530.

Ruiz-Villanueva V, Badoux A, Rickenmann D, Böckli M, Schläfli S, Steeb N, Stoffel M, Rickli C. 2018. Impacts of a large flood along a mountain river basin: the importance of channel widening and estimating the large wood budget in the upper Emme River (Switzerland). *Earth Surface Dynamics* **6**: 1115–1137.

Ruiz-Villanueva V, Mazzorana B, Blade E, Burkli L, Iribarren-Anacona P, Mao L, Nakamura F, Ravazzolo D, Rickenmann D, Sanz-Ramos M, Stoffel M, Wohl E. 2019. Characterization of wood-laden flows in forested river basins. *Earth Surface Processes and Landforms* **44**: 1694–1709.

Sabater S, Gregory SV, Sedell JR. 1998. Community dynamics and metabolism of benthic algae colonizing wood and rock substrata in a forest stream. *Journal of Phycology* **34**: 561–567.

Sabo Department. 2000. *Guideline for driftwood countermeasures.* Ministry of Construction, Japan. Available at: www.sabo-int.org/guideline/pdf/driftwoodCountermeasure Guideline.pdf.

Sanhueza D, Picco L, Ruiz-Villanueva V, Iroumé A, Ulloa H, Barrientos G. 2019. Quantification of fluvial wood using UAVs and structure from motion. *Geomorphology* **345**: 106837.

Schalko I. 2018. Large wood accumulation probability at a single bridge pier. In *Proceedings of the 37th IAHR World Congress*, August 13–18, Kuala Lumpur; 1704–1713.

Schalko I, Lageder C, Schmocker L, Weitbrecht V, Boes RM. 2019. Laboratory flume experiments on the formation of spanwise large wood accumulations: part II – effect on local scour. *Water Resources Research* **55**: 4871–4885.

Schenk ER, Moulin B, Hupp CR, Richter JM. 2014. Large wood budget and transport dynamics on a large river using radio telemetry. *Earth Surface Processes and Landforms* **39**: 487–498.

Schmocker L, Hager WH. 2011. Probability of drift blockage at bridge decks. *Journal of Hydraulic Engineering* **137**: 470–479.

Scott DN, Wohl E. 2017. Evaluating carbon storage on subalpine lake deltas. *Earth Surface Processes and Landforms* **42**: 1472–1481.

Scott DN, Wohl E. 2018a. Geomorphic regulation of floodplain soil organic carbon concentration in watersheds of the Rocky and Cascade Mountains, USA. *Earth Surface Dynamics* **6**: 1101–1114.

Scott DN, Wohl EE. 2018b. Natural and anthropogenic controls on wood loads in river corridors of the Rocky, Cascade, and Olympic Mountains, USA. *Water Resources Research* **54**: 7893–7909.

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

Sobota DJ, Gregory SV, Van Sickle J. 2006. Riparian tree fall directions and modeling large wood recruitment to streams. *Canadian Journal of Forest Research* **36**: 1243–1254.

Steeb N, Rickenmann D, Badoux A, Rickli C, Waldner P. 2017. Large wood recruitment processes and transported volumes in Swiss mountain streams during the extreme flood of August 2005. *Geomorphology* **279**: 112–127.

Sutfin NA, Wohl E. 2019. Elevational differences in hydrogeomorphic disturbance regime influence sediment residence times within mountain river corridors. *Nature Communications* **10**: 2221.

Sutfin NA, Wohl EE, Dwire AA. 2016. Banking carbon: a review of organic carbon storage and physical factors influencing retention in floodplains and riparian ecosystems. *Earth Surface Processes and Landforms* **41**: 38–60.

Swanson FJ, Gregory SV. 2018. Development of riparian perspectives in the wet Pacific Northwest since the 1970s. In *Riparian research and management: Past, present, future, Vol. 1*, Johnson RR, Carothers SW, Finch DM, Kingsley KJ, Stanley JT (eds). General Technical Report RMRS-GTR-377. US Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO; 25–31.

