AGU PUBLICATIONS

Reviews of Geophysics

REVIEW ARTICLE

10.1002/2015RG000514

Key Point:

- We review critical questions which remain open regarding large wood dynamics

Correspondence to:
V. Ruiz-Villanueva,
virginia.ruiz@dendrolab.ch

Citation:
Ruiz-Villanueva, V., H. Piégay, A. M. Gurnell, R. A. Marston, and M. Stoffel (2016), Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges, *Rev. Geophys.*, *54*, 611–652, doi:10.1002/2015RG000514.

Received 1 DEC 2015
Accepted 10 JUL 2016
Accepted article online 15 JUL 2016
Published online 17 SEP 2016
Corrected 3 NOV 2016

This article was corrected on 3 NOV 2016. See the end of the full text for details.

Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges

Virginia Ruiz-Villanueva[1,2], Hervé Piégay[3], Angela M. Gurnell[4], Richard A. Marston[5], and Markus Stoffel[1,2,6]

[1]Dendrolab.ch, Institute of Geological Sciences, University of Bern, Bern, Switzerland, [2]Institute for Environmental Sciences, University of Geneva, Geneva, Switzerland, [3]University of Lyon, CNRS UMR, Lyon, France, [4]School of Geography, Queen Mary University of London, London, UK, [5]Department of Geography, Kansas State University, Manhattan, Kansas, USA, [6]Department of Earth Sciences, University of Geneva, Geneva, Switzerland

Abstract Large wood is an important physical component of woodland rivers and significantly influences river morphology. It is also a key component of stream ecosystems. However, large wood is also a source of risk for human activities as it may damage infrastructure, block river channels, and induce flooding. Therefore, the analysis and quantification of large wood and its mobility are crucial for understanding and managing wood in rivers. As the amount of large-wood-related studies by researchers, river managers, and stakeholders increases, documentation of commonly used and newly available techniques and their effectiveness has also become increasingly relevant as well. Important data and knowledge have been obtained from the application of very different approaches and have generated a significant body of valuable information representative of different environments. This review brings a comprehensive qualitative and quantitative summary of recent advances regarding the different processes involved in large wood dynamics in fluvial systems including wood budgeting and wood mechanics. First, some key definitions and concepts are introduced. Second, advances in quantifying large wood dynamics are reviewed; in particular, how measurements and modeling can be combined to integrate our understanding of how large wood moves through and is retained within river systems. Throughout, we present a quantitative and integrated meta-analysis compiled from different studies and geographical regions. Finally, we conclude by highlighting areas of particular research importance and their likely future trajectories, and we consider a particularly underresearched area so as to stress the future challenges for large wood research.

1. Introduction

Over recent decades, large wood in rivers has received increasing interest among scientists who have recognized its significance as a functional component of fluvial ecosystems, considering it to be as important as sediment and riparian vegetation [*Gurnell et al.*, 2002; *Gregory et al.*, 2003; *Gurnell,* 2013; *Wohl,* 2011, 2013; *Le Lay et al.*, 2013]. Large wood significantly influences river morphology and sediment dynamics [*Montgomery et al.*, 2003; *Wohl and Scott*, 2016] and represents a key component of stream ecosystems [*Gregory et al.*, 2003]. It also plays an important role in supporting the biodiversity of fluvial corridors, influencing the nutrient cycle, and providing a variety of physical habitats [*Gurnell*, 2013]. Although the removal of wood from rivers has been a widespread practice [*Wohl*, 2014], reintroduction of wood into fluvial systems has recently become a component of many river restoration projects aimed at improving the hydrological, morphological, and ecological status of degraded streams and rivers [*Kail et al.*, 2007; *Abbe*, 2011; *Antón et al.*, 2011].

Large wood, like sediment, remains relatively stable for most of the time within river corridors, with only the smaller and loose wood pieces able to move. However, large quantities of wood may be mobilized during infrequent, high-magnitude flood events [*Mao et al.*, 2013] and may induce potential hazards for human populations and infrastructure [*Comiti et al.*, 2012; *Badoux et al.*, 2015; *Lucía et al.*, 2015]. The deposition of wood at critical locations (e.g., bridges) can cause a reduction of channel cross-sectional area and related conveyance loss [*Gippel et al.*, 1996; *Beebe*, 2000], thus inducing more frequent flooding. This may be accompanied by other processes such as bed aggradation, channel avulsion, and local scouring. Therefore, understanding how, where, and why wood moves is fundamental to interpreting and predicting the way in which wood is stored in river systems. The potential related damage during floods makes wood management necessary, although in many regions no clear guidelines exist on how to manage wood. Overall, an integrated approach to large wood management along the entire river continuum is needed rather than site-specific responses to local problems generated by network-wide dynamics. Integrated management requires a holistic view covering the watershed, forest, and riparian management; maintenance of water courses; and nonstructural and administrative measures [*Rudolf-Miklau and Hübl,* 2010; *Mao et al*., 2013].

The challenge is to find sustainable conditions that can maintain wood and the good ecological status of rivers while minimizing the potential hazards. Therefore, the quantification of the large wood dynamics within river networks is crucial for managing rivers under contemporary human pressures. Approximately 3000 contributions on "woody debris," "large wood," or "in-stream wood" were published between 1904 and 2015 with enormous advances in scientific understanding, particularly over the last two decades. From these publications, which may also include aspects that are not exclusively related to dynamics of large wood in rivers in the strictest sense (e.g., focusing on biomass estimation, biodiversity analysis, biological studies, restoration assessments, and social science), 149 contributions can be described as review papers. Some of the most recent reviews concerning wood in rivers include *Gurnell et al.* [2002], *Gurnell* [2012, 2013], *Wohl et al.* [2010], *Wohl* [2011, 2013], or *Le Lay et al.* [2013]. In these papers, the authors describe the impact of wood on river morphology, the main characteristics of wood that govern its dynamics, and the characteristics of rivers that dictate the way in which wood is mobilized, transported, and retained [*Gurnell et al*., 2002; *Le Lay et al*., 2013]. The authors also consider interactions between wood and riparian vegetation [*Gurnell*, 2013] and the ways in which wood drives and responds to floodplain dynamics [*Wohl*, 2013]. In some of the reviews [*Gurnell,* 2012] the importance of wood for stream ecosystems and as a key component in river restoration is also highlighted.

To date, however, tools to understand, quantify, and model large-wood-related processes have not been reviewed in an integrated way. *MacVicar et al.* [2009] provided a partial exception as they describe the integrated use of repeat high-resolution aerial surveys, measurement of wood physical characteristics, and the use of passive and active radio frequency identification tags, radio transmitters, and videos to establish an overview of large wood dynamics. Other research has focused on field surveys that capture a set of properties of wood at the time of survey, with *Wohl et al.* [2010] summarizing and defining the most important features to be considered. In terms of the temporal dynamics of large wood, long-term observations are extremely rare [*Iroumé et al*., 2014], although methods for monitoring and tracking wood are progressing rapidly [*MacVicar and Piégay,* 2012; *Ravazzolo et al*., 2015a] and modeling is increasingly being used. In this latter context, *Welber* [2013] provided recent examples of physical experiments, and *Ruiz-Villanueva et al.* [2014a] proposed a numerical model to simulate transport of large wood in rivers.

Knowledge on how much wood we should expect to have in a river or how much wood we might expect to be transported during floods is essential. *Bisson et al.* [1987] explored these issues some decades ago and concluded that no simple answers existed. The problem is compounded by a severe lack of information from many biogeographical regions, but some generalizations are now possible based on information available from the open literature. Therefore, this review synthesizes information from the literature to provide for the first time a comprehensive qualitative and quantitative summary of recent advances regarding the different processes involved in large wood dynamics including the recruitment, transfer, and storage of wood in fluvial systems.

Following *Martin and Benda* [2001], wood dynamics can be considered from two perspectives: a mass balance approach and a transport mechanism viewpoint (Figure 1). The first perspective can be understood as a large wood cycle similar to the water cycle and equivalent to the floodplain large wood cycle described by *Collins et al.* [2012]: in other words, the linkages and feedbacks associated with the primary processes (i.e., recruitment, transport, and deposition) that govern wood dynamics and mass balance in fluvial systems. The main questions related to large wood dynamics from the perspective of a mass balance approach concern wood budgeting and wood fluxes or wood "discharge" (i.e., how much wood would be transferred from upstream to downstream) and their complexity through space and time. The second perspective is large wood mechanics or the physical factors controlling wood entrainment and transport processes. The questions to be answered under this second perspective are related to hydraulics and fluid mechanics.

Our aim is to provide a comprehensive review of recent advances in the field of large wood dynamics in rivers, compiling technical and scientific advances that can contribute to the understanding of the large

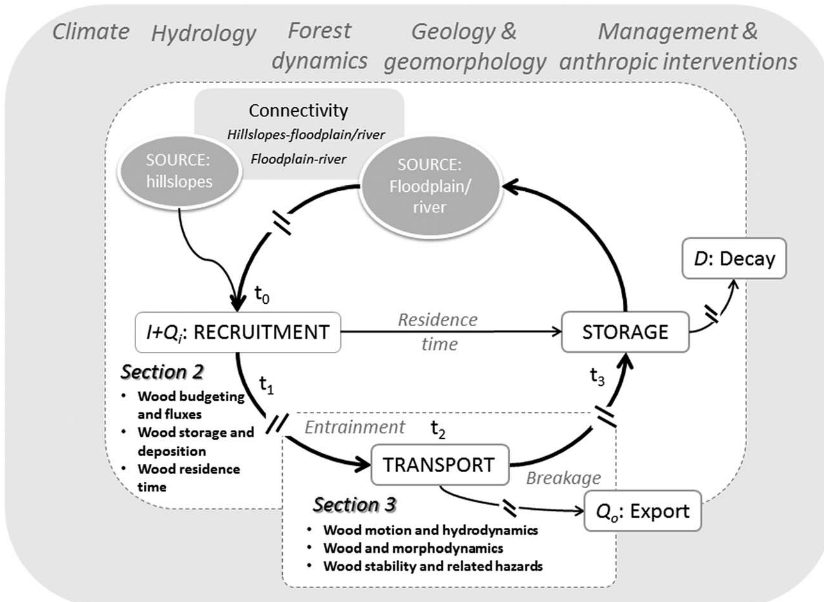

Figure 1. Large wood dynamics in forested river basins illustrated as a cycle where recruitment from wood sources (i.e., hillslopes and fluvial corridor) might be transported and/or stored. The nonlinearity of these processes is illustrated as t_0–t_3, as recruitment and transport can be induced by steady and episodic disturbances. The time between the processes (t_0–t_3) may vary among different rivers or within the same river, and this defines the residence time of wood in the system. The two white rectangles show the main aspects described in this paper: section 2 focuses on the wood budget, and section 3 focuses on wood transport. I is lateral wood recruitment, D is in situ decay, and Q_i and Q_o are fluvial transport of wood into and out of the system.

wood cycle in river basins and wood mechanics. This paper is organized as follows: section 2 reviews advances in the quantification of elements of the wood budget, including the quantification of wood fluxes, the analysis of wood storage and the description of preferential sites for wood deposition, and the assessment of residence time of wood in rivers. Section 3 reviews advances in quantifying wood motion, in particular, considering the tracing of wood kinematics and how measurements and modeling can be combined to integrate our understanding of how large wood moves in river systems. This section also describes some potential large-wood-related hazards and summarizes advances in their estimation. Section 4 highlights areas of particular research importance and their likely future trajectories from the previous sections and develops a particularly underresearched area so as to stress the future challenges faced by large wood research.

Throughout, we present and analyze quantitative information from different studies and geographical regions. We compiled information on wood fluxes exported during floods, showing data from 83 events, including recent events from France, Italy, and Switzerland but also data from Japan and Canada. We update previous databases about wood storage in rivers to 390 sites (including data from Canada, Chile, France, Italy, New Zealand, Poland, Spain, and the U.S.). We also provide a synthetic overview on the mean residence time of large wood in different river systems. Lastly, we assembled all published data on the movement of individual pieces of wood in rivers, integrating for the first time aspects of wood mobility across a variety of environmental settings.

2. Advances in Quantifying Large Wood Budgeting

This section is focused on the three main processes driving the large wood budget: wood recruitment or delivery, wood transfer, and wood deposition. These processes are considered in relation to three themes: wood budgeting and fluxes (section 2.2), wood storage and depositional sites (section 2.3), and wood residence time (section 2.4). However, before considering these processes, we review how large wood is defined and measured. Therefore, in section 2.1, we summarize the most common definitions of large wood and the recommended metrics for quantifying large wood.

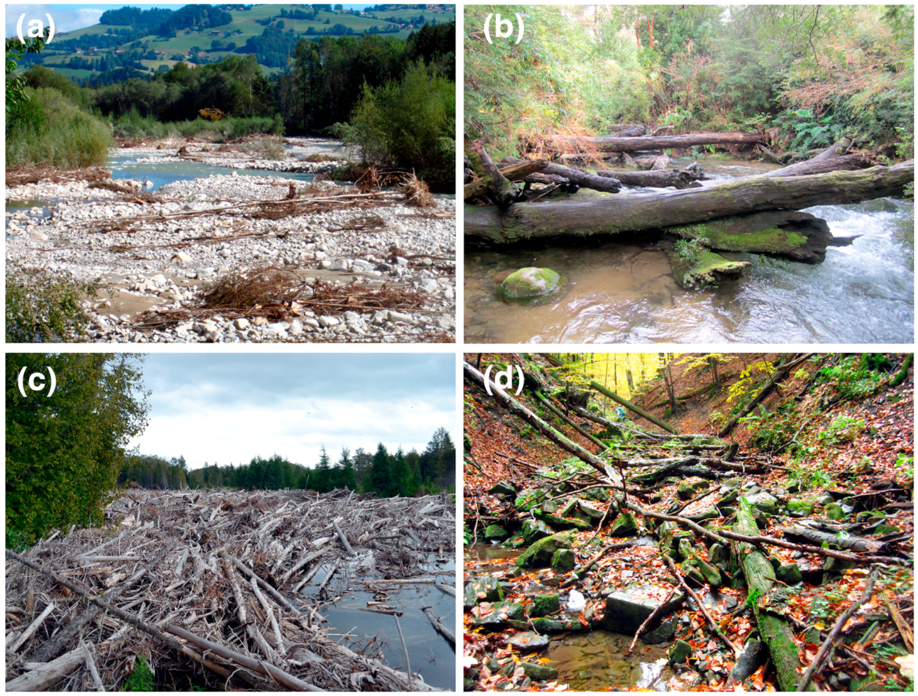

Figure 2. Rivers showing different types and sizes of wood accumulations. (a) The braided Sense River (Switzerland) usually shows wood accumulations comprised of a mix of individual, larger wood pieces, and whole, multistemmed shrubs (photograph: V. Ruiz-Villanueva). (b) The wood accumulations in the Vuelta de Zorra stream (Chile) are almost entirely composed of very large wood pieces (photograph: V. Ruiz-Villanueva). (c) Wood raft at the Saint-Jean River in Canada (photograph: H. Piégay). (d) Second-order stream in the Mazák River basin, Beskydy Mountains (Czech Republic), with wood mainly recruited from hillslopes forming log bridges or log ramps (photograph: V. Ruiz-Villanueva).

2.1. Background: Defining Large Wood Volume and Mass

Large wood in rivers can occur in a variety of sizes and forms ranging from very large accumulations and jams to individual logs (Figure 2). By large wood we generally refer to wood pieces that have dimensions of at least 10 cm in diameter and 1 m in length [*Swanson and Lienkaemper*, 1978; *Keller and Tally,* 1979; *Bryant,* 1981; *Marston,* 1982; *Platts et al*., 1987; *Nakamura and Swanson,* 1994; *Wohl et al*., 2010]. However, other definitions have been utilized in order to scale wood size to stream dimensions [*Hassan et al*., 2005; *Seo et al*., 2010]. For example, *Bilby and Ward* [1991] defined large wood as any piece of wood larger than 10 cm in diameter and 2 m long in large streams in the foothills of the Cascade Range and Willapa Hills; *Angradi et al.* [2004] chose 5 m and 0.3 m for length and diameter, respectively, in a large meandering river; and *Comiti et al.* [2006] used 0.3 m for length and 0.05 m for diameter in headwater alpine streams.

Whatever definition is used, measurements of individual pieces of large wood are often converted to volumes, commonly using the equation for a cylinder. This introduces some imprecision in estimating the volume of wood pieces that have a complex morphology [*Wohl et al*., 2010]. To address differences between species, *Bragg et al.* [2000] developed an equation to calculate volume with species-specific coefficients. To simplify calculations and streamline repeat measurements, large wood has also been reported in various size classes [e.g., *Marcus et al*., 2002; *Daniels*, 2006]. Imprecision in calculating large wood volumes is magnified when large wood jams are present because many wood pieces are not visible and the spacing between pieces is difficult to measure [*Livers et al*., 2015]. Therefore, some researchers have applied a wood-air box model to estimate volume [*Piégay and Marston,* 1998; *Thévenet et al*., 1998; *Gurnell et al.,* 2000; *Wyzga and Zawiejska*, 2005; *Wyzga et al*., 2015], whereas others have made a distinction between a large wood accumulations of two to four pieces and jams containing more than four pieces [*Moore et al*., 2002]. In some very large rivers (drainage areas from 30,000 to 500,000 km^2) and deltas, large wood may accumulate in very extensive wood rafts [*Sedell and Froggatt*, 1984; *Triska*, 1984; *Sedell et al*., 1988; *Wohl,* 2011; *Boivin et al*., 2015]. In this case, exact volume estimation is very challenging and is usually approximated using the area occupied by wood [*Boivin et al*., 2015; *Benacchio et al*., 2015].

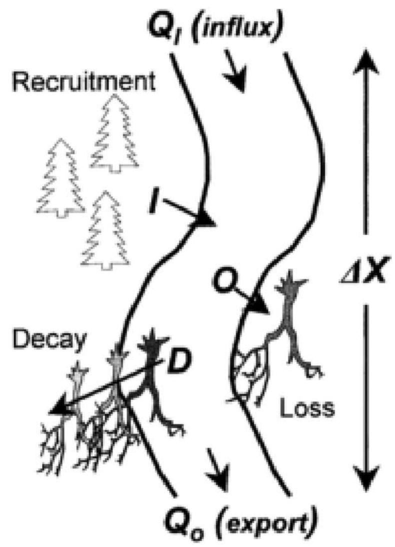

Figure 3. Illustration of variables used in wood budgeting analysis for the Game Creek basin, southeast Alaska [after *Martin and Benda*, 2001]. *I* is lateral wood recruitment; *O* is loss of wood from the active channel caused by overbank deposition during flood events, abandonment of jams, and burial; *D* is in situ decay; and Q_i and Q_o are fluvial transport of wood into and out of a segment of length Δx.

As highlighted by *Hering et al.* [2000], the different sampling procedures and metrics used for wood volume estimation together with the definition of survey area boundaries within which wood properties are recorded (e.g., including/excluding elements located on banks) result in marked differences in wood volume estimates and consequent uncertainties when combining estimates across different studies. Agreement on the measurement and reporting of variables could help to resolve some of these uncertainties [*Barker et al.*, 2002; *Wohl et al.*, 2010].

At the reach scale, recording of wood volume is recommended (e.g., $m^3\,100^{-1}$ m, $m^3\,ha^{-1}$, and pieces · 100^{-1} m) to facilitate comparisons between sites and regions [*Wohl et al.*, 2010]. However, when large wood budgets are being calculated, volumetric mass balance is usually expressed in cubic meters, m^3, of wood per year [*Boivin et al.*, 2015]. When large wood transport is being monitored and wood flux or wood discharge is assessed, the recommended metric is $m^3\,s^{-1}$ or kg s^{-1} [*Turowski et al.*, 2013].

Mass quantification is strongly influenced by wood density and the degree of wood decay, which are critical parameters when evaluating a large wood mass budget. Decay may in some cases be discerned from visual indicators such as the presence/condition/absence of leaves/needles, bark, sapwood, and heartwood (e.g., *Maser et al*. [1979], *Wohl et al*. [2010], and *Harmon et al*. [2011]; see also section 2.4.2). These findings underline the importance of reporting more about wood storage than mere volumes: the geography of the stored wood matters [*Wohl and Cadol,* 2011; *Ryan et al*., 2014; *Jackson and Wohl*, 2015].

2.2. Large Wood Budget and Fluxes

2.2.1. Large Wood Recruitment and Budgeting

A first conceptual framework for large wood budgeting was proposed by *Martin and Benda* [2001] (Figure 3). They considered the volumetric mass balance of large wood within a unit channel length; in small basins (~100 km^2), where channels are narrow compared to tree height or length, large wood mobility is fairly low, and so some large wood budgeting assumptions can be based on the existing in-channel wood. In this context, large wood recruitment comes from processes close to the river such as tree mortality, tree toppling following fires and windstorms, bank erosion, and also large wood delivery to the river from surrounding hillslopes by episodic disturbances such as debris flows, landslides, and snow avalanches [*Bragg*, 2000; *Benda and Sias*, 2003; *Lancaster et al*., 2003; *Miller et al*., 2003; *Reeves et al*., 2003, 2006]. Other processes that were considered to affect the large wood budget included wood decay and wood transport. In some landscapes wildfires may dominate long-term wood supply. *Benda and Sias* [2003] proposed equations to provide theoretical predictions of wood delivery and other characteristics in response to different fire cycles, but they were not able to fully test their modeling because of a lack of field observations to quantify different parameters. More recently, *Benda and Bigelow* [2014] applied the same approach to small streams in northern California (drainage basin area <30 km^2) and showed that differences in large wood storage mainly reflect local difference in bank erosion rates, forest mortality, and mass wasting, which are related to differences in basin physiography, orographic and geological settings, and forest types and management.

A strategy of using the total large wood deposited as a surrogate for large wood output at the watershed scale has been adopted in small Alpine catchments by *Rickenmann* [1997] and *Rimböck* [2003]. This has allowed the

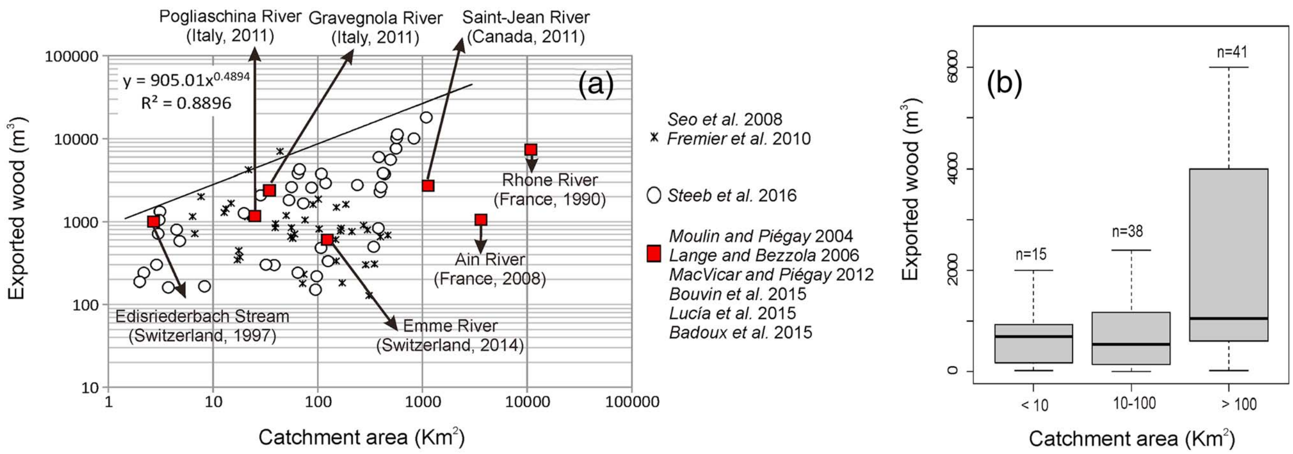

Figure 4. (a) Large wood volume (m^3) exported (wood volume quantified at retention structures and bridges, deposited along streams, and retained in reservoirs and in lakes) from different watersheds during different flood events (only the upper values from sources are plotted in the graph). The black line shows the upper boundary as a power function. Data from *Seo et al.* [2008] and *Fremier et al.* [2010] cannot be related to single flood events because wood volume is quantified annually. (b) Boxplots of exported volume of large wood grouped by catchment area.

development of pioneer empirical equations linking large wood volume to catchment size. These studies distinguished between wood volume that is effectively transported [exported] and large wood potential that could be recruited and transported by exceptional flood events. They estimated the latter from processes that could introduce wood to the streams and the standing wood volumes from areas where such large wood mobilization processes are probable. Distinguishing between these two different concepts is important. The former refers to the volume of large wood that is recruited and then exported from a watershed (here referred to as *exported wood*), whereas the latter refers to the potential volume of wood that could be recruited and subsequently exported during extreme events. The latter could be used as an indicator of the magnitude of wood flux a given basin could produce under specific circumstances. As observed by *Rickenmann* [1997], a relationship exists between the drainage area and the volume of large wood exported during floods, but such empirical formulae (which do not take account of other key processes and parameters) should be used with caution.

