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State of Science

Reflections on the history of research on large wood in rivers

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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

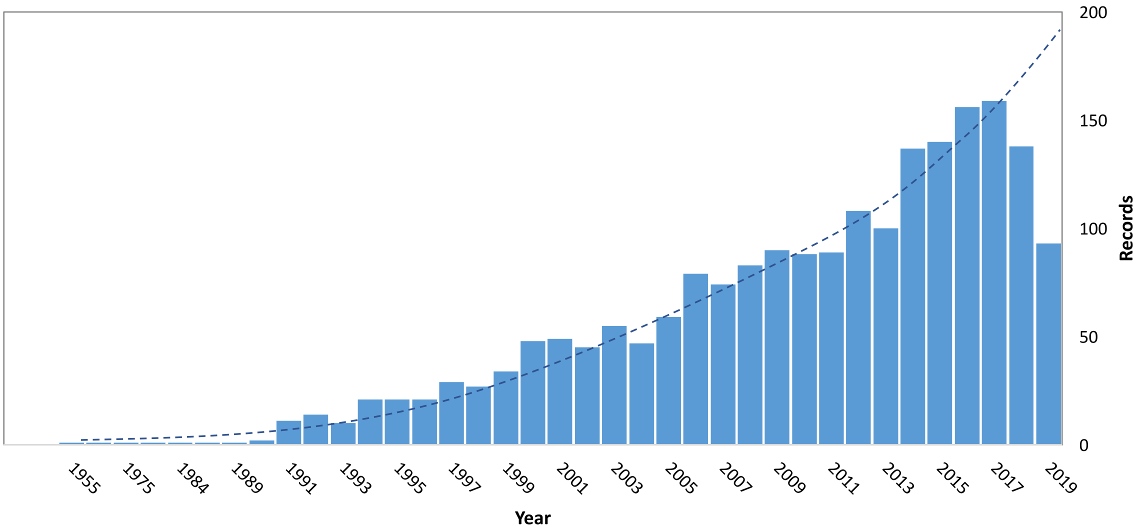

Figure 1. Annual number of articles published in English with the keywords 'wood*' (using the * includes other words such as 'woody') and 'river', and excluding papers published in unrelated fields (e.g. agriculture, archaeology, arts, biochemistry) found in the ISI Web of Sciences (last accessed 8 August 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.

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