Swanson FJ, Jones JA. 2002. Geomorphology and hydrology of the H. J. Andrews Experimental Forest, Blue River, Oregon. In *Field Guide to Geologic Processes in Cascadia: Field trips to accompany the 98th annual meeting of the Cordilleran section of the Geological Society* *of America*, Moore GW (ed). Special Paper 36. Oregon Department of Geology and Mineral Industries: Portland, OR; 288–314.

Swanson FJ, Lienkaemper GW, Sedell JR. 1976. *History, physical effects, and management implications of large organic debris in western Oregon streams. General Technical Report PNW-56.* US Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station: Portland, OR.

Swanson FJ, Janda RJ, Dunne T, Swanston DN (eds). 1982. Sediment budgets and routing in forested drainage basins. In *General Technical Report PNW-141*. US Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station: Portland, OR.

Swanson FJ, Bryant MD, Lienkaemper GW, Sedell JR. 1984. *Organic debris in small streams, Prince of Wales Island, southeast Alaska. General Technical Report PNW- GTR-166*. US Department of Agriculture, Forest Service, Pacific Northwest Research Station: Portland, OR.

Swanson FJ, Jones JA, Crisafulli CM, Lara A. 2013. Effects of volcanic and hydrologic processes on forest vegetation: Chaiten Volcano, Chile. *Andean Geology* **40**: 359–391.

Takahashi T. 2014. *Debris Flow: Mechanics, prediction and countermeasures*, 2nd edn. CRC Press: Boca Raton, FL.

Thompson DM. 2006. Did the pre-1980 use of in-stream structures improve streams? A reanalysis of historical data. *Ecological Applications* **16**: 784–796.

Tonon A, Iroumé A, Picco L, Oss Cazzador D, Lenzi MA. 2017. Temporal variations of large wood abundance and mobility in the Blanco River affected by the Chaiten volcanic eruption, southern Chile. *Catena* **156**: 149–160.

Triska FJ, Cromack K, Jr. 1980. The role of wood debris in forests and streams. In *Forests: Fresh perspectives from ecosystem analysis*, Waring RH (ed). Oregon State University Press: Corvallis, OR; 171–190.

Triska FJ, Sedell JR, Gregory SV. 1982. Coniferous forest streams. In *Analysis of Coniferous Forest Ecosystems in the Western United States*, Edmonds RL (ed). Hutchinson Ross Publishing: Stroudsburg, PA; 292–332.

Uchiogi T, Shima J, Tajima H, Ishikawa Y. 1996. Design methods for wood-debris entrapment. *Proc.Interpraevent, Tagungspublikation Bd.* **5**: 279–288.

Ulloa H, Iroumé A, Picco L, Korup O, Lenzi MA, Mao L, Ravazzolo D. 2015a. Massive biomass flushing despite modest channel response in the Rayas River following the 2008 eruption of Chaiten volcano, Chile. *Geomorphology* **250**: 397–406.

Ulloa H, Iroumé A, Mao L, Andreoli A, Diez S, Lara LE. 2015b. Use of remote imagery to analyse changes in morphology and longitudinal large wood distribution in the Blanco River after the 2008 Chaiten volcanic eruption, southern Chile. *Geografiska Annalar Series B* **97**: 523–541.

Umazano AM, Melchor RN, Bedatou E, Bellosi ES, Kraus JM. 2014. Fluvial response to sudden input of pyroclastic sediments during the 2008–2009 eruption of the Chaitén Volcano (Chile): the role of logjams. *South American Journal of Earth Sciences* **54**: 140–157.

Valdebenito G, Iroumé A, Jara C, Alvarado D, Fuentes C. 2015. Large wood delivery from buried dead wood: the use of Ground Penetrating Radar (GPR) to characterize excess pyroclastic deposits in the Blanco River, southern Chile. In *Proceedings of the Third International Conference Wood in World Rivers*; 137–139.

Van Sickle J, Gregory SV. 1990. A model of woody debris input into streams. *Canadian Journal of Forest Research* **20**: 1593–1601.