More detailed models have been used at regional and catchment scales to identify the potential source areas of large wood, including different recruitment processes, and to compute potential recruitable volumes of wood and transport rates [*Czarnomski et al.*, 2008; *Marcus et al.*, 2011; *Wohl*, 2011; *Eaton et al.*, 2012; *Eaton and Hassan*, 2013]. Recent approaches have employed geographic information systems [*Mazzorana et al.*, 2009; *Rigon et al.*, 2012; *Lucía et al.*, 2014b] and have applied fuzzy-logic principles [*Ruiz-Villanueva et al.*, 2014a] to quantify wood potential volume in a spatially distributed way. However, a reliable prediction of potential wood fluxes still remains to be developed. We reviewed available data concerning large wood exported during floods and the relationship between exported wood volume, flood magnitudes, and drainage basin characteristics (Figure 4). Following the work by *Rickenmann* [1997], we updated his database from the original 34 events to 83, including recent events from France, Italy, and Switzerland [*Lange and Bezzola*, 2006; *MacVicar and Piégay*, 2012; *Badoux et al.*, 2015; *Lucía et al.*, 2015; *Steeb et al.*, 2016; data compiled by *Seo et al.* [2008] from observations of wood volumes exported and stored in reservoirs in Japan, information from the Génissiat reservoir in France [*Moulin and Piégay,* 2004]; and the large raft in the Saint-Jean River in Canada [*Boivin et al.*, 2015]. These last two sources were only used to provide an upper limit or maximum value of wood volume during the highest-magnitude floods observed.

The graph shown in Figure 4a provides an upper limit for large wood delivery following exceptional floods according to catchment size, which is consistent with some of the observations of *Seo et al.* [2008] in Japan, of *Rickenmann* [1997] and *Waldner et al.* [2007] in Swiss basins, and of *Lucía et al.* [2015] in Italy, and thus seems a fairly robust global generalization. Observations conducted on the Rhône and the Ain rivers (France) in Figure 4a represent systems that have produced sizeable amounts of wood in the absence of exceptionally large events (i.e., usually smaller than the 10 year flood). Thus, for the first time, the graph allows case studies to be compared and to assess how exceptional wood delivery is for a given event. Nevertheless,

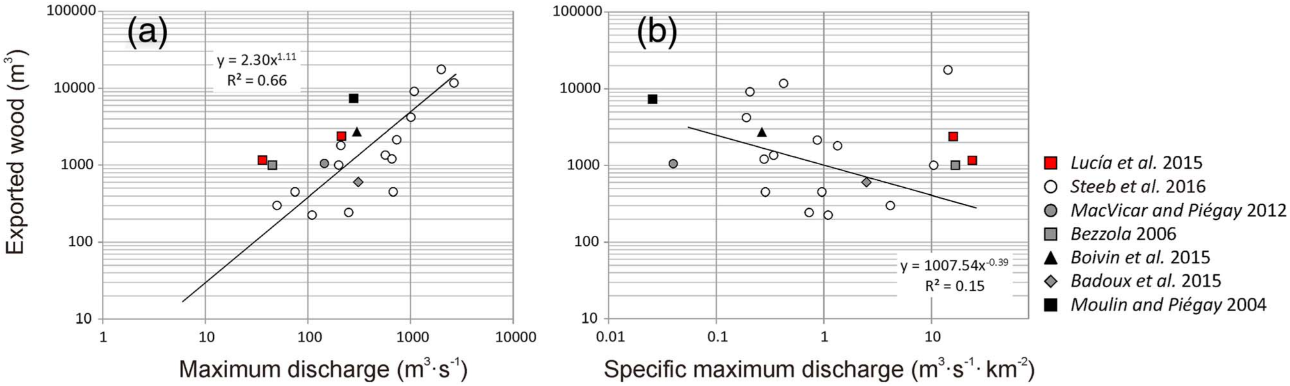

Figure 5. Relationship between large wood volume exported during flood events and (a) the maximum discharge observed and (b) the specific maximum discharge observed.

we still need to better characterize the magnitude of events to be able to distinguish secondary factors such as land use (wood availability) and other key acting processes (i.e., factors promoting delivery). Among these parameters are the magnitude (Figure 5) and frequency of floods; but several others (including riparian forest management, river, and/or antecedent flood characteristics) are all likely to be highly influential. Thus, *Millington and Sear* [2007] noted that the first significant flood after recruitment plays a disproportionately large role in wood dispersal, while subsequent events can be relatively ineffective in removing wood regardless of their magnitude. When the relationship between the exported wood volume and the maximum discharge of the transporting flood event is analyzed, a positive relationship is revealed (Figure 5a). However, because flood frequency (i.e., return period) is not considered (although, in general, all analyzed events were characterized by high intensity, therefore low frequency) the absolute values of discharge cannot be considered a causative indicator (i.e., 1000 $m^3 s^{-1}$ can be a minimum flow on a large river, and no wood would be exported; whereas 100 $m^3 s^{-1}$ could be a very extreme event in a medium to small river, transporting a significant amount of wood). However, the relationship presented in Figure 5a provides information on size effects that seems to be fairly constant (for 10 $m^3 s^{-1}$ we have 100 m^3 of wood; for 1000 $m^3 s^{-1}$ we have 10,000 m^3). When specific discharge ($m^3 s^{-1} km^{-2}$) is related to the exported large wood, the relationship is negative (Figure 5b), indicating that larger watersheds (which in general have lower specific discharge) export larger quantities of wood. This means that for a given event in a smaller catchment, less wood is exported even when more wood could be recruited (in comparison with a larger river) because large wood mobility is generally lower in small rivers and more wood is trapped, although many other factors can influence this process.

2.2.2. Monitoring Wood Flux at the Catchment and Reach Scales

The ability to accurately determine wood fluxes is fundamental to understanding wood transport processes and also is a critical need in river and flood management. Observation windows in which to gather this data can be reservoirs [*Moulin and Piégay,* 2004; *Seo et al*., 2008], delta branches [*Boivin et al*., 2015], natural lakes [*Waldner et al*., 2007], or trapping structures, such as those described by *Lyn et al.* [2003] where wood can be trapped for days, months, years, or decades.

Moulin and Piégay [2004] were the first to use historical data on routine wood removal to link wood output and discharge in the Génissiat reservoir on the Rhône. They identified a critical discharge, the one in 1.5 year flood, above which wood output increased significantly. They also estimated statistical relationships between wood delivery and peak flow that were complex because of the time series characteristics, particularly the timing of a critical flood and the origin of floods, which tapped wood sources and intermediate storage areas of different subcatchments. *Seo et al.* [2008, 2010] analyzed archived series of wood trapping within 131 reservoirs in Japan. They showed changes with catchment size. Intermediate catchments (drainage areas between 100 and 1000 km^2) exported more wood per unit area than smaller ($<$10 km^2) and larger ones ($>$1000 km^2). They hypothesized that these results were related to wood recruitment and to trapping, which can differ according to river size. In intermediate-sized rivers, recruitment is high and similar to small catchments, but trapping efficiency is much lower than in small catchments because rivers have a larger width relative to tree height/length. Even small trees can be trapped in the narrow streams of headwater catchments and may persist for decades within the stream channel and its margins.

A similar analysis by *Boivin et al.* [2015] used adjustments in a 3 km long wood raft at the mouth of the Saint-Jean River to estimate minimum wood delivery from the catchment. They used information from aerial photos, field measurements, and wood volume calculations using the method of *Thévenet et al.* [1998]. The raft volume (≈25,000 m^3 between 1963 and 2013) combined with wood storage in the channel (≈5950 m^3) compared favorably with estimated wood recruitment between 1963 and 2004 (≈27,000 m^3 ± 400 m^3). The analysis was applied at a decadal scale, expressing mass balance in m^3 per year, but also at annual and event scales, allowing for a better link to be established among Q_o, I, and O within the studied reach and confirming that a delay can exist between wood production and export downstream, thereby explaining the complex relationship between peak flow intensity and Q_o. The precise causes of this delay remain unclear but depend on the functioning of wood trapping areas that may need to reach a certain storage threshold before they deliver wood downstream. However, analogies can be drawn with torrents or debris flows where the term susceptibility is usually used as a first step in identifying active systems (the spatial probability of occurrence) without incorporating their particular physical setting [*Bertrand et al.*, 2013].

In some recent research, assessment of Q_o has focused on shorter timescales by considering not only wood output (m^3 per year or per event) but also wood flux or transport rate (m^3 per day, hour, or even second). The approaches developed to attain this improved temporal resolution not only consider how much wood a drainage basin can produce as a whole over a few years, months, or during a single event but also how much a reach can produce by simultaneously considering upstream input Q_i and downstream output Q_o. *Moulin and Piégay* [2004] evaluated the feasibility of continuously monitoring wood raft evolution within the reservoir of Génissiat on the Rhône using ground photography. This has now been automated [*Benacchio et al.*, 2015], allowing hourly wood flux to be estimated from 12 min observations of wood raft area and an empirical relationship between raft area and extracted wood volume. *Lyn et al.* [2003] were the first to use ground cameras to study wood delivery to a given point. They monitored a bridge that was sensitive to wood trapping in order to assess deflector efficiency. Unfortunately, they did not quantify wood flux but rather used the photographs qualitatively to confirm that wood transport was intermittent with short periods of active wood delivery occurring mainly on the rising limb of flow events.

While all of the previously described methods depend on the presence of a fixed trapping structure, *MacVicar and Piégay* [2012] evaluated the potential of using a streamside video camera to detect large wood passage and measure quasi-instantaneous rates of large wood transport. Based on visual detection of wood pieces during three floods on the Ain River, France, they determined the critical discharge for wood transport as approximately two thirds of the bankfull discharge and concluded that transport rates were approximately four times higher on the rising limb of the hydrograph than on the falling limb. They also defined a step-by-step protocol to study the large wood transport rate from video, including tests of detection frequency, wood velocity, and piece size, which all depend on orthorectification of the images and flow stage. Subsequently, processing of the video data was automated so that transport rates could be estimated in real time [*MacVicar et al.*, 2012]. Comparison of the number of automatically detected wood pieces with those that were visually detected revealed an ~90% agreement between the two methods. Errors accrued in relation to detection of wood piece size (as only a part of a wood piece is usually visible) and discontinuity in the series due to the absence of records at night. Similarly, *Kramer and Wohl* [2014] monitored large wood transport with time-lapse photography (1 to 15 min) on the Slave, a large subarctic river with very low surface velocity. They also identified a critical discharge for large wood transport (~4500 m^3 s^{-1}) and observed more wood being transported on the flood rising limb than falling limb. In a different approach, *Turowski et al.* [2013] estimated wood flux from direct field measurements using wood traps and basket samplers, permitting investigation of a wide range of wood piece sizes and coarse particulate organic matter transported from a small catchment, the Erlenbach (0.7 km^2) in Switzerland. From repeated surveys, they established a rating curve of the form

$$Q_{wood} = aQ^b \tag{1}$$

where $a = 4.42 \times 10^{-15}$, $b = 4.47 \pm 0.21$, $R^2 = 0.94$ (Q_{wood} in kg s^{-1} and Q in l s^{-1}). The authors also showed that a single scaling exponent (1.8) can describe the mass distribution of coarse particulate organic matter heavier than 0.1 g. This scaling was also observed on the Ain River data [*MacVicar and Piégay,* 2012].

Numerical modeling provides another approach to investigating wood flux under unsteady flow conditions. *Ruiz-Villanueva et al.* [2016a] analyzed the influence of the hydrograph (in terms of peak discharge, time to peak, and total flood duration) on the transport of previously deposited wood in the Czarny Dunajec River (Poland). Model results revealed a lag between the beginning of a flood and large wood remobilization, where the lag is related to the flood responsible for the initial wood deposition. Furthermore, the peak in large wood transport is generally reached before the flood peak, and wood transport decreases close to or slightly after the hydrograph peak. During the falling limb of the hydrograph, large wood transport is usually negligible unless an additional supply of wood is provided to the river, as the available wood has already been subject to the same or larger discharges during the rising limb. As a consequence, hysteresis is seen in the relationship between discharge and large wood transport, which has also been observed in the field using video monitoring of the Ain River [*MacVicar and Piégay,* 2012].

2.3. Large Wood Storage and Deposition

2.3.1. Surveys of Large Wood Stored in Rivers

To quantify wood storage (i.e., wood deposited in a river reach), a wide variety of surveying and computing methods have been used. Information gathered from either field surveys or aerial imagery is often used to determine the amount of large wood stored within a reach [*Lassettre et al*., 2007]. Field surveys have employed the line-intersect method [*Wallace and Benke,* 1984], have focused on transects [*Baillie et al*., 2008], or have inventoried all wood pieces in a study reach [*Máčka et al*., 2011]. Aerial imagery helps to overcome the sampling problem inherent in field studies, which are usually confined to a set of reaches of the studied river. However, high-resolution images (i.e., image resolution of at least 10 cm) are required to accurately measure large wood pieces. *Pecorari et al.* [2007] and *Comiti et al.* [2008] suggested that the resolution of the image should be at least twice the minimum log diameter if they are to be measured with low error (<15%). In addition to air photographs, a considerable amount of fluvial research and development has been performed on images captured by airborne and spaceborne, multispectral and hyperspectral imaging systems [*Marcus and Fonstad,* 2008; *MacVicar et al*., 2009; *Carbonneau and Piégay,* 2012]. One crucial aspect is the spatial resolution of such data sets [*Greenberg et al*., 2009; *Rango et al*., 2006]. The platforms from which the data sets are captured (e.g., ground-tethered devices, conventional planes and helicopters, or unmanaged aerial and ultralight vehicles) influence the spatial resolution achieved [*Carbonneau et al*., 2012] with the choice of platform constrained by costs, flying ability, flying regulations, and limitations regarding battery autonomy.

High-resolution, multispectral imagery in four or more bands combined with good geometric correction, image mosaicking, and the application of appropriate automatic classification techniques offer a viable tool for stream mapping and detection of individual logs and log jams [*Leckie et al*., 2005].

High spatial resolution hyperspectral (HSRH) imagery is capable of acquiring detailed information of the distribution of stored wood over an entire stream's length, but the spatial resolution (typically >1 to 5 m) is usually insufficient to map accurately smaller deposits of large wood. However, objects with a clear spectral signal, such as wood, can be distinguished even when they make up only a fraction of a pixel [*Marcus et al*., 2003; *Smikrud and Prakash*, 2006].

New platforms such as kites, microlights, and drones are becoming widely used in fluvial environments [*Lejot et al*., 2007]. They are very promising tools that could provide very high resolution images to allow detailed wood censuses along channels that capture spatial and temporal changes in wood storage [*Haschenburger and Rice*, 2004; *Ali and Tougne,* 2009; *MacVicar et al*., 2009; *Bertoldi et al*., 2013; *Ulloa et al*., 2015].

Airborne light detection and ranging (LIDAR) and terrestrial laser scanning (TLS) also have been recently evaluated to analyze large wood characteristics [*Fleece*, 2002; *Kasprak et al*., 2012; *Tonon et al*., 2014]. The TLS appears to be a reliable tool for providing additional data on wood characteristics, such as orientation with respect to the flow direction, shape, and as also shown by *Boivin and Buffin-Bélanger* [2010], wood accumulation porosity. For larger wood pieces, TLS has proved capable of discriminating between coniferous and deciduous wood based on the foliage of woody elements [*Tonon et al*., 2014]. Analysis that is lidar-based has been found to provide a comprehensive solution for detecting log jams in lowland rivers where vegetation cover is not obscuring the deposits [*Abalharth et al*., 2015].

2.3.2. How Much Large Wood Is Retained in Rivers?

The above mentioned measurement approaches have been employed in many studies, generating a large body of published information on wood storage in rivers. We compiled and analyzed such data from the scientific literature, updating the databases compiled by *Gurnell* [2003, 2013] from 314 to 390 sites, for which

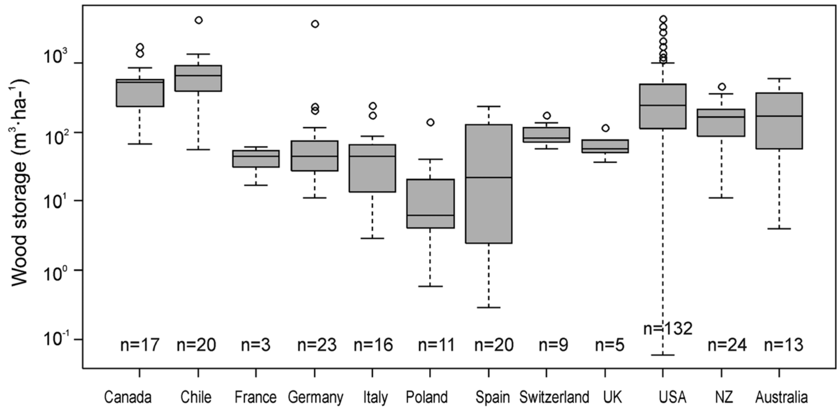

Figure 6. Boxplot of log-transformed specific large wood volume storage ($m^3\ ha^{-1}$) estimated during wood inventories and grouped according to geographical region (country). "*n*" shows the number of river reaches or sites. UK: United Kingdom; USA: United States of America; and NZ: New Zealand.

the amount of channel-stored wood (specific wood storage expressed as mass of wood per hectare of channel area; $m^3\ ha^{-1}$) is either quoted or estimated from other published data or graphs. For most sites it was also possible to quantify drainage area, channel width, channel slope, and information concerning the nature of the riparian woodland.

Figure 6 shows that river systems in Canada and Chile, as well as in the U.S. and New Zealand, have significantly more wood than European river systems, which is potentially related to their naturalness. Variability in European systems is fairly high and may be linked to various factors, such as the time of observation or the degree of naturalness and maintenance pressure [*Evans et al*., 1993]. Even where riparian woodland is present, European floodplain vegetation has been managed for many centuries, unlike many riparian zones in Canada, Chile, the U.S., and New Zealand. For example, active floodplains along lowland alluvial rivers in France have been used for grazing and (when human pressure has been high) for arable agriculture, with alluvial forest showing only slight recovery since the end of the Second World War [*Marston et al*., 1995; *Liébault and Piégay,* 2001]. If we can assume large wood stored in the channel is a good minimum estimate of what is produced (i.e., only a small part is exported), then it is possible to compare reaches to identify the most wood productive ones. This does not address questions concerning the amount of large wood produced by individual events nor how representative a synoptic measurement of wood storage is in a temporal context.

Many studies from diverse geographical settings have demonstrated that in-stream storage of large wood varies with position in the watershed (i.e., expressed by measuring drainage area upstream of the point of measurement), bankfull channel width, channel slope, and the type of trees (Figure 7).

Specific wood storage (per unit channel area) decreases with drainage area because larger streams have a greater capacity to transport large wood [*Piégay et al*., 1999; *Martin and Benda*, 2001; *Marcus et al*., 2002; *Wohl and Jaeger*, 2009]. For the same reason, large wood storage also decreases as channel width increases and channel slope decreases because channel width normally increases and slope decreases in the downstream direction. When channel width is greater than the typical length of the large wood, the trapping capacity of the channel decreases and pieces are more likely to be transported downstream. In mountainous headwater streams, channels are narrow and confined by hillslopes. As a result, large wood pieces are commonly longer than bankfull channel width in headwater streams, exhibit a random spatial distribution, tend to fall and thus be oriented perpendicularly to the axis of water flow, and often remain suspended above the channel banks [*Bilby and Ward*, 1989]. In these environments large wood usually functions as a dam or log steps once it enters the channel. *Marston* [1982] found that the frequency of log steps increased as channel width increased, until streams became so wide that wood pieces could not be trapped or anchored readily in the banks but instead were floated downstream. In these larger river systems, wood pieces are too small to span the river channel, and so they can only be retained in locations where they become snagged by particular morphological features or marginal vegetation or where they become stranded during the recession of flood flows. *Piégay et al.* [1998] showed that on the Drôme River (1600 km^2), in-channel wood storage along

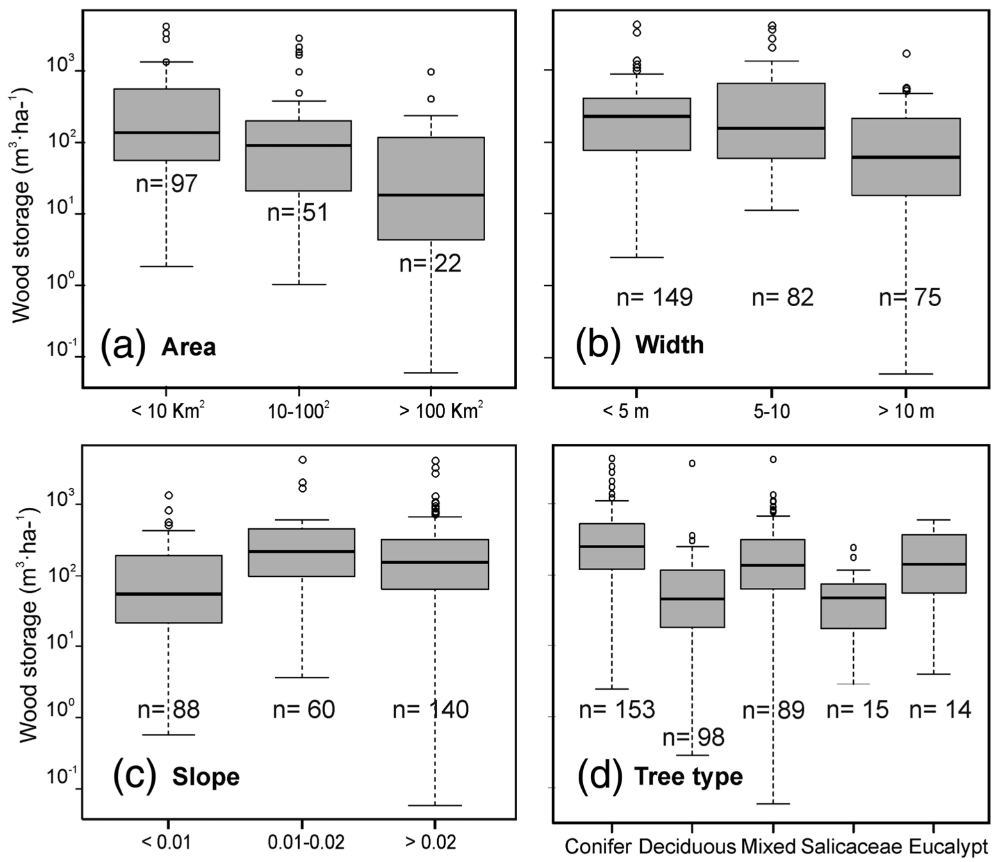

Figure 7. Boxplot of log-transformed specific large wood storage (m3 ha^{-1}) in river channels grouped according to (a) drainage area (km^2), (b) channel width (m), (c) channel slope (m·m^{-1}), and (d) the type of trees bordering the channel.

the main stem is only 1.3–3.7 times the annual wood input delivered from the floodplain by bank erosion. The storage capacity of reaches is also strongly linked to the presence of trapping structures, notably bars. On large rivers, wood recruitment from bank retreat has been well studied by combining estimates of eroded areas from sequences of air photographs with field surveys of sampling plots close to the eroded area and with similar radiometric and textural values on the aerial photos to provide measures of stem density and standing wood volumes [*Piégay et al.*, 1998; *Boivin et al.*, 2015]. Using such data sources, *Boivin et al.* [2015] showed that on the heavily forested Saint-Jean River, Gaspesia (Canada), in-channel wood storage can reach nine times the annual delivery from bank erosion. However, in single-thread wide river channels lacking significant reaches where wood can be deposited (e.g., wider sections with large bars), wood storage is likely to be much lower than the effective recruitment. Using similar methods, researchers have also shown that wood stored in the channel is usually delivered at the end of the last flood event and can be a small part of the quantity introduced into the channel during the flood event. A diffusion effect has also been observed with the amount of stored wood decreasing with distance from the bank erosion source [*Lassettre et al.*, 2007; *Welber et al.*, 2013].

Wyżga and Zawiejska [2010] showed that large wood deposits were more abundant in multithread reaches than in channelized single-thread reaches of the same river. Comparable observations have been reported by other researchers in similar fluvial environments. For example, wood storage was observed to vary significantly between reaches of different geomorphic configurations (island braided and bar braided) along the Tagliamento River in Italy [*van der Nat et al.*, 2003], whereas in the Piave River, Italy, *Pecorari et al.* [2007] reported higher storage in braided than wandering reaches. Contrasting patterns of wood storage have been observed in mountain watercourses of low to medium width in comparison with those of large width. In the former, similar lateral inputs of large wood to stream segments of different width and a lack of long-distance transport of wood result in similar total wood storage but a decrease in specific wood storage as channel width increases. In the latter, preferential retention of large wood in wider river reaches leads to an increase in total and specific wood storage with increasing river width [*Wyzga et al*., 2015]. This propensity for large wood to be preferentially retained in the widest sections of mountain rivers can be used as a natural buffer attenuating transfer to intensively managed valley reaches [*Wyżga and Zawiejska*, 2010; *Wohl et al*., 2016].

Storage of large wood is also related to catchment and riparian tree management [*Piégay and Gurnell*, 1997]. Streamside logging and timber harvest throughout a watershed tends to increase wood loading in streams, unless fallen trees are removed from the channels [*Gomi et al*., 2001]. Historic tie drives reduce wood storage overall and leave persistent changes in channel morphology that affect wood storage for many decades thereafter [*Young et al*., 1994; *Ruffing et al*., 2015]. Large wood storage tends to be higher in streams draining old-growth forest than in young forests [*Jackson and Wohl*, 2015], although exceptions have been reported [*Benda et al*., 2002]. *Bilby and Ward* [1991] and *McHenry et al.* [1998] examined the size distribution of large wood in streams traversing old-growth forests and second-growth forests. They found that following removal of old-growth riparian forests, the loss of old-growth large wood is very rapid initially. Inputs of large wood from second-growth forests up to 73 years old were of smaller diameter, higher mobility and high decay rates than those observed in old-growth settings. Furthermore, large wood is, in general, missing from channelized rivers because of the absence of retentive sites [*Angradi et al*., 2004] and the low wood storage found in many rivers are frequently a consequence of a long history of clearance activities [*Hering et al*., 2000; *Comiti et al*., 2012; *Wohl*, 2014].

Quantitative information on the volume of wood required to maintain adequate habitat is generally lacking in the literature, as well as the role of episodic disturbances in supplying wood to rivers [*Miller et al*., 2002; *Benda et al*., 2003; *King et al*., 2013], despite the fact that the typical distribution of wood storage in relatively undisturbed rivers and streams might be used as the upper limit of what is ecologically useful. The range of values shown in Figures 6 and 7 is quite large, and it is a challenge for ecological research to define the lower limit of the volume of wood required to maintain ecological functioning in various environments. Similarly, for regulated rivers, it is important to define the upper limit of wood volume that can remain or be placed in the channel without compromising the hydraulic efficiency required for conveying flows or for mitigating flood risk [*Kail et al*., 2007].

2.3.3. Preferential Sites of Large Wood Deposits

Since the earliest large wood research, a plethora of studies has analyzed the spatial distribution of large wood describing the variability of its deposition along river systems in a wide range of environments [*Gurnell et al*., 2002; *Abbe and Montgomery*, 2003; *Montgomery et al*., 2003; *Swanson*, 2003; *Bigelow et al*., 2007]. These studies have shown that in steep streams (i.e., channel gradients between 0.06 and 0.20), most large wood deposits comprise pieces anchored on irregularities of the channel boundaries (i.e., bedrock outcrops and boulders) or on trees growing along channel margins [*Abbe and Montgomery*, 2003]. Large wood can occupy a large part of the channel (up to 80% according to *Keller and Swanson*, [1979]. The main large wood features in these low-order channels are channel-spanning log steps (Figure 8) [*Abbe and Montgomery*, 2003], significantly contributing to step-pool long profiles of steep, narrow channels [*Curran and Wohl*, 2003].

In larger and multithread rivers, large wood is preferentially retained on the top of gravel bars, often forming bar apex jams as defined by *Abbe and Montgomery* [2003]. Island-braided reaches may store considerably more large wood than bar-braided reaches due to greater contact between the active channel and forested islands [*Gurnell et al*., 2002]. In contrast, along large single-thread to wandering alluvial rivers, large wood is mainly stored along the outer margins of channels, on concave banks and point bars of meandering rivers, and also along the edges of islands and secondary channels in wandering rivers [*Gurnell et al*., 2002; *Abbe and Montgomery*, 2003; *Gurnell*, 2013].

2.4. Assessing the Residence Time of Large Wood

The residence time of wood refers to the average amount of time that a piece of large wood spends in a river system. It begins from the moment that a standing tree enters the river system from bank erosion, landslides, logging, storms, and mortality and ends when the same piece of large wood leaves the river system. Residence time has been calculated as the difference between the year of a specific survey and the year of mortality often based on an empirically derived cumulative distribution of large wood ages [*MacVicar et al*., 2009]. This approach requires an aggregate, steady state view that assumes that over several decades, and over an entire watershed or reach, wood is recruited to the channel at approximately the same rate that it

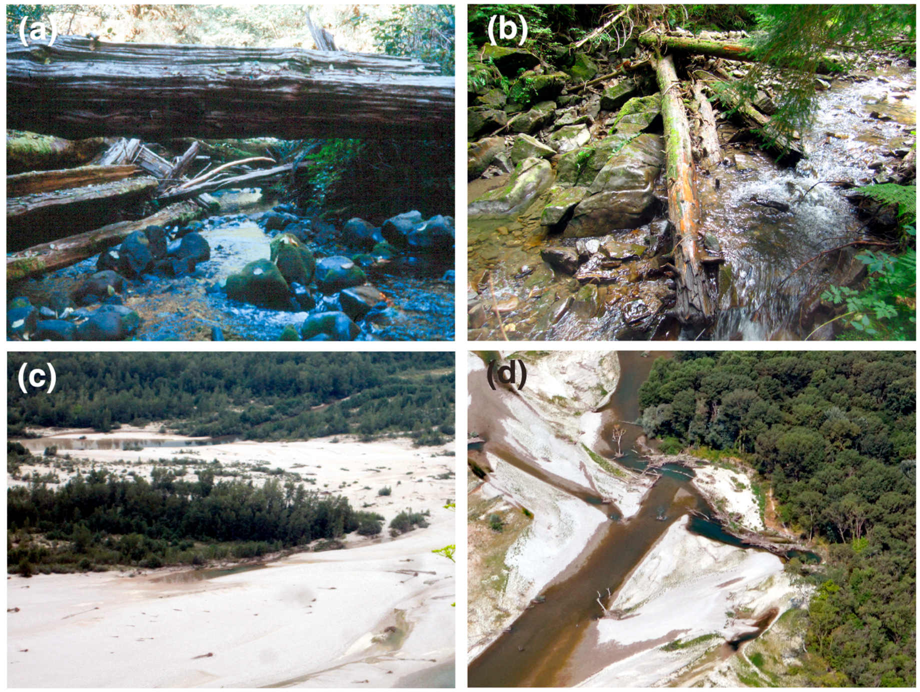

Figure 8. (a) Bridge log, ramped log (at left), and log step (in background) in Cape Creek, Lane County, Oregon Coast Range (photograph: R. Marston); (b) log step in the Kamienica stream, Poland (photograph: V. Ruiz-Villanueva); (c) isolated logs deposited on top of bars and wood jams accumulated along island margins of the Tagliamento River, Italy (photograph: V. Ruiz-Villanueva); (d) logs deposited along the outer margins of channels along the Drôme River, France (photograph: H. Piégay).

is depleted. In general terms, we can assume that the larger the system, the larger the residence time, will be provided that inflow and outflow rates are held constant. However, under natural conditions, *Hyatt and Naiman* [2001] argued that residence time cannot easily be determined until a wood piece disappears from the channel, a point that is not practically measurable. As a consequence, they used the term depletion rate instead, which refers to the removal of large wood from a channel through decay, transport, and burial. In contrast to residence time, the term depletion also takes account of the various factors affecting wood and sees depletion in a stream as a product of the interaction between downstream transport, burial, and decay of large wood [*Gurnell et al*., 2002].

2.4.1. Quantifying Time From Death and Depletion Rate

The amount of time that a piece of large wood has spent in a stream can be assessed using dating approaches (e.g., dendrochronological techniques or radiocarbon dating) or with semiquantitative yet more descriptive approaches (e.g., wood decay, wood density, and resistance). Dendrochronology has been used in a series of studies [e.g., *Hyatt and Naiman*, 2001; *Jones and Daniels*, 2008; *Jochner et al*., 2015], mostly in temperate climates in which trees form annual rings. Analyses were primarily based on ring-width series, preferably from conifer wood, with their growth patterns matched against reference chronologies from riparian trees of the same species. This approach allows determination of the year of formation of the last ring in a wood core [*Fritts*, 1976; *Cook and Kairiukstis*, 1990] but also provides information about tree age before it entered the stream system. *Hyatt and Naiman* [2001], for instance, analyzed the size and species composition of large wood in the Queets River (U.S.) and compared it with the size and species composition of forest trees, allowing them to determine a depletion rate for large wood in the active channel.

In cases where large wood pieces are decayed and so are unable to provide cores for dating or are simply much older than the locally available reference chronologies, sample dating can be attempted with radiocarbon (^{14}C) techniques. Radiocarbon dating will provide reasonable estimates (yet usually less precise than dendrochronology [*Stoffel et al*., 2010]) for the time since death, which can then be used to assess the mean residence time of in-channel wood. However, while the approach is certainly very valuable for older wood pieces, analyses of modern samples may contain ambiguities especially in regions that have been subjected to elevated ^{14}C concentrations from atmospheric nuclear tests [*Hyatt and Naiman*, 2001]. *MacVicar et al.* [2009] were able to avoid this ambiguity by correlating existing annual measurements of ^{14}C in wood and other vegetation against the ^{14}C data obtained from tree rings in wood samples, such that an estimate for the year of mortality could be given with a resolution of ±2 years.

The residence time of large wood is governed by a series of variables with climate representing a first-order control [*Wohl*, 2013]. In addition, differences in tree species composition (in terms of chemical content), wood piece size (i.e., diameter and length), wood position (suspended, ground, buried, and fully submerged), site conditions (temperature, moisture levels, oxygen, and carbon dioxide levels), channel bed stability, channel morphology, flood intensity, and riparian forest composition will further influence the residence time of large wood [e.g., *Harmon et al*., 1986; *Naiman et al*., 2002; *Scherer*, 2004; *Wohl*, 2013]. Large wood from mature stands persists longer than large wood from younger stands where the wood is typically shorter, smaller in diameter, more easily broken, and less easily anchored [*Maser et al*., 1988].

In general terms, turnover times in tropical forests would be typically in the order of <10 years for fallen wood [*Lang and Knight*, 1979; *Clark et al*., 2002], whereas wood has been described to persist for centuries in temperate and boreal environments [*Knowles and Grant*, 1983; *Veblen*, 1986; *Hofgaard*, 1993; *Krankina and Harmon*, 1995].

2.4.2. Wood Decay as a Proxy for Residence Time

Decomposition rate (or decay coefficient) and subsequent breakdown of large wood is yet another critical factor as it chiefly determines how pieces decrease in size and thus increase in mobility [*Gurnell*, 2003; *Sear et al*., 2010; *Wohl et al*., 2012]. The decomposition rate involves a series of biological and physical processes [*Harmon et al*., 1986] including fragmentation or breakage, leaching, collapse and settling, seasoning, transport, respiration, and biological transformation.

Decomposition of wood is most often expressed as a negative exponential decay rate function of

$$M_f = M_i \cdot e^{[-kt]} \tag{2}$$

where M_i is the initial mass, density, or volume of wood; M_f is the quantity of material left at time t (in years); and k represents the decay rate constant. Although numerous studies have calculated wood decomposition rates in terrestrial ecosystems, only a few have documented decomposition rates in stream environments [*Golladay and Webster*, 1988; *Murphy and Koski*, 1989; *Hyatt and Naiman,* 2001; *Bilby*, 2003]. The decomposition of cubes, sticks, and twigs of wood have revealed a wide array of decomposition rates among tree and shrub species [e.g., *Díez et al*., 2002; *Janisch et al*., 2005], with notable differences also occurring when wood from different parts of a plant and pieces of different size or diameter are compared [*Janisch et al*., 2005]. These studies have shown that decay coefficients in streams range from ~0.01 to 1.20 per year, but variations are highly dependent on wood species, wood chemistry, piece size, and stream environment [*Scherer,* 2004]. The estimated decomposition rate of old-growth conifer wood in temperate climates has been reported to be in the order of 1% per year, but differences exist between species [*Grette*, 1985]. For North American coastal stream ecosystems, *Benda and Sias* [2003] confirmed these values, obtaining rates of decomposition 1 to 3% per year but again with clear differences between species [*Naiman et al*., 2002]. The lignin content in conifers may be responsible for slower decay, in addition to leachates from debris that have been described to impede microbial decay as well [*Melillo et al*., 1982]. For the Ain River (France), *MacVicar et al.* [2009] inferred that 20–30 years of in-channel storage in exposed conditions would be sufficient to decompose logs from a deciduous softwood species, *Populus nigra*, to the point that they would breakup into smaller pieces during transport.

The relative importance of different depletion processes for in-stream wood is also poorly understood [*Hassan et al*., 2005]. According to *Harmon et al.* [1986], tree species directly influences decay and breakage because it governs the resistance of wood to biochemical decay processes and mechanical breakage. Nevertheless, river organisms, especially bacteria, living within the channel or on the floodplain, critically influence decay and breakage of wood by colonizing and biogeochemically altering, ingesting, or breaking apart wood [*Harmon et al*., 1986; *Bilby*, 2003; *Le Lay et al*., 2013].

Environmental factors also have an important impact on decay rates, including the degree and duration of submersion [*Braccia and Batzer,* 2008; *Collier,* 2014] and water quality [*Gulis et al*., 2008; *Arroita et al*., 2012]. *Bilby et al.* [1999] and *Wohl* [2013] stated that wetting and drying of wood can accelerate decay and that

Table 1. Definition of the Decomposition Classes for the Wood Samples, From 0 (Most Decayed) to 7 (Almost Intact) (Adapted From *MacVicar et al.* [2009])

Class	Conditions of the Center	Conditions of the External Surface	Bark Cover (%)	Description
0	Uniformly rotten	Highly degraded, soft	0	
1	Largely rotten	Moderately degraded	0	
2	Largely solid but rotten core, patchy	Moderately degraded	0	
3	Solid but signs of mass loss	Moderately degraded	0	
4	Intact	Slightly degraded, firm	0	No root wad, upper broken bole
5	Intact	Bark loose	(<20%)	Major roots remaining
6	Intact	Bark intact	(20–60%)	Bark intact, limbs and twigs absent; medium roots intact
7	Intact	Bark intact	(60–100%)	Bark intact, limbs and twigs present; dirt or previous vegetation intact

submersion of dense logs within a channel can retard decay. Differences in decomposition rates are also influenced by wood piece size. *Harmon et al.* [1986] demonstrated that biological breakdown of pieces is most active on the surface of large wood, meaning that larger pieces have a lower surface area to volume ratio than small pieces, and so microbial decomposition occurs more slowly [*Bisson et al*., 1987; *Spänhoff and Meyer*, 2004]. At the same time, size also affects the stability of large wood in the stream channel, such that larger resident pieces would experience less physical abrasion [*Naiman et al*., 2002]. In addition, *Wohl* [2013] stated that the degree to which wood is embedded in the streambed is particularly important because even partial burial can greatly enhance wood stability [*Abbe and Brooks,* 2011]. Due to anaerobic conditions, degradation of wood in aquatic ecosystems can be much slower than in terrestrial ecosystems [*Keller and Swanson,* 1979]. However, where aerobic conditions affect aquatic environments, as in intermittent streams, a faster decay rate may be experienced as has been observed in Mediterranean regions [*Vaz et al*., 2013].

Decay of wood can be assessed visually according to the physical condition of the center and surface of large wood pieces or by measuring wood resistance to penetration. Resistance to penetration can be measured using a simple knife penetration test [*Rickli and Bucher,* 2006; *Hottola and Siitonen*, 2008; *Rickli,* 2009] or by employing a rod with a calibrated cone tip driven into the wood to measure impact velocity and penetration depth [*MacVicar et al*., 2009]. Wood density may be a proxy for structural integrity of large wood, and the mass or density loss is often used to quantify decay [*Merten et al*., 2013]. Indeed, penetration measures can be related to density [*Mäkipää and Linkosalo*, 2011] and density to residence time.

Visual decay (see Table 1) has been correlated with wood density [*Eaton and Sanchez*, 2009; *MacVicar et al*., 2009] and appears to have the potential to be used as a fast, inexpensive method for assessing residence time in the field, although *Hyatt and Naiman* [2001] concluded that decay class is not necessarily a particularly good indicator of wood age. They demonstrated that large wood in decay classes 1 and 2 (Table 1) had been dead <10 years and that almost all wood in decay class 7 had been dead >30 years, but age variation and overlap in the intermediate decay classes (3–6) was so high that these classes were virtually meaningless. The oldest wood sampled, including two pieces >1300 years old, were remarkably undecayed and capable of producing a relatively solid increment core. By contrast, many of the younger wood pieces had residence times of <10 years and were grouped in decay classes 3–6. Often these younger, decayed pieces were lodged in wet or shady areas where the surface wood appeared to decay relatively rapidly, again pointing to the influence of location of deposition on wood quality. As a result of these limitations, *MacVicar et al.* [2009] and other authors have recently suggested replacing the classes in Table 1 with only three classes: rotten, decaying, almost intact [*Maser et al*., 1979; *Grette*, 1985; *Andreoli et al*., 2007; *MacVicar et al*., 2009].

We compiled information concerning wood residence time in rivers and analyzed the data with respect to the type of vegetation and the region (Figure 9).

Figure 9a provides a synthetic overview on the mean residence time of large wood in river systems, showing that coniferous wood tends to stay longer in a stream than hardwood, deciduous species, indicating increased mobility in the latter, as conifers are usually abundant in headwater streams with low transport capacity. In Figure 9b, mean residence times are shown by region and exhibit substantial differences. For example, in the Queets River, *Hyatt and Naiman* [2001] reported large wood depletion curves with a half-life of large wood ~20 years, and thus, nearly all wood now in residence will be exported, buried, or broken down within three to five decades. *Lienkaemper and Swanson* [1987] similarly found mean residence times of

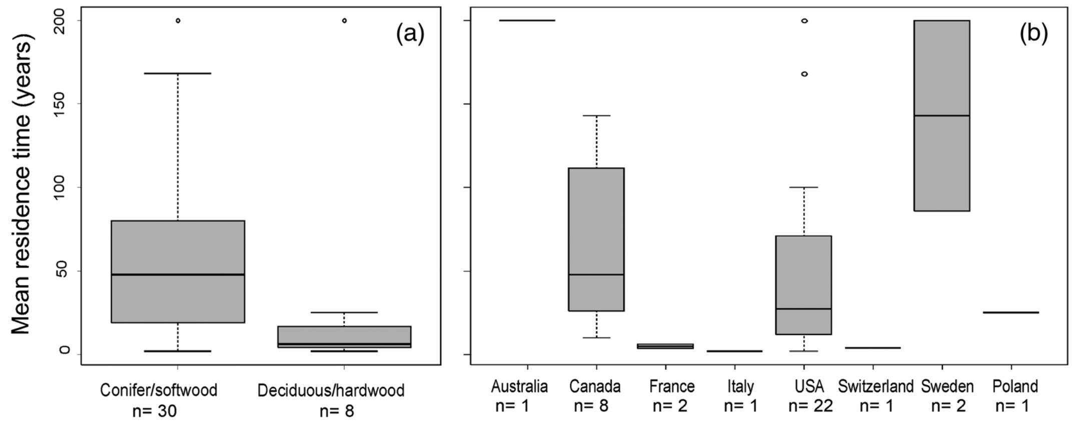

Figure 9. Boxplot of mean residence time (in years) of wood grouped by (a) tree type and (b) region.

12–83 years. In contrast, a study performed in Sweden by *Dahlström et al*. [2005] demonstrated that the oldest piece of pine wood originated from the late 1600s, while the oldest spruce pieces were just over 100 years old. At the same time, the authors also point to the limited data on deciduous trees, which possibly indicates rapid decomposition. Based on a sample of multiple radiocarbon dates from eight trees, *Webb and Erskine* [2003] reported a maximum residence time since 240 ± 40 years B.P. for water gum (*Tristaniopsis laurina*) timber in a study site in southeastern Australia. Large wood in tropical streams has the potential to be more mobile than its equivalent in temperate streams because of warm and humid conditions promoting decay [*Zabel and Morrell,* 1992] and more frequent and flashier floods [*Cadol et al*., 2009].

Several studies have also shown that some large wood can remain buried or jammed in the river floodplain where it can persist for hundreds of years [*Swanston and Swanson*, 1976; *Swanson et al*., 1984; *Swanson and Lienkaemper*, 1978; *Murphy and Koski*, 1989; *Becker et al*., 1991; *Hyatt and Naiman*, 2001; *Davies and Gibling*, 2011], and then it can be exhumed and reintroduced to the active channel [*Naiman et al*., 2002]. Wood buried in alluvium may have extraordinarily long residence times, facilitated by preservation from aerobic decomposition [*Bilby et al*., 1999] and shelter from transport processes. On the Queets River floodplain in Washington, buried large wood may persist for 3000 years [*Abbe and Montgomery*, 1996]. In-stream wood in Tasmania was dated at 2,000 years old, and buried floodplain large wood was over 17,000 years old [*Nanson et al*., 1995]. In western Europe, *Becker and Kromer* [1986] dated buried wood in the Rhine and Danube Rivers at >10,000 years, whereas *Guyette et al.* [2008] showed that large wood in alluvial sediments in streams of Missouri, USA, dated to 14,000 years ago.

3. Advances in Quantifying Large Wood Entrainment and Transport Mechanics

The previous section reviewed approaches used and knowledge gained regarding wood budgeting in space and time and in mass or volume per unit time considering its input, storage, and output. This section focuses on large wood entrainment and transport mechanics and the complex relationships with flow and morphodynamics with an explicit physics-based understanding. This second perspective on wood dynamics is illustrated in Figure 10 [from *Martin and Benda*, 2001, Figure 1b] and should be compared with Figure 3 [from *Martin and Benda*, 2001, Figure 1a], which illustrates the large wood budget and flux perspective on wood dynamics that was reviewed in section 2. The following subsections review advances in quantifying wood motion (section 3.1), general principles of large wood entrainment (section 3.2), and how measurements and modeling can be combined to integrate our understanding of how large wood moves in river systems (section 3.3). This section also describes some of the potential large-wood-related hazards and large wood stability assessment (section 3.4).

3.1. Field-Based Observations of Large Wood Entrainment and Transport Mechanisms

Direct observations of wood movements are rare, but tracing of large wood movement is even less common. Tracing or tagging wood is the most accurate approach to analyzing large wood kinematics when transport distances are fairly short [*Comiti et al*., 2006, 2008; *Warren and Kraft*, 2008; *Wohl and Goode*,

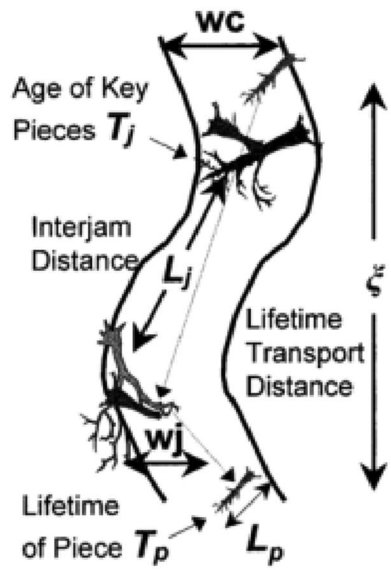

Figure 10. Illustrations of variables used to study large wood entrainment and transport in the Game Creek basin, southeast Alaska [after *Martin and Benda,* 2001]. L_p is piece length; w_c is channel width; w_j is the width (normal to the channel axis) of the in-channel portion of the jam; ε is transport distance over the lifetime; L_j is the distance between jams; T_p is the lifetime of wood in fluvial environments (individual pieces or aggregated); and T_j is jam longevity.