Vannote RL, Minshall GW, Cummins KW, Sedell JR, Cushing CE. 1980. The River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences* **37**: 130–137.

Ward GM, Aumen NG. 1986. Woody debris as a source of fine particulate organic matter in coniferous forest stream ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences* **43**: 1635–1642.

Webster J, Patten B. 1979. Effects of watershed perturbation on stream potassium and calcium dynamics. *Ecological Monographs* **49**: 51–72.

West AJ, Lin CW, Lin TC, Hilton RG, Liu SH, Chang CT, Lin KC, Galy A, Sparkes RB, Hovius N. 2011. Mobilization and transport of coarse woody debris to the oceans triggered by an extreme tropical storm. *Limnology and Oceanography* **56**: 77–85.

Wohl E. 2010. *Mountain Rivers Revisited*. American Geophysical Union Press: Washington, D.C.

Wohl E. 2013a. Floodplains and wood. *Earth-Science Reviews* **123**: 194–212.

Wohl E. 2013b. Landscape-scale carbon storage associated with beaver dams. *Geophysical Research Letters* **40**: 3631–3636.

Wohl E. 2014. A legacy of absence: wood removal in US rivers. *Progress in Physical Geography* **38**: 637–663.

Wohl E. 2017. Bridging the gaps: an overview of wood across time and space in diverse rivers. *Geomorphology* **279**: 3–26.

Wohl E, Cadol D. 2011. Neighborhood matters: patterns and controls on wood distribution in old-growth forest streams in the Colorado Front Range, USA. *Geomorphology* **125**: 132–146.

Wohl E, Goode JR. 2008. Wood dynamics in headwater streams of the Colorado Rocky Mountains. *Water Resources Research* **44**: 1–14.

Wohl E, Ogden FL. 2013. Organic carbon export in the form of wood during an extreme tropical storm, Upper Rio Chagres, Panama. *Earth Surface Processes and Landforms* **38**: 1407–1416.

Wohl E, Dwire K, Sutfin N, Polvi L, Bazan R. 2012. Mechanisms of carbon storage in mountainous headwater rivers. *Nature Communications* **3**: 1263.

Wohl E, Bledsoe BP, Jacobson RB, Poff NR, Rathburn SL, Walters DM, Wilcox AC. 2015. The natural sediment regime in rivers: broadening the foundation for ecosystem management. *Bioscience* **65**: 358–371.

Wohl EE, Bledsoe BP, Fausch KD, Kramer N, Bestgen KR, Gooseff MN. 2016. Management of large wood in streams: an overview and proposed framework for hazard evaluation. *Journal of the American Water Resources Association* **52**: 315–335.

Wohl E, Hall RO, Lininger KB, Sutfin NA, Walters DM. 2017. Carbon dynamics of river corridors and the effects of human alterations. *Ecological Monographs* **87**: 379–409.

Wohl E, Lininger KB, Scott DN. 2018a. River beads as a conceptual framework for building carbon storage and resilience to extreme climate events into river management. *Biogeochemistry* **141**: 365–383.

Wohl E, Scott DN, Lininger KB. 2018b. Spatial distribution of channel and floodplain large wood in forested river corridors of the Northern Rockies. *Water Resources Research* **54**: 7879–7892.

Wohl E, Kramer N, Ruiz-Vallenueva V, Scott D, Comiti F, Gurnell A, Piégay H, Jaeger K, Walters D, Fausch K. 2019. The natural wood regime in rivers. *Bioscience* **69**: 259–273.

Zalamea M, Gonzalez G, Ping CL, Michaelson G. 2007. Soil organic matter dynamics under decaying wood in a subtropical wet forest: effect of tree species and decay stage. *Plant and Soil* **296**: 173–185.

Zischg A, Galatioto N, Deplazes S, Weingartner R, Mazzorana B. 2018. Modelling spatiotemporal dynamics of large wood recruitment, transport, and deposition at the river reach scale during extreme floods. *Watermark* **10**: 1134–1153.