2008; *Iroumé et al*., 2010; *Lassettre and Kondolf*, 2012; *Ravazzolo et al*., 2013]. Tagging is usually achieved with paint or by inserting metal plates that can be located with a metal detector [*Moulin*, 2005; *Warren and Kraft,* 2008; *Wohl and Goode*, 2008; *Iroumé et al*., 2010]. Recently, large wood has also been tracked with transponders, active and passive RFID radio transmitters [*MacVicar et al*., 2009; *Schenk et al*., 2014], and GPS [*Ravazzolo et al*., 2015b]. *Schenk et al.* [2014] used both active RFID and metal tags installed on wood pieces to track their movements along the lower Roanoke River, North Carolina, during floods. They monitored large wood movements during the flood rising limb, estimating a mean traveled distance of 13.3 km and a maximum distance of 72 km within a week.

Passive RFID transponders and radio transmitters are reliable for large wood tracking. Radio transmitters are suited to multiyear (~5 year) surveys and can be detected at a distance of 800 m, whereas passive RFID are limited by a read range of 0.30 m but are suitable for longer-term studies. Active RFID combine a moderate read range (with an antenna) and low cost with the ability to monitor large wood transport during floods. Active GPS is still costly but provides the only method to track the entire large wood movement trajectory, recording periods of rest and movement from the position of the wood at different times [*Ravazzolo et al*., 2015b].

We assembled all available literature to compile published data on the movement of individual pieces of large wood in rivers (Table 2).

The data presented in Table 2 permitted a first integrated analysis of some aspects of large wood mobility across a variety of environmental settings. Figure 11 shows contrasts in annual transport rate (percentage of logs moved related to the total surveyed) observed in different regions. Widely varying conditions can be observed, ranging from very small upland streams with low annual transport rates such as those studied in Chile to very active wide systems such as the ones studied in Italy. However, the inherent variability in these data is related to the different conditions adopted in the experiments, such as the hydrological regime during the study and the type (artificial or natural logs, previously placed or introduced to the river), shape, and number of large wood pieces monitored (in relation to the natural conditions at the site). Furthermore, the overall investigative approach adopted varied considerably. For example, *Latterell and Naiman* [2007] mapped and dated logs deposited along the Queets River; *Haga et al.* [2002] and *Millington and Sear* [2007] monitored artificial, introduced wood dowels; whereas *Lucía et al.* [2014a] and *Jochner et al.* [2015] used natural logs, but some were introduced into the studied areas. These differences make comparison of results difficult. For example, when logs are introduced into a river, it is likely that they will move even under low flow conditions until they find a more stable position typical of sites where wood might naturally be deposited. Furthermore, monitoring times ranged between 5 months [*Jochner et al*., 2015] and more than 100 months [*Lienkaemper and Swanson*, 1987], and in most cases flow conditions were below or close to the bankfull discharge, although *Berg et al.* [1998] reported near extreme flows.

Despite these cautions, the data set displayed in Figure 11 reveals useful information, most notably that a maximum traveled distance during a single event of more than 100 km [*Schenk et al*., 2014] is possible and that distances of a hundred meters to a few kilometers are commonly observed (Figures 11b and 11c).

10.1002/2015RG000514

Table 2. Mean Annual Transport Rate (in %) and Distance Traveled by Tagged Logs Derived From Published Studies

Location	River	Mean River Width (m)	Mean River Slope	Mean Drainage Area (km^2)	Number of Tagged Logs	Monitoring Time (months)	Mean Annual Transport Rate (%)	Mean Traveled Distance (m)	Maximum Traveled Distance (km)	Maximum Discharge (m^3/s)	Source
Chile	Tres Arroyos	10.65	0.11	9.07	322	24	8.8				*Andreoli et al.* [2007]
U.S.	Ogeechee River and tributaries in the Coastal Plain		0.02		290		17	11,090	101	600	*Benke and Wallace* [1990]
U.S.	Six streams in central Sierra Nevada	2.10–12.8	0.02–0.078	8.3–25	1700	36	15.9	215.5			*Berg et al.* [1998]
Costa Rica	10 streams	4.9–13.4	0.002–0.062	0.003–0.067		28	9–39				*Cadol and Wohl* [2010]
U.S.	Popular Creek	15	0.001	56	140	15	83	95	>320	15	*Daniels* [2006]
UK	Highland Water	4.5	0.01	9.25	162	32	55	148	5.6	36.8	*Dixon and Sear* [2014]
UK						<12	36			5	*Gregory et al.* [1985]
U.S.							6				*Gregory et al.* [1991]
U.S.							18				*Grette* [1985]
Japan	Oyabu Creek	9	0.04	5.3	63	9	92	840	4	14.4	*Haga et al.* [2002]
Chile	Vuelta de Zorra	9.8	0.01	9.07	484	4	12.4	117	0.5	1.45	*Iroumé et al.* [2010]
Chile	Four streams	4.8–12.9	0.01–0.1	4.31–17.8	79–395	12	7–14.8				
Africa	Kuiseb River				2105				125	159	*Jacobson et al.* [1999]
Switzerland	Erlenbach		0.18	0.7	236	6		10		1.25	*Jochner et al.* [2015]
U.S.	Three streams in Oregon Coast Range	6–7	0.0004–0.01	7–15.5	238	36	44	203	0.7		*Keim et al.* [2000]
U.S.	Queets	125	0.006	386	222	24	36.5	conifer 1520, hardwood 916	12		*Latterell and Naiman* [2007]
U.S.		13.75	0.2	30.3		84–108	10			3.08	*Lienkaemper and Swanson* [1987]
Italy	Rienz	3.5	0.01	630	238		34.5	500	3		*Lucía et al.* [2014a]
UK	Highland Water	4.5	0.01	9.25	74	118	30.4	209.45	1.2	2.59	*Millington and Sear* [2007]
Chile	2 streams	9.8, 10.6	0.01, 0.04	9.07, 5.87		12	2.5, 16				*Mao et al.* [2008]
Alaska		19.5	0.17		252		2				*Murphy and Koski* [1989]
Italy	Tagliamento	800	0.003		113	17	78	6,555.5	51.1		*Ravazzolo et al.* [2015b]
Switzerland	10 streams			0.081–0.3			33–72				*Rickli and Bucher* [2006]
U.S.	Roanoke	85	0.0016		290, 54		80, 41	1,190, 1,330	101.1, 72.1	600	*Schenk et al.* [2014]
U.S.	Little Topshaw Creek	35	0.002	37			61				*Shields et al.* [2004]
Italy	Tagliamento	up to 1500	0.01	2,580			89	13,000	51		*van der Nat et al.* [2003]
U.S.	Rocky Branch	8	0.065	7.4	112	36	25	5	0.3	356	*Warren and Kraft* [2008]
U.S.	Headwaters Colorado Rocky Mountains	5.4	0.06	20.5			19.5				*Wohl and Goode* [2008]
U.S.	Crow's Creek	7	0.055	49.5		12	20.5				*Young et al.* [1994]

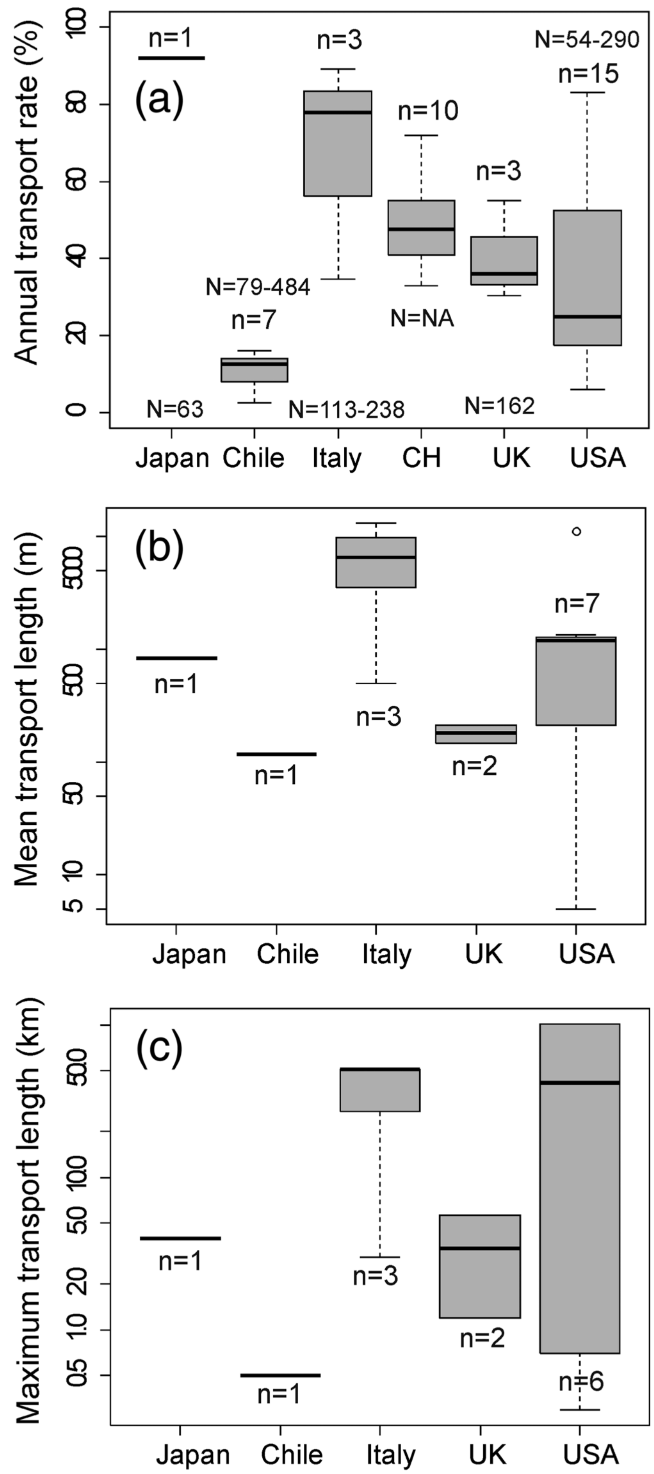

Figure 11. Boxplots of (a) annual transport rate (%) of tagged logs grouped by region (*n* shows the number of monitored sites and N the number of tagged pieces), (b) mean transport distance of tagged pieces, and (c) maximum transport distance of tagged pieces. CH: Switzerland; UK: United Kingdom; and USA: United States of America.

Furthermore, the previously mentioned size effect is helpful in explaining the annual wood transport rate in terms of slope and channel width even if our meta-analysis only provides a small data set (Figure 12). The three variables (slope, channel width, and specific discharge) that are illustrated appear to be useful proxies of the size effect on downstream wood delivery. On small, narrow, upland streams, wood is mainly trapped in the channel and not delivered downstream; whereas on large, gently sloping, downstream systems, trapping structures are less numerous and large wood is more easily transported downstream. This suggests the need to distinguish the aspects of large wood production and large wood delivery or output within a given reach or catchment that differ according to river or catchment size.

3.2. General Physical Principles of Large Wood Entrainment and Transport

Two fundamental questions are usually embedded in attempts to quantify or monitor large wood mobility: how does large wood move in rivers and what are the factors that control large wood transport? To answer the first question, the pioneer flume experiments of *Braudrick and Grant* [2000] provided a basis for a quantitative model of large wood movement. They described the incipient motion of a piece of wood (assuming this as a cylinder) by the balance of forces acting on the mass center of the piece (Figure 13). These forces are (i) the driving forces, including the gravitational force F_g acting on the log, equal to the effective weight of the log in a downstream direction, and the drag force F_d, also acting in the flow direction, which is the downstream drag exerted on the log by the water in motion, and (ii) the resisting forces, including the friction force F_f acting in the direction opposite to flow, which is equal to the normal force W_{eff} acting on the log multiplied by the coefficient of friction between the wood and the bed. According to the balance of forces,

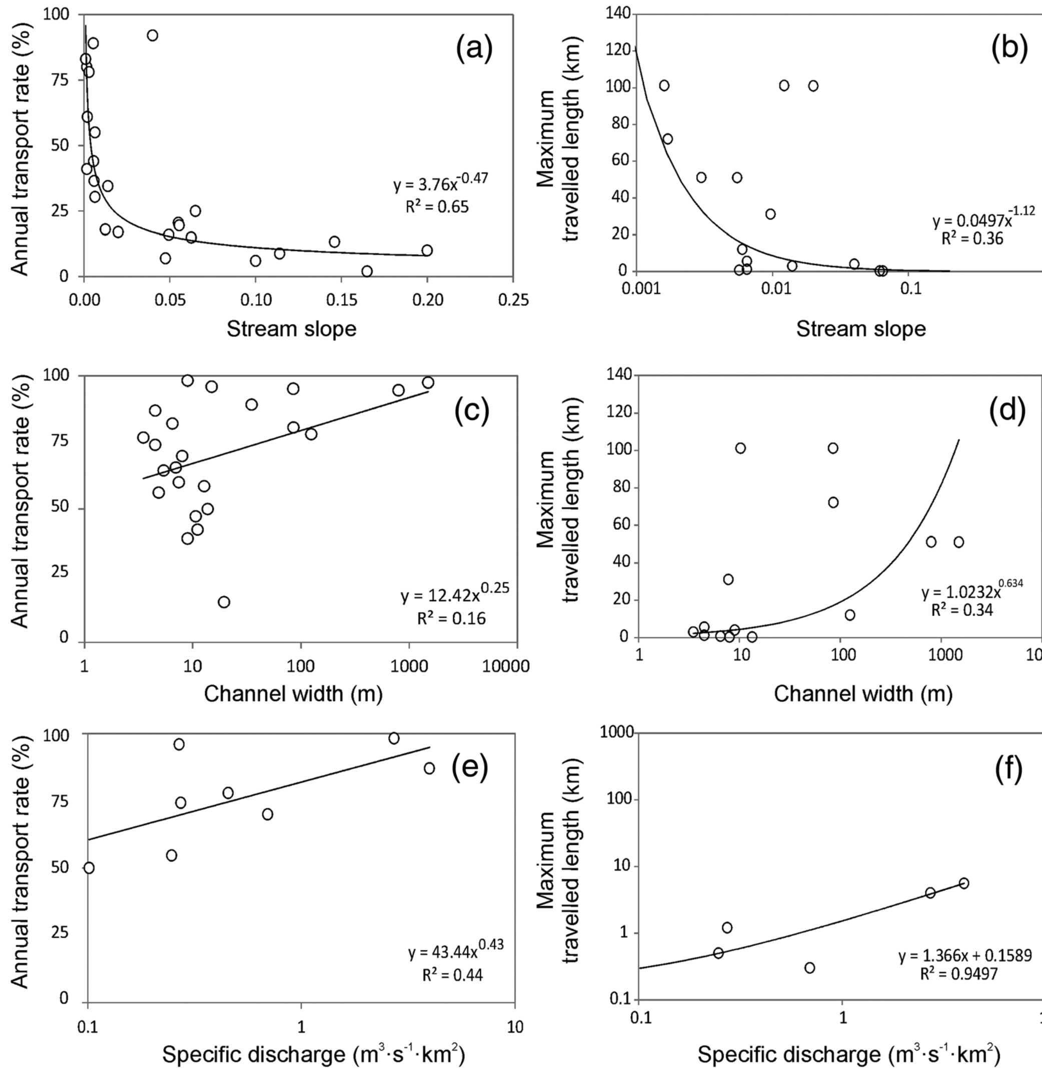

Figure 12. Relationships between the annual transport rate (%) and maximum traveled length (km) of tagged logs and the log transformed (a, b) channel slope; (c, d) channel width; and (e, f) specific maximum discharge recorded during tracking experiments.

once the log is in motion, two possible transport mechanisms are possible: traction (sliding or rolling on the river bed) or flotation, based on the hydrodynamic conditions and the log size and wood density.

The factors controlling large wood motion were also analyzed by *Braudrick and Grant* [2000, 2001] who studied the influence of different log characteristics (orientation, size, density, and presence of roots) on large wood mobility, comparing a theoretical approach with the results of flume experiments and field observations. Dimensionless ratios were proposed to describe transport and the probability that wood will be deposited, the relative log input rate, which is the volumetric log input rate divided by the discharge ($Q_{\log} \cdot Q_w^{-1}$); the relative log length, which is the log length divided by channel width ($L_{\log} \cdot w_c^{-1}$); and the relative log diameter, which is the log diameter divided by the average depth of the channel ($D_{\log} \cdot d_w^{-1}$). In their experiments they observed that wood floats until $D_{\log} \cdot d_w^{-1}$ drops below the critical value for flotation for a given density. Similarly, floating wood is deposited or lodged when $L_{\log} \cdot w_c^{-1}$ increases above a certain threshold, which varies depending on the river morphology. To define the likelihood of large wood retention or deposition, *Braudrick and Grant* [2001] proposed the variable "debris roughness," which varies with $D_{\log} \cdot d_w^{-1}$ and $L_{\log} \cdot w_c^{-1}$ and characterizes a stream reach in a similar way to hydraulic roughness.

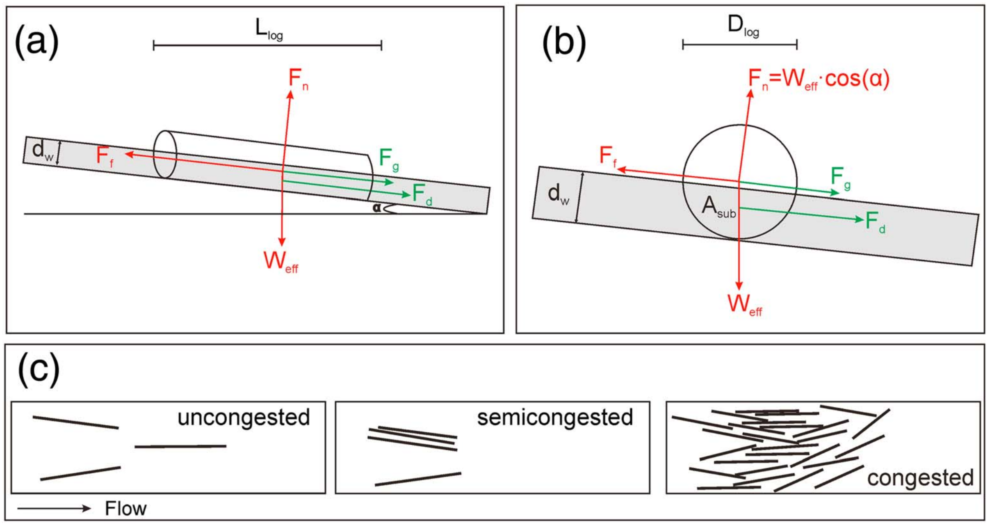

Figure 13. (a, b) Schematic and body force diagrams of some of the components of the force balance acting on a log without a root wad (according to *Braudrick and Grant* [2000]). (c) Wood transport regimes according to *Braudrick et al.* [1997]. F_g is gravitational force, F_d is drag force, F_f is friction force, W_{eff} is normal force, d_w is water depth, L_{log} is log length, D_{log} is log diameter, and α is the angle.

Wood piece dimensions with respect to channel morphology and water level seem to provide a good first-order approximation for the likelihood of piece movement, and these have been used by many researchers [*Lienkaemper and Swanson*, 1987; *Bilby and Ward*, 1989; *Abbe et al.*, 1993]. However, other factors besides length and diameter can affect frequency of wood piece transport, such as the presence of root wads or branches, which can inhibit large wood movement by anchoring pieces to the river bed, increasing drag and thereby decreasing mobility [*Abbe and Montgomery*, 1996; *Buxton*, 2010; *Welber et al.*, 2013]. In general terms, smaller logs are likely to move farther than larger ones [*Young et al.*, 1994]. However, two factors can make larger pieces more mobile than smaller pieces, namely, the higher momentum of larger moving pieces and the reduced influence of local changes in the depth and velocity fields. Larger pieces have higher mass and, therefore, higher momentum, which allows them to overcome frictional resistance offered by obstructions, such as individual bed particles, shallow bars, and banks. Longer pieces also encompass a wider range of water velocities and water depths than shorter pieces, reducing the influence of local reductions in velocity and depth. This effect has been observed in braided multithread channels during flume experiments and numerical modeling [*Welber et al.*, 2013; *Ruiz-Villanueva et al.*, 2016b].

Another parameter influencing large wood dynamics is wood density. Wood density is one of the main parameters controlling the initial motion (i.e., entrainment) and transport of wood in rivers [*Gurnell*, 2003]. A common value of 500 kg m^{-3} has been widely used in the literature [*Harmon et al.*, 1986]. However, wood density varies quite widely as a function of several factors, including tree species, wood type (i.e., early and latewood), tree age, decay status, and water sorption [*Thévenet et al.*, 1998; *Millington and Sear*, 2007; *MacVicar et al.*, 2009; *Curran*, 2010; *Shmulsky and Jones*, 2011], but unlike more general forest assessments, wood density has only rarely been accurately quantified in fluvial systems studies [*Harmon et al.*, 1986; *Abbe and Brooks*, 2011].

For example, the relative frequency histogram in Figure 14a summarizes estimates of the density of wood from tropical tree species, whereas the enormous variability in wood density of pieces of wood stored at the Génissiat dam in the Rhône River in France is presented in Figure 14b. Although 45% of the tropical trees densities (Figure 14a) fall in the range of 0.4 to 0.6 g cm^{-3}, more than half fall outside of this range ($n = 1180$, mean = 0.58 g cm^{-3}, standard deviation = 0.16 g cm^{-3}, maximum = 1.25 g cm^{-3}, and minimum = 0.12 g cm^{-3}; data from *Brown*, [1997]). These estimates are for wood that is dry and free of decay, specifically for oven dried biomass per unit green volume. Further, variability is introduced when moisture and varying decay status is included, particularly as decay not only affects wood density but also the potential of wood to absorb moisture from the water column. Thus, Figure 14b shows the variability in the density of in-stream wood (including contained moisture) delivered from a single catchment in France surveyed after different floods. Environmental conditions and processes in rivers are very different from the forests that supply the wood,

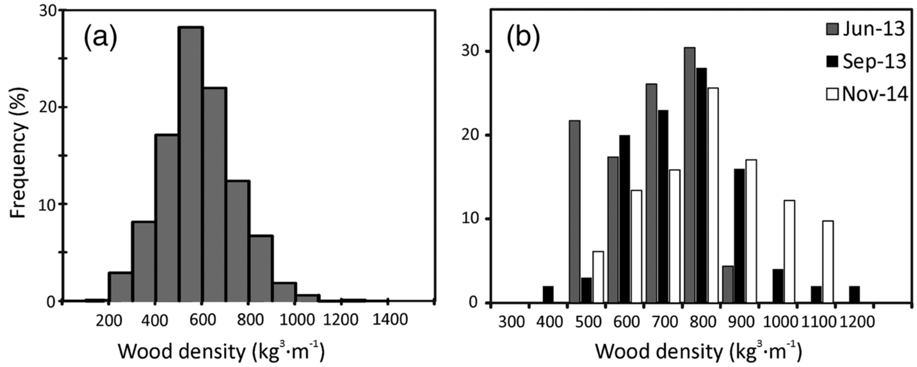

Figure 14. Relative frequency of wood density (kg m^{-3}) for (a) American, African, and Asian tropical tree species [*Brown*, 1997] and (b) in-stream wood pieces stored in a reservoir and extracted during several surveys (June 2013, September 2013, and November 2014, [*Ruiz-Villanueva et al.*, 2016c]).

suggesting that using standard values or relationships extracted from inventories of living trees or dead wood in forests should be incorporated into fluvial large wood studies with caution [*Ruiz-Villanueva et al.*, 2016c].

Hydraulic parameters are also often used to explain large wood mobility, for example, using the simplified continuity or Manning equations [*Braudrick and Grant,* 2001; *Wilcox and Wohl,* 2006]. Unit or total stream power are also often used to analyze large wood mobility and deposition [*Seo and Nakamura*, 2009; *Wohl and Goode*, 2008; *Wohl and Jaeger*, 2009; *Marcus et al.*, 2011; *Rigon et al.*, 2012; *Dixon and Sear,* 2014; *Iroumé et al.*, 2015; *Lucía et al.*, 2015].

Three distinct transport regimes (i.e., uncongested, semicongested, and congested; Figure 13) have been proposed [*Braudrick et al.*, 1997]. Large wood transport is considered uncongested when piece-to-piece contact between logs occurs rarely or not at all during movement. During congested transport, logs move as a single mass because the spacing between logs is small, with many piece-to-piece contacts preventing logs from moving independently of each other with little rotation or pivoting of individual logs. Semicongested transport is intermediate between these two transport types with some logs moving individually and others moving in clumps.

Two primary patterns of large wood transport have been observed within these dominant transport regimes: steady or pulsed movement. Wood moves in pulses during congested transport and semicongested transport, when a cohort of logs moves together [*Braudrick et al.*, 1997]. This could be associated with episodic wood loading due to disturbances such as bank erosion, landslides, or debris flows [*Miller et al.*, 2003; *Wohl et al.*, 2009; *Wohl,* 2011]. Congested transport has been observed to increase the probability of wood jam formation, as large wood pieces occupy more of the available space than they would do individually under uncongested transport [*Bocchiola et al.*, 2008].

Besides the factors controlling wood motion, the effect of large wood on stream hydraulics has been a further major research topic, especially the effects on flow resistance [*Young*, 1991; *Gippel*, 1995; *Shields and Gippel*, 1995]. Flume experiments and visual estimates have been used to quantify the effects of removal of wood from streams [*Young*, 1991; *Shields and Gippel*, 1995], and variables contributing to flow resistance were manipulated in a step-pool channel in order to measure the effects of various parameters (i.e., large wood configurations, steps, grains, discharge, and slope) on total flow resistance. Results have illustrated the complexity of flow resistance and have highlighted flow conditions (discharge) as the dominant variable [*Wilcox and Wohl*, 2006]. In small mountain streams the presence of wood may increase flow resistance by up to 1 order of magnitude [*Comiti et al.*, 2008]. Wood has significant influence on energy dissipation, bed scour, bank erosion, and sediment storage [*Shields and Smith*, 1992; *Cherry and Beschta*, 1989; *Piégay and Marston*, 1998; *Daniels and Rhoads*, 2003, 2004, 2007]. On meander bends, large wood accumulations on the outside of the bend serve to deflect high flows toward the inner bank, which can influence meander migration and avulsions [*Daniels*, 2006].

3.3. Linking Large Wood and Hydrodynamics

The understanding of large wood entrainment and motion allowed the first attempts to use models to simulate large wood transport. Without explicitly taking account of the influence of large wood on the hydraulics,

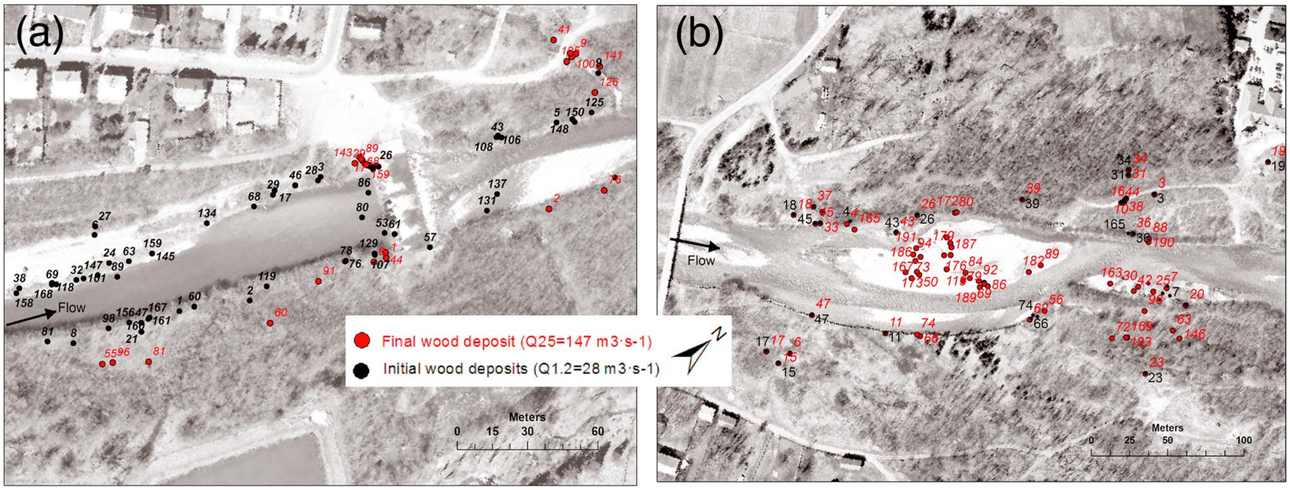

Figure 15. Numerical model results: black circles illustrate the location of initial logs and red circles the final location after being mobilized by a simulated 25 year flood in two different reaches of the Czarny Dunajec River (Poland): (a) single and channelized reach with weirs and (b) an unmanaged, multithread reach.

computational fluid dynamics (CFD; i.e., one- or two-dimensional (1-D or 2-D) hydraulic modeling) have been used, first computing the hydraulics and then using the results to calculate large wood mobilization and deposition [*He et al*., 2009; *Merten et al*., 2010; *Comiti et al*., 2012; *Hafs et al*., 2014]. As an example, *Merten et al.* [2010] applied the 1-D HEC-Ras model to estimate unit stream power, stage, mean water velocity, energy grade slope, and the hydrodynamic drag acting on wood pieces lying on the river bed.

Mazzorana et al. [2011] made one of the first attempts to simulate wood transport using CFD. On a cell-by-cell basis and under unsteady conditions, they delineated possible pathways for a given wood volume and computed the transport conditions using results from a hydrodynamic 2-D simulation for different time steps.

Lagasse et al. [2010] explicitly included the effect of large wood on the hydraulic calculations, using the 1-D hydraulic model HEC-Ras to simulate a wood raft on a bridge by setting the width dimensions of the wood accumulation to form a continuous blockage. They also simulated wood accumulating on the bottom of the bridge deck, and they also proposed the use of two 2-D models (FESWMS and RMA2) to simulate the additional drag force caused by a bridge pier and wood accumulation as an effective Manning roughness coefficient. *Ruiz-Villanueva et al.* [2013] presented a similar approach, using HEC-Ras to simulate the effect of bridge clogging due to large wood accumulation during a flash flood. They reduced the cross-sectional area of the bridge section to produce clogging curves (i.e. the relationship between the percentage of obstruction and the backwater elevation).

In a further step, a 2-D hydrodynamic model coupling large wood transport and hydrodynamics was developed by *Ruiz-Villanueva et al.* [2014a]. This model fully couples a 2-D hydrodynamic model based on the finite volume method with a second-order Roe scheme with a Lagrangian framework (i.e., discrete element method) for large wood dynamics (i.e., considering logs or wood pieces as specific objects that are tracked through time). The model was validated by flume experiments and has already been applied to several real cases to study different aspects of large wood dynamics, such as the large-wood-related hazards in small mountain streams [*Ruiz-Villanueva et al*., 2014b, 2014c], the factors controlling wood transport [*Ruiz-Villanueva et al*., 2015] and deposition [*Ruiz-Villanueva et al*., 2016b], and the influence of flood hydrograph in wood dynamics [*Ruiz-Villanueva et al*., 2016a].

Some of these results showed (Figure 15) that in single-thread channels, the factor controlling large wood transport is the log length, while in wider-braided, multithread channels the main factor is the log diameter. These observations are in agreement with those made by many other researchers in the field and in flume experiments [*Welber et al*., 2013; *Bertoldi et al*., 2014]. In addition, the preferential sites for large wood to be deposited under different flow conditions were also identified by means of a depositional probability. Results showed that the preferential sites of wood deposition vary and the probability of deposition is significantly controlled by the relative elevation of the different geomorphic units in relation to the water level [*Ruiz-Villanueva et al*., 2016b].

Allen and Smith [2012] conducted one of the few 3-D modeling attempts. They quantified the numerical effect of wood geometric simplifications on the surrounding flow field, comparing 3-D CFD modeling results with flume experiments. Following the same approach, *Lai and Bandrowski* [2014] and *Lai et al.* [2015] presented a strategy for combining field observations and 3-D models. However, 3-D modeling of wood is still rare because mesh representation of complex wood shapes can be a daunting task and because simulation of related flows is very challenging and computationally demanding.

3.4. Understanding the Complexity of Interactions Between Large Wood, Morphodynamics, and Vegetation

The presence of wood in channels usually results in declining sediment and organic matter transport capacity, causing local or channel-wide aggradation and altering hydraulic forces and associated erosion and deposition, influencing bank stability [*Wohl*, 2013]. As monitoring or observing these interactions in the field is very challenging, modeling is also being used increasingly as a tool for deciphering complex relationships between large wood dynamics and morphological processes. As described before, while the use of numerical modeling is relatively recent, physical modeling has been used for this purpose over several decades. *Cherry and Beschta* [1989] were probably the first to conduct flume experiments that investigated the effect of large wood on stream morphology. They analyzed the effect of a single fixed log on local scour and found that maximum scour depth was significantly correlated with the vertical orientation of the dowels and the channel opening ratio, and scour surface area was significantly correlated with the flow depth and the vertical orientation of the log. Experiments conducted by *Braudrick et al.* [1997] were the first to model large wood dynamics (transport, deposition, and remobilization) and morphological evolution of the bed of a mobile bed flume. Subsequently, *Braudrick and Grant* [2001] studied the transport and deposition of wood in the context of different channel patterns, observing that large wood tended to deposit on the outside of bends, heads of islands, and bar cross overs, which was in general agreement with field observations.

More recently, *Welber et al.* [2013] and *Bertoldi et al.* [2014] studied the strong relationship between large wood and channel planform dynamics in a mobile bed flume modeling a braided channel. Results showed that large wood deposition patterns were mainly determined by the formation and shape of sediment bars. The downstream distribution and accumulation size indicated that travel distance is primarily controlled by log diameter, whereas log length and presence of roots affect the tendency to form large jams. These experiments highlighted also the tendency of complex morphologies to create scattered distributions of logs, with jams generally including a limited number of logs and deposits of single logs being common. This is a major difference compared with wood retention patterns in single-thread, narrower rivers where many authors have reported the occurrence of log jams containing tens or even hundreds of wood elements. In order to analyze the relationships between riparian vegetation and large wood dynamics, *Bocchiola et al.* [2006] mimicked the transport of logs among standing trees (using vertical rigid obstacles in a flume). They observed two different lodging mechanisms, bridging and leaning, and were able to calculate the probability of occurrence of the two lodging mechanisms depending on the space between obstacles, the length of the wood and the flow conditions, and the formation of jams.

A recent, pioneer experiment investigated the coupled effects of living vegetation and large wood dynamics on river morphology [Figure 16; *Bertoldi et al*., 2015, Figure 8]. The experiments confirmed that vegetation increases bank stability, reducing erosion, and the number of active channels [*Tal and Paola*, 2010; *Van Dijk et al*., 2013] and also showed how this affects large wood dynamics, promoting the formation of stable wood jams where logs accumulated constantly during sequences of floods, further increasing the effect on river morphology. They confirmed the important joint impact of riparian woodland and large wood on river channel form and dynamics, illustrating their aggregate effects on morphology.

Numerical modeling is still challenging, but it provides another approach for analyzing large wood-morphology dynamics. In order to include the complexity and stochastic variability of large wood dynamics in a determinist model, *Ruiz-Villanueva et al.* [2015] proposed a multirun approach (modifying different input parameters of the model), which by manipulating and controlling boundary conditions, as done in a flume, modeled different scenarios to extract general patterns of large wood transport and deposition and to compute probabilities. Following this approach, the proposed model (i.e., Iber-Wood) can be used to simulate sediment transport and wood transport, to analyze feedbacks between wood and sediment. However, this is a complex process that requires validation data, and it is still in its early stages [*Bladé et al*., 2016].

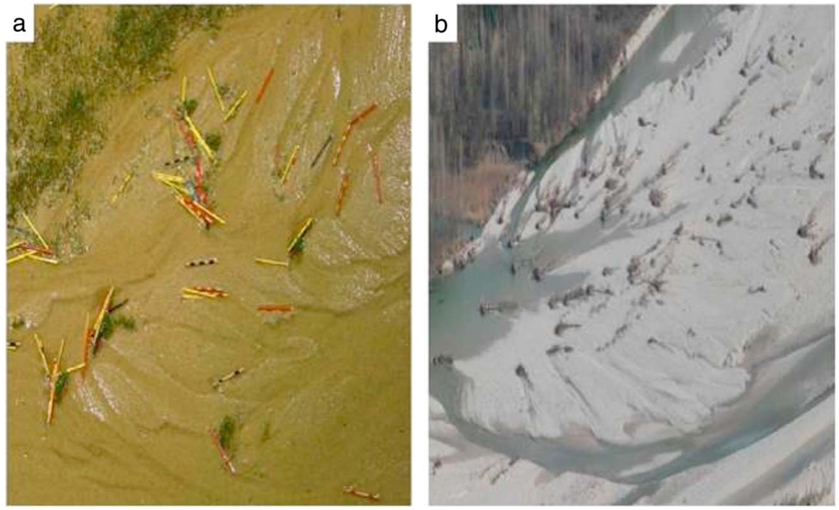

Figure 16. Comparisons between (a) flume-scale and (b) field-scale (Tagliamento River, Italy) wood deposition patterns in a braided morphology [from *Bertoldi et al.*, 2015, Figure 8; Used with the permission of Elsevier].

3.5. Large Wood Stability and Related Hazards

As described in the previous sections, the presence of large wood induces changes in hydraulic and sediment transfer patterns, and it creates flow resistance and obstructions within the channel [*Young*, 1991; *Gippel*, 1995; *Shields and Gippel*, 1995; *Wilcox and Wohl*, 2006; *Comiti et al*., 2008]. The impacts on the flow resistance and flow patterns may increase flow complexity and dissipate energy, therefore increasing channel stability. However, when large wood is not stable and is transported, mainly during high flows, it can cause a substantial increase in the destructive power of floods. Therefore, large wood stability is an important issue that should be analyzed carefully. In the case of single logs and small streams, stability analysis of each piece could be evaluated [*Richmond and Fausch*, 1995; *D'Aoust and Millar,* 1999, 2000; *Abbe*, 2000; *Braudrick and Grant*, 2000; *Shields et al*., 2000; *Brooks et al*., 2003, 2006; *Abbe and Brooks*, 2011; *Rafferty*, 2013; *Wohl et al*., 2016]. However, potential hazards associated with large wood strongly depend on the volume of wood within a channel and on whether a large volume of wood remains stationary or becomes mobile during floods [*Wohl et al*., 2016].

When wood interacts with critical stream geometry configurations (e.g., narrow sections or bridges), a decrease in channel cross-sectional area usually reduces flow velocity and channel conveyance and produces a backwater effect upstream. This backwater effect of afflux can be accompanied by bed aggradation, channel avulsion, and local scouring processes, which can ultimately lead to embankment/bridge collapse and floodplain inundation [*Diehl*, 1997; *Comiti et al*., 2007, 2012; *Lyn et al*., 2007; *Mao et al*., 2010; *Badoux et al*., 2015; *Lucía et al*., 2015]. As a result, the nearby area can be flooded more frequently [*Ruiz-Villanueva et al*., 2013] and may result in the incorrect/uncertain estimation of flood risk.

The experiments of *Lagasse et al.* [2010] were one of the first studies to analyze interactions between large wood and infrastructures. They analyzed bridge pier scour and its relationship with the shape of the wood accumulation, showing that rectangular, blocky wood masses tend to produce the greatest scour at the pier when the extent of the large wood accumulation upstream of the pier is on the order of 1 flow depth. Total scour at the pier also significantly increased with the total frontal area of flow blockage (as a percentage of the cross-sectional area of the approach channel). The authors concluded that given the same size and shape of logs, a slender pier with a wood accumulation will experience less total scour than a wider pier with the same amount of wood under the same hydraulic conditions of the approaching flow. With similar aims, *Pagliara and Carnacina* [2011] proposed empirical relationships (based on laboratory experiments) to estimate the effect of large wood accumulation on bridge pier scour, in terms of the relative maximum scour and temporal scour evolution.

Lyn et al. [2003] analyzed the potential for wood to accumulate at bridge piers by investigating relationships between large wood accumulations and channel hydraulics (i.e., flow depth and velocity). In general, the

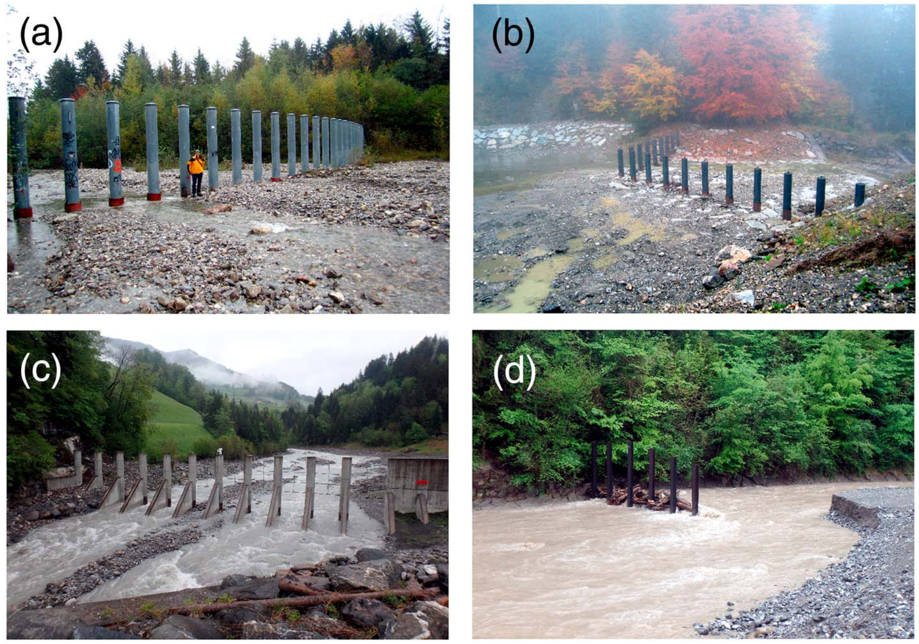

Figure 17. Retention structures installed in rivers: (a) vertical piles crossing the entire river width in the Gürbe stream, (Switzerland); (b) V-shaped sectional dam in the Grossbach (Switzerland); (c) complex rake and cable net in the Chiene (Switzerland); and (d) small vertical rack at the outer side in the Grosse Melcha (Switzerland).

experiments showed that under small flow velocities and depths, the potential for wood accumulation increased. They also analyzed the effectiveness of deflectors in reducing the likelihood of wood clogging at piers, concluding that under certain conditions large wood accumulations developed even in the presence of deflectors. In addition, the shape of the piers has been found to be important for the blocking probability, with triangular and flat shape piers more prone to accumulate large wood [*DeCicco et al*., 2015]. Bridges without piers were physically modeled by *Schmocker and Hager* [2010] and *Gschnitzer et al.* [2015] who explored the blocking probability of bridge decks using different log dimensions, bridge types, and flow characteristics. Their findings highlighted freeboard and flow Froude number as the main factors driving bridge deck blockage probability.

In general, relatively small and loose wood pieces are the most mobile and large pieces (longer than the bankfull width and/or partly buried) are relatively less mobile, and they often trap smaller pieces, reducing overall wood mobility. With this idea, large wood management could be adapted to different river basins [*Gurnell*, 2013]. For example, *Mazzorana et al.* [2009] proposed a catchment-wide approach for assessing potential large wood hazard, whereas *Piégay and Landon* [1997] proposed gradual wood removal based on subreach characteristics and objectives along the channel network of the Drôme River, France. These catchment-wide assessments and management approaches can then be complemented by local solutions (e.g., retention structures) to protect particularly vulnerable areas [*Piton and Recking*, 2015; *Wohl et al*., 2016]. Retention structures have been installed in many watercourses to prevent large wood transport (e.g., upstream of critical bridges) and to retain large wood [*Uchiogi et al*., 1996; *Wallerstein and Thorne*, 1996]. Such structures have been installed in many locations, such as the Alps (Austria, Italy, and Switzerland; Figure 17), and have adopted different designs [*Piton and Recking*, 2015], including vertical piles crossing the entire river width (Figure 17a), V-shaped sectional dams (Figure 17b), complex rakes (Figure 17c), or cable nets (Figure 17d).

Flume experiments are usually used to evaluate the efficiency of these structures. For example, physical models made by *Rimböck and Strobl* [2002] and *Bezzola et al.* [2004] used rack structures with different configurations and orientations to test their wood retention capacity. More recently, *Schmocker and Hager* [2013] and *Schmocker and Weitbrecht* [2013] designed a bypass channel located at outer river bends, with a rack parallel to the main flow, where wood logs are stored in a side channel located at the outer bank.

Hydraulic models can also be used to design retention structures and to identify the most effective installation location along a river. *Comiti et al.* [2012] used a 1-D (HEC-Ras) and a 2-D model (Flo-2D) to derive flow paths, flooded areas, flow depth, and velocity, as well as Froude number distributions, to identify the most suitable sites for the installation of retention structures along the Rienz River in Italy. Models can be used to predict entrapment and to analyze the potential impacts. *Mazzorana et al*., [2011] proposed a retention probability for each colliding log to estimate entrapment at the considered obstacle. In the model developed by *Ruiz-Villanueva et al*. [2014a], interactions among logs and internal conditions and obstacles can also be simulated. Using the model, they reproduced a flash flood event that transported a significant amount of large wood and triggered the blocking of a bridge opening, enhancing the flood effects upstream [*Ruiz-Villanueva et al*., 2014b]. In order to identify the most critical bridges for wood passage along a river passing through a village in a mountainous region in Spain, the same authors used the numerical model under different scenarios, identifying one bridge as critical and the potential effects of this bridge clogging on flood risk [*Ruiz-Villanueva et al*., 2014c].

4. Remaining Challenges

In this concluding section, we revisit and summarize some key challenges identified in previous sections and consider how these may develop in the future (section 4.1). We then consider an area that we have only briefly touched on in the preceding text because it has been relatively neglected. This research area, the properties of the trees that provide the sources of the large wood to the fluvial large wood dynamics (section 4.2), presents a major challenge for future research.

4.1. Open Questions and Future Challenges

Unlike water and sediment dynamics, for which extensive research commenced at the beginning of the twentieth century [*Haschenburger*, 2013], research on large wood dynamics in rivers has only become an important focus for research over the last three decades. As a result, this research remains at a relatively early stage, perhaps similar to that reached in the 1960s for water or suspended sediment monitoring, with many fundamental questions still open.

One important aspect is the regional applicability of preliminary empirical formulae based on catchment size and another is the need to better link wood volume delivered with peak flow frequency, a topic highlighted by many researchers for future attention. In addition, it is desirable to take into account other influential factors such as land cover, basin physiography, and drainage network connectivity. In this context, additional case studies (particularly incorporating monitoring of large wood movement) would greatly facilitate and reinforce the quality and utility of meta-analyses. Recent and varied technological advances make such research feasible, and further testing is desirable to improve the precision and accuracy of the collected data. For example, video monitoring is now operational, and equipped sites are providing data, but the technique needs to be applied to a larger set of reaches to evaluate its transferability, and the efficiency of detection algorithms also needs to be tested over longer periods of time. Tracking techniques (e.g., RFID or GPS) also have been proved useful for understanding large wood travel distance and related hydraulic conditions of transport and deposition; but again, these approaches need to be applied on different rivers and under different flow conditions to establish transferable laws and to understand the impact of local conditions (river patterns and basin contexts) on travel patterns.

Improved understanding of spatial and temporal variability of wood transport conditions are needed to improve large wood transport prediction and assessments of the susceptibility of catchments to produce large wood. Buoyancy and other wood properties vary in time and in different catchments in relation to flow magnitude and to the spatial properties of flood events, but a continuous survey of relevant wood characteristics (species, size, and decomposition rate) remains challenging. In addition, the critical question of how rapidly a single trunk, perhaps with branches and bark, can pass through a channel reach remains unanswered. The assessment of large wood transport rates is subject to uncertainty because it is influenced not only by flow properties, particularly magnitude of the flow peak, but also by other factors related to large wood production potential and output. The latter are difficult to describe and even more complicated to quantify because "seasonal" effects appear to have a high impact, indicated by factors such as the time since the last flood event, the timing and intensity of a transporting event, or forest management practices and breakage process during wood transport.

Enormous efforts have been made to incorporate numerical modeling into the analysis of large wood dynamics. Such models might be particularly useful to river managers, but considerable research is needed before their systematic application is feasible. The first and most obvious challenges to the development of modeling tools are the continuing development of knowledge and computer technology. Such developments should lead to models of greater detail that, at the same time, can be run for longer river reaches and longer periods of time (e.g., long-lasting floods and sequencing of floods) and should also lead to developing or applying models that reproduce more accurately the complex shape of wood pieces, although the incorporation of logs with root wads or branches remains a particular challenge. Furthermore, when any model is to be used for prediction or for understanding processes it is necessary to verify the model, to obtain enough field data to properly set boundary conditions, and to validate results. Thus, the challenge is related not only to model development and computing power but also to obtain enough good quality data.

Large-wood-related topics are crucial to flood risk assessment, particularly in European mountain environments where human occupation and pressures are significant, and at the same time river and torrent margins are becoming more and more forested. Therefore, large wood research, in particular, in these environments, is critical for planning actions and risk prevention. Furthermore, in relation to management of regulated rivers in which maximization of flow capacity is a priority, the optimum large wood loading is the minimum required to maintain ecological integrity, and thus, a pressing research question is to determine the minimum loading of large wood required to sustain viable aquatic communities.

4.2. Tree and Wood Properties

The preceding sections of this paper have amply illustrated that to date, large wood research has focused strongly on themes related to large wood budgets and physics related to entrainment and transport. However, the behavior of large wood within fluvial systems is highly variable and is strongly linked to the tree species, and yet this aspect has received remarkably little explicit attention. While research from the northwestern U.S. has amply illustrated how large wood generated from large, slow-decaying conifers behaves within fluvial systems, less evidence is available from other biogeographical regions of the World. Although a rapidly increasing body of international research has emerged since the start of the 21st century, which indicates the importance of tree species in determining wood behavior. Key tree properties (which include the density and susceptibility to decay of the large wood that is produced, aboveground and belowground tree architecture, strength, and biomass, and the ability of trees and wood to interact with sediment erosion, deposition processes through regeneration from living wood, and the production of adventitious roots or shoots when plants are buried) have the potential to profoundly influence the large wood cycle. These constitute a set of remaining key challenges in large wood research, which deflect the focus to some extent from the large wood in river systems to the trees that produce this wood and are elaborated in this final section of our paper.

4.2.1. Dead Wood Properties

Much research effort has been devoted to establishing the quantities and dimensions of large wood pieces and accumulations found within river channels and, to a lesser extent, within areas marginal to the active channel on the channel banks and floodplain surfaces. To date, little account has been taken of buried wood in fluvial research, and the few existing studies have focused on slow-decaying dead wood buried in naturally functioning floodplains. These studies have shown that enormous quantities of wood may be buried in alluvial deposits and so are available for remobilization by bank erosion and lateral migration of river channels [e.g., *Nanson et al*., 1995; *Brooks and Brierley*, 2002; *Arsenault et al*., 2007]. Indeed, large buried, slow-decaying wood jams, have been described as forming floodplain "hard points" [*Montgomery and Abbe*, 2006] on which riparian forest develops to maturity, eventually providing the largest wood pieces to the large wood cycle [*Collins et al*., 2012], indicating important connections between buried wood and river and floodplain morphology and turnover that require further research.

In addition, changes in tree species distribution within the riparian forest may also be important. As an example, when streamside conifers of western red cedar (*Thuja plicata*) and Douglas fir (*Pseudotsuga menziesii*) in the Pacific Northwest were removed and replaced with monotypic stands of red alders (*Alnus rubra*), large wood storage decreased because of a drop in the size and density of large wood [*Marston*, 1982; *McHenry et al*., 1998]. *Tabacchi and Planty-Tabacchi* [2003] speculated on the river landscape scale significance of interspecies differences when they considered the likely impact of the replacement of the native white poplar

(*Populus alba*) by the alien boxelder (*Acer negundo*) along French rivers. They hypothesized that the resultant "increase in the proportion of hardwood fragments in wood jams would: (i) increase the stability of the jams; and (ii) decrease the rate of carbon release through decomposition, and thus, carbon supplies in aquatic and terrestrial systems" [*Tabacchi and Planty-Tabacchi,* 2003]. If their hypotheses are correct, this implies a major and very significant change in the functioning of the wood cycle and budgets in such rivers because decomposition has pronounced effects on wood permeability, buoyancy, mobility, and length of storage.

Despite the wide variability in wood properties that is apparent from previous detailed research, the literature needs to be synthesized and distilled so that these properties can be incorporated into wood cycle research at reach to landscape scales.

4.2.2. Tree Canopy Properties

According to *Lintunen and Kaitaniemi* [2010], tree canopy architecture follows species-specific growth rules coupled with responses to the environment, which jointly influence the structure a tree develops during its lifespan. The canopy develops to efficiently balance constantly changing growth resources, displaying a trade-off between safety and efficiency [*Fan et al*., 2011]. Thus, tree canopies vary enormously in size, shape, and flexibility, and these properties vary with age as well as species and as a result of many other factors including competition with surrounding trees [*Cao*, 2001; *Lintunen and Kaitaniemi,* 2010; *McLean et al*., 2011], moisture availability, and the occurrence of disturbances such as major floods [*Lawson et al*., 2015]. As a result, different tree species display traits that reflect their environmental conditions, of which the character and seasonal persistence of their foliage, and the hydraulic, mechanical, and storage properties of their xylem [*Méndez-Alonzo et al*., 2013], are of particular importance to their performance within large wood dynamics. Furthermore, within their environmental range, the growth performance, morphology, and mechanical properties of a single species can vary widely in response to local environmental conditions [*Gurnell*, 2016].

Particularly relevant to large wood dynamics is riparian vegetation and its influence on flow hydraulics [*Jalonen and Järvelä*, 2014]. The flow resistance of riparian vegetation varies with leaf, stem-branch, and stand characteristics, including the degree to which plant canopies are flexible and can reconfigure [*Jalonen and Järvelä*, 2013, 2014]. In laboratory experiments, *Västilä et al.* [2013] found that leaves contributed 74–98% of the total drag of twigs of *Populus nigra*, illustrating the importance of the period of the year when foliage is present. The relative importance of foliage varies with the structure of the canopy (which often varies as trees grow and mature, in relation to the level of inundation experienced by the tree during flood events) and with the period of the year over which the plant shows full foliage [*Jalonen and Järvelä*, 2014; *Västilä and Järvelä*, 2014].

Therefore, the hydraulic resistance of woody riparian vegetation and its role as a morphological component of the river channel-floodplain system have the potential to affect floodplain flow conditions during overbank events that, in turn, affect the degree to which woody plants may be uprooted, break, or may retain other woody or sedimentary material and also the likely fate of mobile wood. It also affects the flow conditions in the channel that influence sediment dynamics and the potential lateral erosion or undermining of the woody vegetation. Recently, laboratory experiments have started to capture some of this complexity [*Manners et al*., 2015], including interactions between living vegetation and wood [*Bertoldi et al*., 2015], but much remains to be explored.

4.2.3. Tree Root Properties

While research on buried dead wood is scarce, research on the impact of buried living wood, in the form of tree root systems, on large wood dynamics is particularly rare. A vast biological literature exists on the underground biomass of trees relating to its architecture and function, and considerable interest also exists in the mechanical properties of root systems and their consequent contribution to stabilizing soils and sediments [*Pregitzer*, 2008; *Bardgett et al*., 2014]. This literature provides an important starting point for considering how the root systems of trees of different species and in different environmental contexts might influence large wood dynamics.

Uprooting resistance is a useful measure of the overall physical performance of a root system and so is particularly relevant to the influence of roots on the large wood dynamics. *Burylo et al.* [2009] reviewed the literature on this topic and concluded that stem basal diameter, tap root length, root topology, and the proportion of fine lateral roots are all important influences on root anchorage and uprooting resistance. In relation to tree species, *Gale and Grigal* [1987] found that early successional species (e.g., pioneer riparian species) had a significantly greater proportion of roots at depth than late successional species, which is probably attributable

Figure 18. (a) Willow sprouting after being transported and deposited on a bar in the Sense River, Switzerland (photograph: V. Ruiz-Villanueva); (b) exposed tree root system; and (c) sprouting deposited poplar log, Tagliamento River, Italy (photographs: A. M. Gurnell).

to the ability of the former to adapt to sites where moisture and nutrients are limiting, whereas the shallower roots of the latter are adapted to sites where resources are concentrated in near-surface soils. Furthermore, tree species adapted to dry climates generally have deeper root systems with greater specific root length than those more suited to more moist conditions, and the biomass of finer roots is often less [*Brunner et al*., 2015]. Root systems also consist of many different sizes of root (Figure 18), which perform different functions. While coarse woody roots provide perennial anchorage structures that transport water and nutrients and store nutrients and carbohydrates, fine roots forage for resources and are more ephemeral [*Comas et al*., 2013]. The length and diameter structures of these fine roots differ considerably among trees species [*Pregitzer et al*., 2002]. In addition, root strength generally varies with root diameter, with different strength-diameter relationships apparent for different tree species [*Simon and Collison*, 2002; *Pollen et al*., 2004]. Finally, the 3-D distribution of root position, orientation, and size defines the architectural structure of the root system [*Danjon et al*., 2013].

Although root properties vary considerably between species, they also vary enormously within species in relation to the age of the tree and also because roots respond strongly to environmental gradients and interactions among species [*Brassard et al*., 2009; *Pasquale et al*., 2012; *Bardgett et al*., 2014]. In riparian systems, alluvial sedimentary structures are complex and ever changing in response to sediment erosion and deposition, and they have highly varying moisture retention characteristics, providing an extremely complex environment within which tree root systems develop. We know little about rooting depth, strength, and architecture among riparian tree species or how these vary under different environmental conditions, but these properties have important impacts on the ability of trees to reinforce sediments [*Docker and Hubble*, 2008], avoid uprooting [*Edmaier et al*., 2014], and when uprooted, to reinforce the portion of the root system that is released and the portion that may be retained within the soil [*Danjon et al*., 2013]. When translated into the context of the large wood dynamics, root biomass determines the amount of living belowground wood present within a river corridor, root reinforcement affects river bank dynamics and the rate of release of trees to the river channel, and root architecture influences the proportion of the root system that remains to reinforce bank and floodplain sediments and the proportion that becomes part of the river's wood load when a tree is uprooted or undermined.

4.3. Living Wood

Large wood and trees are closely linked within fluvial systems, but the nature of that linkage varies according to the dominant tree species and environmental conditions. In their description of the large wood cycle in the rivers of the northwest U.S., *Collins et al.* [2012] emphasized the crucial importance of hard points formed by accumulations of very large pieces of slow-decaying, dead wood on which tree seedlings germinate and grow to maturity over centuries as the wood accumulations become embedded in the floodplain. They also illustrate how removal of the largest wood and trees from this large wood cycle leads to a more disturbed, dynamic river and floodplain environment, where trees do not remain long enough to grow to maturity and produce wood to create future hard points and where, as a result, the river style changes from single thread, sinuous, or anabranching to bar braided.

In other systems, where different tree species dominate that produce wood that decays more rapidly, creation of hard points similar to those described by *Collins et al.* [2012] cannot happen. However, many riparian tree species show other traits that enable them to engineer their fluvial environment. These have been reviewed in detail recently [*Gurnell*, 2014], and so only a brief overview will be presented here.

One extremely important trait is the ability of many riparian species to reproduce vegetatively by sprouting from wood fragments or entire uprooted trees (Figure 18). Thus, although once dead, the wood may decompose rapidly; if it sprouts, its roots systems stabilize alluvial sediments and its shoots interact with fluvial processes to create a range of morphological features, including small (pioneer) landforms. These trap further dead and living wood as well as sediment, expand laterally, aggrade, and coalesce to create large established islands whose surface can protrude several meters above the initial bar surface on which they were initiated [*Gurnell et al*., 2001, 2005]. The trait of sprouting from wood fragments, plus the ability to generate adventitious roots from shoots and shoots from roots, characterize members of the riparian *Salicaceae* and provide them with the ability to produce living hard points from vast, deep webs of roots and shoots developed within and stabilizing sediments that are retained to form islands and floodplains. As in the case of the dead wood hard points, the removal of living wood and trees from a fluvial system greatly disrupts large wood dynamics and can lead to a transformation in river style [*Zanoni et al*., 2008; *Gurnell,* 2016].

In summary, an outstanding challenge for the future of large wood research is to develop an understanding of the key characteristics of tree species found in riparian woodlands. An integrated understanding of wood, canopy, and root properties and growth performance of individual species, and how these vary under different environmental conditions, is fundamental to understanding the large wood budgets and cycles of systems dominated by different tree species.

Appendix A

Glossary

Biomass mass of living or dead organic matter in an organism, expressed as mass of dry matter. For a tree, biomass is expressed in kilograms. By extension, the biomass of an area is the sum of the biomasses of the organisms found in the area. This is usually measured in kg per unit area.

Bridge log log that spans the channel, above the streambed, touching both banks, and resting on the floodplain.

Clogging deposition of large wood pieces of different sizes, at a given point in the river, which results in reduced cross-sectional area.

Contributing area synonym of source area, refers to the probable area delivering large wood within a basin which is used in developing large wood budgets.

Decay biological process by which cellulose and lignin are converted to carbon dioxide and water with a release of energy.

Decomposition rate series of biological and physical processes that includes fragmentation or breakage, leaching, collapse and settling, seasoning, transport, respiration, and biological transformation contributing to destroy wood.

Depletion	removal of large wood from a channel through decay, transport, and burial processes.
Driftwood	often used as synonym of large wood but refers to the mechanism which allows the downstream migration of large wood when simply drifting with the flow.
Entrainment	initiation of motion; process of initial motion.
Floodplain	part of the valley bottom that undergoes flooding.
Flow resistance	resistance due to friction (momentum transfer to the solid walls) and dissipation of mechanical energy when the configuration or the direction of flow is sharply changed by the formation of vortices and secondary flows.
Hardwood	generic term for a broadleaf tree (i.e., a tree that is not a conifer). This includes both deciduous trees (e.g., willow, alder, cottonwood, and maple) and evergreen trees.
Hydraulics	science studying flow behavior of liquids, in particular, flow processes in open channels.
Hydrology	science that studies water, its spatial and temporal distribution on the Earth's surface, and its associated biological, chemical, and physical characteristics.
In-stream/in-channel wood	tree or portion of a tree (including snags, tree tops, logs, chunks of wood, limbs, branches, stumps, and root wads) that has fallen into a stream. Sometimes used as synonymous with large wood.
Jam/dam/logjam	accumulation of wood pieces, usually a minimum of two or three, within a river channel or along its banks, including at least one piece, which may completely or partly block the channel.
Key piece/log/member	piece of large wood that, either because of its size or because of its position, is stable within a stream channel and can trap and stabilize other wood pieces, creating a jam. The key piece is responsible for creating the jam or is the piece responsible for stabilizing and maintaining the jam.
Large wood (or LW)	tree or portion of a tree (including snags, tree tops, logs, chunks of wood, limbs, branches, stumps, and root wads) that has fallen into a fluvial corridor; usually considered to be greater than 0.1 m in diameter and over a meter long.
Living wood	wood piece capable of sprouting.
Log orientation	angle of a wood piece with respect to the overall flow direction.
Log step	single key member large enough to remain immobile during at least moderate flows with possible racked wood-oriented oblique or perpendicular to flow, forming a step within the flow channel which is usually followed by a plunge pool.
Loose log	log that rests entirely on the streambed.
Manning equation	empirical equation used to estimate the velocity, and hence discharge, of a flow.
Manning's n	roughness coefficient expressing the resistance to flow in a channel.
Monitoring	gathering information about something; may involve measuring or simply observing change.
Organic matter	carbon-based matter of organic origin. This includes vegetable matter as well as the bodies of dead animals.
(Coarse) particulate organic matter (POM or CPOM)	pieces of organic matter with a size larger than 1 mm; it spans the range from leave and wood fragments over twigs and branches to logs and complete trees, being large wood at the top of this range.
Ramp log	log with one side that rests on one bank and the other on the streambed.

Reach/stretch	stream length, which is relatively homogenous with regard to the hydrology, physical form, water quality, and aquatic life; typically 5 to 20 times the width in length.
Recruitment	process(es) of large wood delivery to streams, such as bank erosion, hillslope failures, blowdown, fluvial transport, decay, or mortality.
Residence time	time which a piece of large wood spends in a river system. Often, it is, however, calculated as the difference between the year of a specific survey and the year of mortality.
Roughness	general measure of the hydraulic resistance caused by obstructions to flow (often measured by the "*n*" coefficient in Manning's equation).
Shear stress	force applied to a stream bed (product of the water depth, water surface slope, and weight density of water).
Softwood	generic term for wood from gymnosperm trees such as conifers.
Source area	synonym of contributing area; refers to the probable area delivering wood within a basin which is used in developing wood budgets.
Storage capacity	wood accumulated within a river reach and is usually measured in $m^3\ 100^{-1}$ m, $m^3\ ha^{-1}$ (also referred as specific wood storage) or pieces $\cdot\ 100^{-1}$ m.
Trap efficiency/retention efficiency	proportion of wood material trapped in a particular storage zone (e.g., a dam or stream reach).
(Large) wood budget	balance between the standing crop of wood stored within a river reach and the quantity of wood produced; input to the reach and output from it within a specific time period.
(Large) wood delivery	process(es) of wood recruitment to streams, such as bank erosion, landslides, fluvial transport, decay, or mortality.
(Large) wood deposit/wood storage	accumulation of driftwood within a channel or its alluvial corridor
(Large) wood discharge/wood flux	volume (or mass) of wood transferred in a certain time; usually measured in $m^3\ s^{-1}$ or $kg\ s^{-1}$.
(Large) wood dynamics	processes involved in the motion and equilibrium of wood under the action of forces.
(Large) wood input	amount of wood (usually volume or mass of wood including previously stored wood and freshly recruited wood) transferred to the inlet of the considered river reach or watershed in a certain time.
(Large) wood load	amount of wood (usually volume or mass) introduced to the channel by different recruitment processes.
(Large) wood mobility	rate and manner with which wood moves through river systems.
(Large) wood output/wood export	amount of wood (usually volume or mass of wood including previously stored wood and freshly recruited wood) transferred to the outlet of the considered river reach or watershed in a certain time.
(Large) wood potential	wood volume or mass which can potentially be transferred or exported from a watershed during a critical event.
Wood raft	accumulation of wood that completely spans the active channel and has a length at least several times the average channel width.
(Large) wood retention	duration and manner with which wood is retained within river systems.
Wood-air volume	measurement of piece/jam size along three orthogonal axes and the estimation of wood to air ratios for logs, jams, and shrubs to improve volume estimates in log jams.
(Large) woody debris (or LWD)	commonly used over the past decades by scientists and river managers to refer large wood; is nowadays considered inappropriate because it is negatively perceived whereas large wood has significant positive biological effects in term of habitat structure. It is preferably replaced by large wood or in-channel wood.
Woody plants	vegetation with a distinct trunk and branch structure, ranging from trees to small shrubs.

Acknowledgments

Many people contributed ideas and data to the development of this paper. In particular, we are grateful to Bartłomiej Wyżga, Dieter Rickenmann, Andrea Andreoli, and Walter Bertoldi for their contribution with data and excellent suggestions. V.R.V. and M.S. acknowledge financial support by the Polish-Swiss project FLORIST (Flood risk on the northern foothills of the Tatra Mountains; PSPB 153/2010) and the *Schwemmholzmanagement Programme* (WoodFlow Project) founded by the Swiss Federal Office for the Environment (FOEN/BAFU). H.P. acknowledges Pierre Lemaire, Veronique Benacchio, Laure Tougne, Bruce MacVicar, Thomas Buffin-Belanger, and Maxime Boivin for early discussions. R.M. thanks the Dendrolab.ch at the University of Bern for hosting him during his sabbatical leave from Kansas State University. Edits from Susan Basta and comments by Mark Moldwin and two anonymous reviewers substantially improved the paper. All data set analyzed in this study may be accessible by contacting the first author.

References

Abalharth, M., M. A. Hassan, B. Klinkenberg, V. Leung, and R. McCleary (2015), Using lidar to characterize logjams in lowland rivers, *Geomorphology*, *246*, 531–541, doi:10.1016/j.geomorph.2015.06.036.

Abbe, T. (2000), Patterns, mechanics and geomorphic effects of wood debris accumulations in a forest river system, PhD dissertation, Univ. of Washington, Seattle, Wash., 219 pp.

Abbe, T. (2011), History of wood in rivers and the benefits of reintroducing wood to rivers forests, trees, people and logjams A Brief Historical Context.

Abbe, T., and A. Brooks (2011), Geomorphic, engineering, and ecological considerations when using wood in river restoration, in *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*, edited by A. Simon, S. J. Bennett, and J. M. Castro, pp. 419–451, AGU, Washington, D. C.

Abbe, T. B., and D. R. Montgomery (1996), Large woody debris jams, channel hydraulics and habitat formation in large rivers, *Regul. Rivers Res. Manage.*, *12*, 201–221.

Abbe, T. B., and D. R. Montgomery (2003), Patterns and processes of wood debris accumulation in the Queets River Basin, Washington, *Geomorphology*, *51*(1-3), 81–107, doi:10.1016/S0169-555X(02)00326-4.

Abbe, T. B., D. R. Montgomery, K. Fetherston, and E. McClure (1993), A process-based classification of woody debris in a fluvial network: Preliminary analysis of the Queets River, Washington, *EOS Trans. AGU*, *74*, 296.

Ali, I., and L. Tougne (2009), Unsupervised video analysis for counting of wood in river during floods, *Proceeding ISVC '09 Proceedings of the 5th International Symposium on Advances in Visual Computing, Part II*, pp. 578 – 587.

Allen, J. B., and D. L. Smith (2012), Characterizing the impact of geometric simplification on large woody debris using CFD, *Int. J. Hydraul. Eng.*, *1*(2), 1–14, doi:10.5923/j.ijhe.20120102.01.

Andreoli, A., F. Comiti, and M. A. Lenzi (2007), Characteristics, distribution and geomorphic role of large woody debris in a mountain stream of the Chilean Andes, *Earth Surf. Processes Landforms*, *1692*, 1675–1692, doi:10.1002/esp.1593.

Angradi, T. R., E. W. Schweiger, D. W. Bolgrien, P. C. Ismert, and T. Selle (2004), Bank stabilization, riparian land use and the distribution of large woody debris in a regulated reach of the Upper Missouri River, North Dakota, USA, *River Res. Appl.*, *20*, 829–846.

Antón, A., A. Elosegi, L. García-Arberas, J. Díez, and A. Rallo (2011), Restoration of dead wood in Basque stream channels: Effects on brown trout population, *Ecol. Freshwater Fish*, *20*, 461–471, doi:10.1111/j.1600-0633.2010.00482.x.

Arroita, M., I. Aristi, L. Flores, A. Larranaga, J. Diez, J. Mora, A. M. Romani, and A. Elósegi (2012), The use of wooden sticks to assess stream ecosystem functioning: Comparison with leaf breakdown rates, *Sci. Total Environ.*, *440*, 115–122.

Arsenault, D., E. Boucher, and E. Bouchon (2007), Asynchronous forest–stream coupling in a fire-prone boreal landscape, insights from woody debris, *J. Ecol.*, *95*, 789–801.

Badoux, A., M. Böckli, D. Rickenmann, C. Rickli, V. Ruiz-Villanueva, S. Zurbrügg, and M. Stoffel (2015), Large wood transported during the exceptional flood event of 24 July 2014 in the Emme catchment (Switzerland), *Proceedings of the Wood in World Rivers Conference*, Padova, Italy, July 2015.

Baillie, B. R., L. G. Garrett, and A. W. Evanson (2008), Spatial distribution and influence of large woody debris in an Old-Growth Forest River System, New Zealand, *For. Ecol. Manage.*, *256*(1-2), 20–27, doi:10.1016/j.foreco.2008.01.051.

Bardgett, R. D., L. Mommer, and F. T. De Vries (2014), Going underground, root traits as drivers of ecosystem processes, *Trends Ecol. Evol.*, *29*, 692–699.

Barker, J. R., M. Bollman, P. L. Ringold, J. Sackinger, and S. P. Cline (2002), Evaluation of metric precision for a riparian forest survey, *Environ. Monit. Assess.*, *75*, 51–72.

Becker, B., and B. Kromer (1986), Extension of the Holocene dendrochronology by the Preboreal Pine Series, 8800 to 10,100 BP, *Radiocarbon*, *28*, 961–967.

Becker, B., B. Kromer, and P. Trimborn (1991), A stable-isotope tree-ring timescale of the late Glacial/Holocene boundary, *Nature*, *353*, 647–649.

Beebe, J. T. (2000), Flume studies of the effect of perpendicular log obstructions on flow patterns and bed topography, *Great Lakes Geogr.*, *7*, 9–25.

Benacchio, V., H. Piégay, T. Buffin-Bélanger, L. Vaudor, and K. Michel (2015), Automatic imagery analysis to monitor wood flux in rivers (Rhône River, France), *Proceedings of the third International Conference of Wood in World Rivers*, Padova 6-10 July 2015.

Benda, L. E., and J. C. Sias (2003), A quantitative framework for evaluating the mass balance of in-stream organic debris, *For. Ecol. Manage.*, *172*(1), 1–16, doi:10.1016/S0378-1127(01)00576-X.

Benda, L., and P. Bigelow (2014), On the patterns and processes of wood in northern California streams, *Geomorphology*, *209*, 79–97.

Benda, L., P. Bigelow, and T. Worsley (2002), Recruitment of wood to streams in old growth and second growth redwood forests in northern California, *Can. J. For. Res.*, *32*, 1460–1477.

Benda, L., D. Miller, J. Sias, D. Martin, R. Bilby, C. Veldhuisen, and T. Dunne (2003), Wood recruitment processes and wood budgeting, *Am. Fish. Soc. Symp.*, *37*, 49–73.

Benke, A. C., and J. B. Wallace (1990), Wood dynamics in coastal plain blackwater streams, *Can. J. Fish. Aquat. Sci.*, *47*, 92–99.

Berg, N., A. Carlson, and D. Azuma (1998), Function and dynamics of woody debris in stream reaches in the Central Sierra Nevada, California, *Can. J. Fish. Aquat. Sci.*, *55*(8), 1807–20.

Bertoldi, W., A. M. Gurnell, and M. Welber (2013), Wood recruitment and retention: The fate of eroded trees on a braided river explored using a combination of field and remotely-sensed data sources, *Geomorphology*, *180-181*, 146–155, doi:10.1016/j.geomorph.2012.10.003.

Bertoldi, W., M. Welber, L. Mao, S. Zanella, and F. Comiti (2014), A flume experiment on wood storage and remobilization in braided river systems, *Earth Surf. Processes Landforms*, *39*(6), 804–813, doi:10.1002/esp.3537.

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

Bertrand, M., F. Liébault, and H. Piégay (2013), Debris-flow susceptibility of upland catchments, *Nat. Hazards*, *67*, 497–511.

Bezzola, G. R., H. Sigg, and D. Lange (2004), Driftwood retention works in Switzerland, in *International Symposium Interpraevent 2004—Riva del Garda*, vol. 3, pp. 29–40, Italy.

Bigelow, P. E., L. E. Benda, D. J. Miller, and K. M. Burnett (2007), On debris flows, river networks, and the spatial structure of channel morphology, *For. Sci.*, *53*(2), 220–238.

Bilby, R. E. (2003), Decomposition and nutrient dynamics of wood in streams and rivers, in *The Ecology and Management of Wood in World Rivers*, *Symposium*, edited by S. V. Gregory, K. Boyer, and A. M. Gurnell, Am. Fish. Soc., Bethesda, Maryland.

Bilby, R. E., and J. W. Ward (1989), Changes in characteristics and function of woody debris with increasing size of streams in western Washington, *Trans. Am. Fish. Soc.*, *118*, 368–378.

Bilby, R. E., and J. W. Ward (1991), Characteristics and function of large woody debris in streams draining olg-growth clear-cut and second-growth forests of streams in southwestern Washington, *Trans. Am. Fish. Soc.*, *118*, 368–378.

Bilby, R. E., J. T. Heffner, B. R. Fransen, J. W. Ward, and P. A. Bisson (1999), Effects of immersion in water on deterioration of wood from five species of trees used for habitat enhancement projects, *N. Am. J. Fish. Manage.*, *19*, 687–695.

Bisson, P. A., R. E. Bilby, M. D. Bryant, C. A. Dolloff, G. B. Grette, R. A. House, M. L. Murphy, K. V. Koski, and J. R. Sedell (1987), Large woody debris in forested streams in the Pacific Northwest: Past, present, and future, in *Streamside Management, Forestry and Fishery Implications*, vol. 57, edited by E. O. Salo and T. W. Cundy, pp. 143–190, Inst. of For. Resour., Univ. of Washington, Seattle.

Bladé, E., V. Ruiz-Villanueva, M. Stoffel, and G. Corestein (2016), Challenges of numerical modelling of flow, sediment, and wood in rivers, *Proceedings of the third International Conference of Wood in World Rivers*, Padova, 6-10 July 2015.

Bocchiola, D., M. C. Rulli, and R. Rosso (2006), Flume experiments on wood entrainment in rivers, *Adv. Water Resour.*, *29*(8), 1182–1195.

Bocchiola, D., M. C. Rulli, and R. Rosso (2008), A flume experiment on the formation of wood jams in rivers, *Water Resour. Res.*, *44*, W02408, doi:10.1029/2006WR005846.

Boivin, M., and T. Buffin-Bélanger (2010), Using a terrestrial lidar for monitoring of large woody debris jams in gravel-bed rivers. 7th Gravel bed Rivers Conference, 5–10 September 2010, Tadoussac, Quebec, Canada (poster).

Boivin, M., T. Buffin-Bélanger, and H. Piégay (2015), The raft of the Saint-Jean River, Gaspé (Québec, Canada): A dynamic feature trapping most of the wood transported from the catchment, *Geomorphology*, *231*, 270–280.

Braccia, A., and D. P. Batzer (2008), Breakdown and invertebrate colonization of dead wood in wetland, upland, and river habitats, *Can. J. For. Res.*, *38*(10), 2697–2704.

Bragg, D. C. (2000), Simulating catastrophic and individualistic large woody debris recruitment for a small riparian system, *Ecology*, *81*, 1383–1394.

Bragg, D. C., J. L. Kershner, and D. W. Roberts (2000), Modeling large woody debris recruitment for small streams of the central Rocky Mountains, *USDA Forest Serv. General Tech. Rep. RMRS-GTR-55*, 36 pp.

Brassard, B. W., H. Y. H. Chen, and Y. Bergeron (2009), Influence of environmental variability on root dynamics in northern forests, *Crit. Rev. Plant Sci.*, *28*(3), 179–197.

Braudrick, C. A., and G. E. Grant (2000), When do logs move in rivers?, *Water Resour. Res.*, *36*(2), 571–583, doi:10.1029/1999WR900290.

Braudrick, C. A., and G. E. Grant (2001), Transport and deposition of large woody debris in streams: A flume experiment, *Geomorphology*, *41*(4), 263–283, doi:10.1016/S0169-555X(01)00058-7.

Braudrick, C. A., G. E. Grant, Y. Ishikawa, and H. Ikeda (1997), Dynamics of wood transport in streams: A flume experiment, *Earth Surf. Processes Landforms*, *22*, 669–83.

Brooks, A. P., and G. J. Brierley (2002), Mediated equilibrium, the influence of riparian vegetation and wood on the long-term evolution and behavior of a near-pristine river, *Earth Surf. Processes Landforms*, *27*(4), 343–367.

Brooks, A. P., G. J. Brierley, and R. G. Millar (2003), The long-term control of vegetation and woody debris on channel and flood-plain evolution: Insights from a paired catchment study in southeastern Australia, *Geomorphology*, *51*(1-3), 7–29, doi:10.1016/S0169-555X(02)00323-9.

Brooks, A., T. Abbe, T. Cohen, N. Marsh, S. Mika, A. Boulton, T. Broderick, D. Borg, and I. Rutherfurd (2006), *Design Guideline for the Reintroduction of Wood Into Australian Streams*, Land & Water Australia, Canberra.

Brown, S. (1997), *Estimating Biomass and Biomass Change of Tropical Forests: A Primer*, *FAO For. Pap.*, 134 pp., FAO - Food and Agriculture Organization of the United Nations, Rome.

Brunner, I., C. Herzog, M. A. Dawes, M. Arend, and C. Sperisen (2015), How tree roots respond to drought, *Front. Plant Sci.*, *6*, 547.

Bryant, M. D. (1981), Organic debris in salmonid habitat in southeast Alaska: Measurement and effects, in *Acquisition and Utilization of Aquatic Habitat Inventory Information*, edited by N. B. Armantrout, pp. 259–265, Am. Fish. Soc., Portland.

Burylo, M., F. Rey, C. Roumet, E. Buisson, and T. Dutoit (2009), Linking plant morphological traits to uprooting resistance in eroded marly lands (Southern Alps, France), *Plant Soil*, *324*(1-2), 31–42.

Buxton, T. H. (2010), Modeling entrainment of waterlogged large wood in stream channels, *Water Resour. Res.*, *46*, W10537, doi:10.1029/2009WR008041.

Cadol, D., and E. Wohl (2010), Wood retention and transport in tropical, headwater streams: La selva Biological Station, Costa Rica, *Geomorphology*, *123*(1-2), 61–73, doi:10.1016/j.geomorph.2010.06.015.

Cadol, D., E. Wohl, J. R. Goode, and K. L. Jaeger (2009), Wood distribution in neotropical forested headwater streams of La Selva, Costa Rica, *Earth Surf. Processes Landforms*, *34*(9), 1198–1215, doi:10.1002/esp.1800.

Cao, K. F. (2001), Morphology and growth of deciduous and evergreen broadleaved saplings under different light conditions in a Chinese beech forest with dense bamboo undergrowth, *Ecol. Res.*, *16*(3), 509–517.

Carbonneau, P., and H. Piégay (2012), *Fluvial Remote Sensing for Science and Management*, 440 pp., John Wiley, Chichester, U. K.

Carbonneau, P., H. Piégay, J. Lejot, R. Dunford, and K. Michel (2012), Centimetre resolution airborne imagery and potential applications to river management, in *Fluvial Remote Sensing for Science and Management*, edited by P. Carbonneau and H. Piégay, pp. 163–191, John Wiley, Chichester, U. K.

Cherry, J., and R. L. Beschta (1989), Coarse woody debris and channel morphology: A flume study, *Water Resour. Bull.*, *25*, 1031–1036.

Clark, D. B., D. A. Clark, S. Brown, S. F. Oberbauer, and E. Veldkamp (2002), Stocks and flows of coarse woody debris across a tropical rain forest nutrient and topography gradient, *For. Ecol. Manage.*, *164*, 237–248.

Collier, K. J. (2014), Wood decay rates and macroinvertebrate community structure along contrasting human pressure gradients (Waikato, New Zealand), *N. Z. J. Mar. Freshwater Res.*, *48*(1), 97–111.

Collins, B. D., D. R. Montgomery, K. L. Fetherston, and T. B. Abbe (2012), The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion, *Geomorphology*, *139–140*, 460–470.

Comas, L. H., S. R. Becker, V. V. Cruz, P. F. Byrne, and D. A. Dierig (2013), Root traits contributing to plant productivity under drought, *Front. Plant Sci.*, *4*, 442.

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

Comiti, F., L. Mao, A. Wilcox, E. Wohl, and M. A. Lenzi (2007), Field-derived relationships for flow velocity and resistance in high-gradient streams, *J. Hydrol.*, *340*(1-2), 48–62, doi:10.1016/j.jhydrol.2007.03.021.

Comiti, F., A. Andreoli, L. Mao, and M. A. Lenzi (2008), Wood storage in three mountain streams of the Southern Andes and its hydro-morphological effects, *Earth Surf. Processes Landforms*, *33*, 244–263.

Comiti, F., V. D. Agostino, M. Moser, M. A. Lenzi, F. Bettella, A. D. Agnese, and B. Mazzorana (2012), Preventing wood-related hazards in mountain basins: From wood load estimation to designing retention structures, Interpraevent 12th Congress Proceedings, Grenoble, France.
Cook, E., and L. Kairiukstis (1990), *Methods of Dendrochronology: Applications in the Environmental Sciences*, Kluwer, Dordrecht.
Curran, J. C. (2010), Mobility of large woody debris (LWD) jams in a low gradient channel, *Geomorphology*, *116*(3-4), 320–329, doi:10.1016/j.geomorph.2009.11.027.
Curran, J. H., and E. E. Wohl (2003), Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington, *Geomorphology*, *51*(1–3), 141.
Czarnomski, N. M., D. M. Dreher, K. U. Snyder, J. A. Jones, and F. J. Swanson (2008), Dynamics of wood in stream networks of the western Cascades Range, Oregon, *Can. J. For. Res.*, *38*(8), 2236–2248, doi:10.1139/X08-068.
D'Aoust, S. G. D., and R. G. Millar (1999), *Large Woody Debris Fish Habitat Structure Performance and Ballasting Requirements*, 119 pp., Watershed Restoration Program, BC Ministry of Environment, Lands & Parks and Ministry of Forests, British Columbia.
D'Aoust, S. G., and R. G. Millar (2000), Stability of ballasted woody debris habitat structures, *J. Hydraul. Eng.*, *126*, 810–17.
Dahlström, N., K. Jönsson, and C. Nilsson (2005), Long-term dynamics of large woody debris in a managed boreal forest stream, *For. Ecol. Manage.*, *210*(1-3), 363–373, doi:10.1016/j.foreco.2005.02.022.
Daniels, M. D. (2006), Distribution and dynamics of large woody debris and organic matter in a low-energy meandering river, *Geomorphology*, *77*, 286–298.
Daniels, M. D., and B. L. Rhoads (2003), Influence of a large woody debris obstruction on three-dimensional flow structure in a meander bend, *Geomorphology*, *51*, 159–173.
Daniels, M. D., and B. L. Rhoads (2004), Effect of large woody debris configuration on three-dimensional flow structure in two low-energy meander bends at varying stages, *Water Resour. Res.*, *40*, W11302, doi:10.1029/2004WR003181.
Daniels, M. D., and B. L. Rhoads (2007), Influence of experimental removal of large woody debris on spatial patterns of three-dimensional flow in a meander bend, *Earth Surf. Processes Landforms*, *32*, 460–474.
Danjon, F., J. S. Caplan, M. Fortin, and C. Meredieu (2013), Descendant root volume varies as function of root type: Estimation of root biomass lost during uprooting in Pinus pinaster, *Front. Plant Sci.*, *4*, 402.
Davies, N. S., and M. R. Gibling (2011), Evolution of fixed-channel alluvial plains in response to Carboniferous vegetation, *Nat. Geosci.*, *4*, 629–633.
DeCicco, P., L. Solari, and E. Paris (2015), Bridge clogging caused by woody debris: Experimental analysis on the effect of pier shape, *Proceedings of the third International Conference of Wood in World Rivers*, Padova 6-10 July 2015.
Diehl, T. (1997), Potential drift accumulation at bridges. U.S. Department of Transportation Federal Highway Administration Research and Development Turner-Fairbank Highway Research Center 6300 Georgetown Pike McLean, Virginia 22101-2296. [Available at http://tn.water.usgs.gov/publications/FHWA-RD-97-028/FHWA-RD-97-028.pdf.]
Díez, J., A. Elosegi, E. Chauvet, and J. Pozo (2002), Breakdown of wood in the Agüera stream, *Freshwater Biol.*, *47*(11), 2205–2215.
Dixon, S. J., and D. A. Sear (2014), The influence of geomorphology on large wood dynamics in a low gradient headwater stream, *Water Resour. Res.*, *50*, 9194–9210, doi:10.1002/2012WR013085.
Docker, B. B., and T. C. T. Hubble (2008), Quantifying root-reinforcement of river bank soils by four Australian tree species, *Geomorphology*, *100*, 401–418.
Eaton, B. C., and M. A. Hassan (2013), Scale-dependent interactions between wood and channel dynamics: Modeling jam formation and sediment storage in gravel-bed streams, *J. Geophys. Res. Earth Surf.*, *118*, 2500–2508, doi:10.1002/2013JF002917.
Eaton, B. C., M. A. Hassan, and S. L. Davidson (2012), Modeling wood dynamics, jam formation, and sediment storage in a gravel-bed stream, *J. Geophys. Res.*, *117*, F00A05, doi:10.1029/2012JF002385.
Eaton, R. J., and F. G. Sanchez (2009), Quantitative and qualitative measures of decomposition: Is there a link?, *South. J. Appl. For.*, *33*(3), 137–141.
Edmaier, K., B. Crouzy, R. Ennos, P. Burlando, and P. Perona (2014), Influence of root characteristics and soil variables on the uprooting mechanics of Avena sativa and Medicago sativa seedlings, *Earth Surf. Processes Landforms*, *39*(10), 1354–1364.
Evans, B. F., C. R. Townsend, and T. A. Crowl (1993), Distribution and abundance of coarse woody debris in some southern New Zealand streams from contrasting forest catchments, *N. Z. J. Mar. Freshwater Res.*, *27*, 227–239.
Fan, P. F., W. Xiao, S. Huo, H. S. Ai, T. C. Wang, and R. T. Lin (2011), Distribution and conservation status of the vulnerable eastern hoolock gibbon Hoolock leuconedys in China, *Oryx*, *45*(1), 129–134.
Fleece, W. C. (2002), Modeling the delivery of large wood to streams with light detection and ranging (lidar) data, *USDA Forest Service Gen. Tech. Rep. PSW-GTR-181. 2*, 71–83.
Fremier, A. K., J. I. Seo, and F. Nakamura (2010), Watershed controls on the export of large wood from stream corridors, *Geomorphology*, *117*(1-2), 33–43.
Fritts, H. C. (1976), *Tree Rings and Climate*, 567 pp., Academic Press, New York.
Gale, M. R., and D. F. Grigal (1987), Vertical root distributions of northern tree species in relation to successional status, *Can. J. For. Res.*, *17*(8), 829–834.
Gippel, C. J. (1995), Environmental hydraulics of large woody debris, *J. Environ. Eng.*, *121*(5), 388–395.
Gippel, C. J., B. L. Finlayson, and I. C. O'Neill (1996), Distribution and hydraulic significance of large woody debris in a lowland Australian river, *Hydrobiologia*, *318*(3), 179–194, doi:10.1007/BF00016679.
Golladay, S. W., and J. R. Webster (1988), Effects of clear-cut logging on wood breakdown in Appalachian mountain streams, *Am. Mid. Nat.*, *119*, 143–155.
Gomi, T., R. C. Sidle, M. D. Bryant, and R. D. Woodsmith (2001), The characteristics of woody debris and sediment distribution in headwater streams, southeastern Alaska, *Can. J. For.*, *31*, 1386–1399.
Greenberg, J. A., S. Z. Dobrowski, and V. C. Vanderbilt (2009), Limitations on maximum tree density using hyperspatial remote sensing and environmental gradient analysis, *Remote Sens. Environ.*, *113*, 94–101.
Gregory, K. J., A. M. Gurnell, and C. T. Hill (1985), The permanence of debris dams related to river channel processes, *Hydrol. Sci. J.*, *30*(3), 371–381.
Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins (1991), An ecosystem perspective of riparian zones, *BioScience*, *41*(8), 540–551.
Gregory, S. V., K. L. Boyer, and A. M. Gurnell (Eds.) (2003), *The Ecology and Management of Wood in World Rivers*, vol. 37, Am. Fish. Soc. Symp., Bethesda, MD.
Grette, G. B. (1985), The role of large organic debris in juvenile salmonid rearing habitat in small streams. Master's thesis, Univ. of Washington, Seattle, Wash., 105 pp.
Gschnitzer, T., B. Gems, B. Mazzorana, and M. Aufleger (2015), Towards a robust assessment of bridge clogging processes in flood risk management, *Proceedings of the third International Conference of Wood in World Rivers*, Padova 6-10 July 2015.

Gulis, V., K. Suberkropp, and A. D. Rosernond (2008), Comparison of fungal activities on wood and leaf litter in unaltered and nutrient-enriched headwater streams, *Appl. Environ. Microbiol.*, *74*(4), 1094–1101.
Gurnell, A. M. (2003), Wood storage and mobility, in *The Ecology and Management of Wood in World Rivers*, vol. 37, edited by S. V. Gregory, K. L. Boyer, and A. M. Gurnell, Am. Fish. Soc. Symp., Bethesda, Maryland.
Gurnell, A. M. (2012), Fluvial geomorphology, wood and river landscapes, *Nat. Geosci.*, *5*(2), 93–94, doi:10.1038/ngeo1382.
Gurnell, A. M. (2013), Wood in fluvial systems, in *Treatise on Geomorphology*, vol. 9, edited by J. Shroder and E. Wohl, chap. 236, pp. 163–188, Academic Press, San Diego, Calif., doi:10.1016/B978-0-12-374739-6.00236-0.
Gurnell, A. M. (2014), Plants as river system engineers, *Earth Surf. Processes Landforms*, *39*, 4–25.
Gurnell, A. M. (2016), Trees, wood and river morphodynamics: Results from 15 years research on the Tagliamento River, Italy, in *River Systems, Research and Management for the 21st Century*, edited by D. Gilvear, Wiley, Chichester, U. K., doi:10.1002/9781118643525.ch7.
Gurnell, A. M., G. E. Petts, N. Harris, J. V. Ward, K. Tockner, P. J. Edwards, and J. Kollmann (2000), Large wood retention in river channels: The case of the Fiume Tagliamento, Italy, *Earth Surf. Processes Landforms*, *25*(3), 255–75.
Gurnell, A. M., G. E. Petts, D. M. Hannah, B. P. G. Smith, P. J. Edwards, J. Kollmann, J. V. Ward, and K. Tockner (2001), Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy, *Earth Surf. Processes Landforms*, *26*(1), 31–62.
Gurnell, A. M., H. Piégay, F. J. Swanson, and S. V. Gregory (2002), Large wood and fluvial processes, *Freshwater Biol.*, *47*, 601–619.
Gurnell, A. M., K. Tockner, P. J. Edwards, and G. E. Petts (2005), Effects of deposited wood on biocomplexity of river corridors, *Front. Ecol. Environ.*, *3*(7), 377–382.
Guyette, R. P., D. C. Dey, and M. C. Stambaugh (2008), The temporal distribution and carbon storage of large oak wood in streams and floodplain deposits, *Ecosystems*, *11*, 643–653.
Hafs, A. W., L. R. Harrison, R. M. Utz, and T. Dunne (2014), Quantifying the role of woody debris in providing bioenergetically favorable habitat for juvenile salmon, *Ecol. Modell.*, *285*, 30–38, doi:10.1016/j.ecolmodel.2014.04.015.
Haga, H., T. Kumagai, K. Otsuki, and S. Ogawa (2002), Transport and retention of coarse woody debris in mountain streams: An in situ field experiment of log transport and a field survey of coarse woody debris distribution, *Water Resour. Res.*, *38*(8), 1126, doi:10.1029/2001WR001123.
Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, and K. W. Cummins (1986), Ecology of coarse woody debris in temperate ecosystems, *Adv. Ecol. Res.*, *15*, 133–302. 4.
Harmon, M. E., C. W. Woodall, B. Fasth, J. Sexton, and M. Yatkov (2011), Differences between standing and downed tree wood density reduction factors: A comparison across decay classes and tree species, Research Paper NRS-15, U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, 40 pp.
Haschenburger, J. K. (2013), Bedload kinematics and fluxes, in *Treatise on Geomorphology*, vol. 9, pp. 103–123, Academic Press, San Diego, Calif.
Haschenburger, K. J., and S. P. Rice (2004), Changes in woody debris and bed material texture in a gravel-bed channel, *Geomorphology*, *60*, 241–267.
Hassan, M. A., M. Church, T. E. Lisle, F. Brardinoni, L. Benda, and G. E. Grant (2005), Sediment transport and channel morphology of small, forested streams 1, *J. Am. Water Resour. Assoc.*, *41*(4), 853–876, doi:10.1111/j.1752-1688.2005.tb03774.x.
He, Z., W. Weimung, and F. D. Shields (2009), Numerical analysis of effects of large wood structures on channel morphology and fish habitat suitability in a Southern U.S. Sandy Creek, *J. Ecohydrol.*, *2*, 370–380, doi:10.1002/eco.60.
Hering, D., J. Kail, and S. Eckert (2000), Coarse woody debris quantity and distribution in Central European streams, *Int. Rev. Hydrobiol.*, *85*, 5–23.
Hofgaard, A. (1993), 50 years of change in a Swedish boreal old-growth Picea abies forest, *J. Veg. Sci.*, *4*, 773–782.
Hottola, J., and J. Siitonen (2008), Significance of woodland key habitats for polypore diversity and red-listed species in boreal forests, *Biodivers. Conserv.*, *17*, 2559–2577.
Hyatt, T. L., and R. J. Naiman (2001), The residence time of large woody debris in the Queets River, Washington, USA, *Ecol. Appl.*, *11*, 191–202.
Iroumé, A., A. Andreoli, F. Comiti, H. Ulloa, and A. Huber (2010), Large wood abundance, distribution and mobilization in a third order Coastal mountain range river system, southern Chile, *For. Ecol. Manage.*, *260*, 480–490.
Iroumé, A., L. Mao, H. Ulloa, C. Ruz, and A. Andreoli (2014), Large wood volume and longitudinal distribution in channel segments draining catchments with different land use, *Open J. Modern Hydrol.*, *4*, 57–66.
Iroumé, A., L. Mao, A. Andreoli, H. Ulloa, and M. P. Ardiles (2015), Large wood mobility processes in low-order Chilean river channels, *Geomorphology*, *228*, 681–693, doi:10.1016/j.geomorph.2014.10.025.
Jackson, K. J., and E. Wohl (2015), Instream wood loads in montane forest streams of the Colorado Front Range, *Geomorphology*, *234*, 161–170.
Jacobson, P. J., K. M. Jacobson, P. L. Angermeier, and D. S. Cherry (1999), Transport, retention and ecological significance of woody debris within a large ephemeral river, *J. N. Am. Benthol. Soc.*, *18*(4), 429–444.
Jalonen, J., and J. Järvelä (2013), Impact of tree scale on drag, experiments in a towing tank. Proceedings of the 35th Iahr World Congress, Vols I and II, 1878–1889.
Jalonen, J., and J. Järvelä (2014), Estimation of drag forces caused by natural woody vegetation of different scales, *J. Hydrodyn.*, *26*(4), 608–623.
Janisch, J. E., M. E. Harmon, H. Chen, B. Fasth, and J. Sexton (2005), Decomposition of coarse woody debris originating by clearcutting of an old-growth conifer forest, *Ecoscience*, *12*(2), 151–160.
Jochner, M., J. M. Turowski, A. Badoux, M. Stoffel, and C. Rickli (2015), The role of log jams and exceptional flood events in mobilizing coarse particulate organic matter in a steep headwater stream, *Earth Surf. Dyn. Discuss.*, *3*, 173–196, doi:10.5194/esurfd-3-173-2015.
Jones, T. A., and L. D. Daniels (2008), Dynamics of large woody debris in small streams disturbed by the 2001 Dogrib fire in the Alberta foothills, *For. Ecol. Manage.*, *256*(10), 1751–1759.
Kail, J., D. Hering, S. Muhar, M. Gerhard, and S. Preis (2007), The use of large wood in stream restoration, experiences from 50 projects in Germany and Austria, *J. Appl. Ecol.*, *44*(6), 1145–1155, doi:10.1111/j.1365-2664.2007.01401.x.
Kasprak, A., F. J. Magilligan, K. H. Nislow, and N. P. Snyder (2012), A lidar-derived evaluation of watershed-scale large woody debris sources and recruitment mechanisms, *River Res. Appl.*, *28*(9), 1462–1476, doi:10.1002/rra.1532.
Keim, R. F., A. E. Skaugset, and D. S. Bateman (2000), Dynamics of coarse woody debris placed in three Oregon streams, *For. Sci.*, *46*, 13–22.
Keller, E. A., and F. J. Swanson (1979), Effects of large organic material on channel form and fluvial processes, *Earth Surf. Process.*, *4*, 361–380.
Keller, E. A., and T. Tally (1979), Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment, in *Adjustments of the Fluvial System, Proceedings of the 10th Binghamton Geomorphology Symposium*, edited by D. D. Rhodes and G. P. Williams, pp. 169–197, Kendall/Hunt, Dubuque.
King, L., M. A. Hassan, X. Wei, L. Burge, X. Chen, and E. Science (2013), Wood dynamics in upland streams under different disturbance regimes, *Earth Surf. Processes Landforms*, *38*(11), 1197–1209, doi:10.1002/esp.3356.

Knowles, P., and M. C. Grant (1983), Age and size structure analyses of Engelmann spruce, ponderosa pine, lodgepole pine, and limber pine in Colorado, *Ecology*, *64*, 1–9.
Kramer, N., and E. Wohl (2014), Estimating fluvial wood discharge using time-lapse photography with varying sampling intervals, *Earth Surf. Processes Landforms*, *39*(6), 844–852, doi:10.1002/esp.3540.
Krankina, O. N., and M. E. Harmon (1995), Dynamics of the dead wood carbon pool in northwestern Russian boreal forests, *Water Air Soil Pollut.*, *82*, 227–238.
Lagasse, P. F., P. E. Clopper, L. W. Zevenbergen, W. J. Spitz, and L. G. Girard (2010), Effects of debris on bridge pier scour, NCHRP Rep. 653, Transp. Res. Board, Washington, D. C. [Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_653.pdf.]
Lai, Y. G., and D. J. Bandrowski (2014), Large wood flow hydraulics: A 3D modelling approach, in *Proceedings of the 7th Intl. Congress on Environmental Modelling and Software of the International Environmental Modelling and Software Society (iEMSs)*. [Available at http://www.iemss.org/society/index.php/iemss-2014-proceedings.]
Lai, Y. G., D. J. Brandowski, and D. L. Smith (2015), Large wood precision prototyping and 3D-hydraulic CFD modelling to evaluate river processes and enhance engineering guidelines, *Proceedings of the third International Conference of Wood in World Rivers*, Padova 6-10 July 2015.
Lancaster, S. T., S. K. Hayes, and G. E. Grant (2003), Effects of wood on debris flow runout in small mountain watersheds, *Water Resour. Res.*, *39*(6), 1168, doi:10.1029/2001WR001227.
Lang, G. E., and D. H. Knight (1979), Decay rates for boles of tropical trees in Panama, *Biotropica*, *11*, 316–317.
Lange, D., and G. R. Bezzola (2006), Schwemmholz. Probleme Und Lösungsansätze, Mitteilungen 188 ISSN:0374-0056. ETH.
Lassettre, N. S., and G. M. Kondolf (2012), Large woody debris in urban stream channels: Redefining the problem, *River Res. Appl.*, *28*(9), 1477–1487, doi:10.1002/rra.1538.
Lassettre, N. S., H. Piégay, S. Dufour, and A. J. Rollet (2007), Decadal changes in distribution and frequency of wood in a free neandering river, the Ain River, France, *Earth Surf. Processes Landforms*, *33*, 1098–1112.
Latterell, J. J., and R. J. Naiman (2007), Sources and dynamics of large logs in a temperate floodplain river, *Ecol. Appl. A Publ. Ecol. Soc. Am.*, *17*(4), 1127–41.
Lawson, J. R., K. A. Fryirs, and M. R. Leishma (2015), Hydrological conditions explain variation in wood density in riparian plants of south-eastern Australia, *J. Ecol.*, *103*(4), 945–956.
Le Lay, Y. F., H. Piégay, and B. Moulin (2013), Wood entrance, deposition, transfer and effects on fluvial forms and processes, problem statements and challenging issues, in *Treatise on Geomorphology*, vol. 12, edited by J. F. Shroder, pp. 20–36, Academic Press, San Diego, Calif.
Leckie, D. G., E. Cloney, and C. J. De Paradine (2005), Automated mapping of stream features with high-resolution multispectral imagery: An example of the capabilities, *Photogramm. Eng. Remote Sens.*, *71*(2), 145–55.
Lejot, J., C. Delacourt, H. Piégay, T. Fournier, M.-L. Trémélo, and P. Allemand (2007), Very high spatial resolution imagery for channel bathymetry and topography from an unmanned mapping controlled platform, *Earth Surf. Processes Landforms*, *32*, 1705–1725.
Liébault, F., and H. Piégay (2001), Assessment of channel changes due to long-term bedload supply decrease, Roubion River, France, *Geomorphology*, *36*, 167–186.
Lienkaemper, G. W., and F. J. Swanson (1987), Dynamics of large woody debris in streams in old-growth Douglas-Fir Forests, *Can. J. For. Res.*, *17*, 150–56.
Lintunen, A., and P. Kaitaniemi (2010), Responses of crown architecture in Betula pendula to competition are dependent on the species of neighboring trees, *Trees*, *24*(3), 411–424.
Livers, B., N. Lininger, N. Kramer, and E. Wohl (2015), Porosity problems, *Proceedings of the Wood in World Rivers Conference*, Padova, Italy, July 2015.
Lucía, A., A. Antonello, D. Campana, M. Cavalli, S. Crema, S. Franceschi, E. Marchese, M. Niedrist, S. Schneiderbauer, and F. Comiti (2014a), Monitoring and modeling large wood transport in a mountain basin of north-eastern Italy, in *Engineering Geology for Society and Territory-River Basins*, vol. 3, edited by G. Lollino et al., pp. 155–158, Springer, Switzerland.
Lucía, A., F. Comiti, M. Borga, M. Cavalli, and L. Marchi (2015), Dynamics of large wood during a flash flood in two mountain catchments, *Nat. Hazards Earth Syst. Sci.*, *3*(2), 1643–1680, doi:10.5194/nhessd-3-1643-2015.
Lucía, F., M. Comiti, M. Borga, and M. Cavalli (2014b), Large wood recruitment and transport during a severe flash flood in north-western Italy, *Eng. Geol. Soc. Terr.*, *3*, 159–162.
Lyn, D. A., T. Cooper, Y. K. Yi, R. N. Sinha, and A. R. Rao (2003), Debris accumulation at bridge crossings, laboratory and field studies, TRB Subject Code: 25-1 Publication No.: FHWA/IN/JTRP-2003/10, SPR-2478.
Lyn, D., T. Cooper, D. Condon, and L. Gan (2007), *Factors in Debris Accumulation at Bridge Piers*, U.S. Department of Transportation, Federal Highway Administration Research and Development, Turner-Fairbank Highway Research Center, Washington.
Máčka, Z., L. Krejčí, B. Loučková, and L. Peterková (2011), A critical review of field techniques employed in the survey of large woody debris in river corridors: A central European perspective, *Environ. Monit. Assess.*, *181*(1-4), 291–316, doi:10.1007/s10661-010-1830-8.
MacVicar, B., and H. Piégay (2012), Implementation and validation of video monitoring for wood budgeting in a wandering piedmont river, the Ain River (France), *Earth Surf. Processes Landforms*, *37*(12), 1272–1289, doi:10.1002/esp.3240.
MacVicar, B. J., A. Henderson, F. Comiti, C. Oberlin, and E. Pecorari (2009), Quantifying the temporal dynamics of wood in large rivers, field trials of wood surveying, dating, tracking, and monitoring techniques, *Earth Surf. Processes Landforms*, *2046*, 2031–2046, doi:10.1002/esp.1888.
MacVicar, B. J., A. Hauet, N. Bergeron, L. Tougne, and I. Ali (2012), River monitoring with ground-based videography. Eds by P. Carbonneau and H. Piégay, *Fluvial Remote Sens. Sci. Manage.*, 367–383.
Mäkipää, R., and T. Linkosalo (2011), A non-destructive field method for measuring wood density of decaying logs, *Silva Fennica*, *45*(5).
Manners, R. B., A. C. Wilcox, L. Kui, A. F. Lightbody, J. C. Stella, and L. S. Sklar (2015), When do plants modify fluvial processes? Plant-hydraulic interactions under variable flow and sediment supply rates, *J. Geophys. Res. Earth Surf.*, *120*, 325–345, doi:10.1002/2014JF003265.
Mao, L., A. Andreoli, F. Comiti, and M. Lenzi (2008), Geomorphic effects of large wood jams on a sub-Antarctic mountain stream, *River Res. Appl.*, *24*, 249–266.
Mao, L., F. Comiti, and M. A. Lenzi (2010), Bedload dynamics in steep mountain rivers: Insights from the Rio Cordon Experimental Station (Italian Alps), in *Bedload-Surrogate Monitoring Technologies*, *Geol. Surv. Sci. Invest. Rep. 2010-5091*, pp. 253–265, U.S. Geol. Surv., Reston, Va.
Mao, L., A. Andreoli, A. Iroumé, F. Comiti, and M. A. Lenzi (2013), Dynamics and management alternatives of in-channel large wood in mountain basins of the southern Andes, *Bosque (Valdivia)*, *34*(3), 15–16, doi:10.4067/S0717-92002013000300008.
Marcus, W. A., and M. A. Fonstad (2008), Optical remote mapping of rivers at sub-meter resolutions and basin extents, *Earth Surf. Processes Landforms*, *33*, 4–24.

Marcus, W. A., R. A. Marston, C. R. Colvard, and R. D. Gray (2002), Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone Ecosystem, USA, *Geomorphology*, *44*(3-4), 323–335, doi:10.1016/S0169-555X(01)00181-7.

Marcus, W. A., C. J. Legleiter, R. J. Aspinall, J. W. Boardman, and R. L. Crabtree (2003), High spatial resolution hyperspectral mapping of in-stream habitats, depths, and woody debris in mountain streams, *Geomorphology*, *55*(1-4), 363–380, doi:10.1016/S0169-555X(03) 00150-8.

Marcus, W. A., J. Rasmussen, and M. A. Fonstad (2011), Response of the fluvial wood system to fire and floods in northern Yellowstone, *Ann. Assoc. Am. Geogr.*, *101*, 22–44.

Marston, R. A. (1982), The geomorphic significance of log steps in forest streams, *Ann. Assoc. Am. Geogr.*, *72*, 99–108.

Marston, R. A., J. Girel, G. Pautou, H. Piégay, J. P. Bravard, and C. Arneson (1995), Channel metamorphosis, floodplain disturbance, and vegetation development, Ain River, France, *Geomorphology*, *13*, 121–131.

Martin, D. J., and L. E. Benda (2001), Patterns of instream wood recruitment and transport at the watershed scale, *Trans. Am. Fish. Soc.*, *130*, 940–958.

Maser, C., R. G. Anderson, K. Cromack Jr., J. T. Williams, and R. E. Martin (1979), Dead and down woody material, in *Wildlife Habitats in Managed Forests: The Blue Mountains of Oregon and Washington*, vol. 553, edited by J. W. Thomas, pp. 78–95, USDA Forest Service Agricultural, Washington, D. C.

Maser, C., R. F. Tarrant, J. M. Trappe, and J. F. Franklin (1988), From the forest to the sea: A story of fallen trees USDA Forest Service, Corvallis, Oregon, *General Tech. Rep.*, PNW-GTR-229.

Mazzorana, B., A. Zischg, A. Largiader, and J. Hubl (2009), Hazard index maps for woody material recruitment and transport in alpine catchments, *Nat. Hazards Earth Syst. Sci.*, *9*, 197–209.

Mazzorana, B., J. Hübl, A. Zischg, and A. Largiader (2011), Modelling woody material transport and deposition in alpine rivers, *Nat. Hazards*, *56*(2), 425–449, doi:10.1007/s11069-009-9492-y.

McHenry, M. L., E. Shott, and R. H. Conrad (1998), Changes in the quantities and characteristics of large woody debris in streams of the Olympic Peninsula, Washington, U.S.A. (1982–1993), *Can. J. Fish. Aquat. Sci.*, *55*, 1395–1407.

McLean, J. P., T. Zhang, S. Bardet, J. Beauchene, A. Thibaut, B. Clair, and B. Thibaut (2011), The decreasing radial wood stiffness pattern of some tropical trees growing in the primary forest is reversed and increases when they are grown in a plantation, *Ann. For. Sci.*, *68*(4), 681–688.

Melillo, J. M., J. D. Aber, and J. F. Muratore (1982), Nitrogen and lignin control of hardwood leaf litter decomposition dynamics, *Ecology*, *63*, 621–626.

Méndez-Alonzo, R., F. Pineda-Garcia, H. Paz, J. A. Rosell, and M. E. Olson (2013), Leaf phenology is associated with soil water availability and xylem traits in a tropical dry forest, *Trees-Struct. Funct.*, *27*(3), 745–754.

Merten, E. C., P. G. Vaz, J. A. Decker-Fritz, J. C. Finlay, and H. G. Stefan (2013), Relative importance of breakage and decay as processes depleting large wood from streams, *Geomorphology*, *190*, 40–47.

Merten, E., J. Finlay, L. Johnson, R. Newman, H. Stefan, and B. Vondracek (2010), Factors influencing wood mobilization in streams, *Water Resour. Res.*, *46*, W10514, doi:10.1029/2009WR008772.

Miller, D., L. Benda, M. Furniss, and M. Penney (2002), Landscape dynamics and forest management: U.S. Forest Service, Rocky Mountain Research Station, *General Tech. Rep.*, RMRS-GTR-101-CD.

Miller, D., C. H. Luce, and L. E. Benda (2003), Time, space, and episodicity of physical disturbance in streams, *For. Ecol. Manage.*, *178*, 121–140.

Millington, C. E., and D. A. Sear (2007), Impacts of river restoration on small-wood dynamics in a low-gradient headwater stream, *Earth Surf. Processes Landforms*, *32*(8), 1204–1218.

Montgomery, D. R., and T. B. Abbe (2006), Influence of logjam-formed hard points on the formation of valley-bottom landforms in an old-growth forest valley, Queets River, Washington, USA, *Quat. Res.*, *65*(1), 147–155.

Montgomery, D. R., B. D. Collins, J. M. Buffington, and T. B. Abbe (2003), Geomorphic effects of wood in rivers, in *The Ecology and Management of Wood in World Rrivers*, edited by S. V. Gregory, K. L. Boyer, and A. M. Gurnell, pp. 21–47, *Am. Fish. Soc.*, Bethesda, MD.

Moore, K., K. Jones, and J. Dambacher (2002), *Methods for Stream Habitat Surveys—Aquatic Inventories Project*, 59 pp., Oregon Department of Fish and Wildlife, Corvallis.

Moulin, B. (2005), Variabilité spatiale et temporelle du bois mort dans le réseau hydrographique de l'Isère à l'amont de Grenoble PhD thesis, Université Jean Monnet-Saint-Etienne.

Moulin, B., and H. Piégay (2004), Characteristics and temporal variability of large woody debris trapped in a reservoir on the river Rhône (Rhône): Implications for river basin management, *River Res. Appl.*, *20*, 79–97.

Murphy, M. L., and K. V. Koski (1989), Input and depletion of woody debris in Alaska streams and implications for streamside management, *N. Am. J. Fish. Manage.*, *9*, 427–436.

Naiman, R. J., E. V. Balian, K. K. Bartz, E. Robert, and J. J. Latterell (2002), Dead wood dynamics in streams, *USDA Forest Service Gen. Tech. Rep.*, PSW-GTR-181.

Nakamura, F., and F. J. Swanson (1994), Distribution of coarse woody debris in a mountain stream, western Cascade Range, Oregon, *Can. J. For. Res.*, *24*, 2395–2403.

Nanson, G. C., M. Barbetti, and G. Taylor (1995), River stabilisation due to changing climate and vegetation during the late Quaternary in western Tasmania, Australia, *Geomorphology*, *13*(1-4), 145–158.

Pagliara, S., and I. Carnacina (2011), Influence of large woody debris on sediment scour at bridge piers, *Int. J. Sediment Res.*, *26*(2), 121–136, doi:10.1016/S1001-6279(11)60081-4.

Pasquale, N., P. Perona, R. Francis, and P. Burlando (2012), Effects of streamflow variability on the vertical root density distribution of willow cutting experiments, *Ecol. Eng.*, *40*, 167–172.

Pecorari, E., F. Comiti, E. Rigon, L. Picco, and M. A. Lenzi (2007), Caratteristiche e quantificazione del legname in alveo in corsi d'acqua di grandi dimensioni: Risultati preliminari sul fiume Piave, *Quaderni di Idronomia Montana*, *27*, 477–488.

Piégay, H., and A. M. Gurnell (1997), Large woody debris and river geomorphological pattern: Examples from S.E. France and S. England, *Geomorphology*, *19*, 99–116.

Piégay, H., and N. Landon (1997), Promoting ecological management of riparian forests on the Drôme River, France, *Aquat. Conserv. Mar. Freshwater Ecosyst.*, *7*, 287–304.

Piégay, H., and R. A. Marston (1998), Distribution of large woody debris along the outer band of meanders in the Ain River, France, *Phys. Geogr.*, *19*, 318–340.

Piégay, H., A. Citterio, and L. Astrade (1998), Ligne de débris ligneux et recoupement de méandres, exemple du site de Mollon sur l'Ain (France), *Zeitzchrift für Geomorphol.*, *42*(2), 187–208.

Piégay, H., A. Thévenet, and A. Citterio (1999), Input storage and distribution of large woody debris along a mountain river continuum, the Drôme River, France, *Catena*, *35*, 13–39.

Piton, G., and A. Recking (2015), Design of sediment traps with open check dams: A review—Part II; woody debris, *J. Hydraul. Eng.*, 1–13, doi:10.1061/(ASCE)HY.1943-7900.0001049.
Platts, W. S., et al. (1987), Methods for evaluating riparian habitats with applications to management, *USDA Forest Service General Tech. Rep., INT-221*.
Pollen, N., A. Simon, and A. Collison (2004), Advances in assessing the mechanical and hydrologic effects of riparian vegetation on streambank stability, in *Riparian Vegetation and Fluvial Geomorphology, Water Science and Application*, edited by S. J. Bennett and A. Simon, pp. 125–139, AGU, Washington, D. C.
Pregitzer, K. S. (2008), Tree root architecture—Form and function, *New Phytol.*, *180*, 562–564.
Pregitzer, K. S., J. L. DeForest, A. J. Burton, M. F. Allen, R. W. Ruess, and R. L. Hendrick (2002), Fine root architecture of nine North American trees, *Ecol. Monogr.*, *72*(2), 293–309.
Rafferty, M. (2013), Development of a computational design tool for evaluating the stability of large wood structures proposed for stream enhancement. M.S. Independent Study, Colorado State University, Fort Collins, Colo. [Available at http://www.engr.colostate.edu/~bbledsoe/streamtools.]
Rango, A., L. A. Aliberte, C. Steele, J. E. Herrick, B. Bestelmeyer, T. Schmugge, A. Roanhorse, and V. Jenkins (2006), Using unmanned aerial vehicles for range-lands: Current applications and future potentials, *Environ. Pract.*, *8*, 159–168.
Ravazzolo, D., L. Mao, B. Garniga, L. Picco, and M. A. Lenzi (2013), Displacement length and velocity of tagged logs in the Tagliamento river, *J. Agric. Eng.*, *44*, 10.
Ravazzolo, D., L. Picco, L. Mao, and M. A. Lenzi (2015a), Instantaneous movements of logs during floods in the Piave River, *Proceedings of the Wood in World Rivers Conference*, Padova, Italy, July 2015.
Ravazzolo, D., L. Mao, L. Picco, and M. A. Lenzi (2015b), Tracking log displacement during floods in the Tagliamento River using RFID and GPS tracker devices, *Geomorphology*, *228*, 226–233, doi:10.1016/j.geomorph.2014.09.012.
Reeves, G. H., K. M. Burnett, and E. V. McGarry (2003), Sources of large wood in the main stem of a fourth-order watershed in coastal Oregon, *Can. J. For. Res.*, *33*(8), 1363–1370.
Reeves, G. H., P. A. Bisson, B. E. Rieman, and L. E. Benda (2006), Postfire logging in riparian areas, *Conserv. Biol.*, *20*(4), 994–1004.
Richmond, A. D., and K. D. Fausch (1995), Characteristics and function of large woody debris in subalpine Rocky Mountain streams in northern Colorado, *Can. J. Fish. Aquat. Sci.*, *52*, 1789–1802.
Rickenmann, D. (1997), Schwemmholz und Hochwasser, *Wasser, Energy, Luft*, *89*, 115–119.
Rickli, C. (2009), Schwemmholz in Wildbächen, Fachleute Naturgefahren Schweiz, Herbstkurs 2009 Wildbacheinzugsgebiete.
Rickli, C., and H. Bucher (2006), Einfluss ufernaher Bestockungen auf das Schwemmholzvorkommen in Wildbächen, Projektbericht Dezember 2006, WSL Publ.
Rigon, E., F. Comiti, and M. A. Lenzi (2012), Large wood storage in streams of the Eastern Italian Alps and the relevance of hillslope processes, *Water Resour. Res.*, *48*, W01518, doi:10.1029/2010WR009854.
Rimböck, A. (2003), Schwemmholzrückhalt in Wildbächen – Grundlagen zu Planung und Berechnung von Seilnetzsperren; Berichte des Lehrstuhl und der Versuchsanstalt für Wasserbau und Wasserwirtschaft Nr. 94.
Rimböck, A., and T. Strobl (2002), *Loads on Rope Net Constructions for Woody Debris Entrapment in Torrents*, vol. 2, pp. 797–807, Intl. Congress Interpraevent Congress Publ., Matsumoto, Japan.
Rudolf-Miklau, F., and J. Hübl (2010), *Managing Risks Related to Drift Wood (woody debris)*, pp. 868–878, Intl. Congress Interpraevent Congress Publ., Taipei, Taiwan.
Ruffing, C. M., M. D. Daniels, and K. A. Dwire (2015), Disturbance legacies of historic tie-drives persistently alter geomorphology and large wood characteristics in headwater streams, southeast Wyoming, *Geomorphology*, *231*, 1–14.
Ruiz-Villanueva, V., J. M. Bodoque, A. Díez-Herrero, M. A. Eguibar, and E. Pardo-Igúzquiza (2013), Reconstruction of a flash flood with large wood transport and its influence on hazard patterns in an ungauged mountain basin, *Hydrol. Processes*, *27*, 3424–3437, doi:10.1002/hyp.9433.
Ruiz-Villanueva, V., A. Díez-Herrero, J. A. Ballesteros, and J. M. Bodoque (2014a), Potential large woody debris recruitment due to landslides, bank erosion and floods in mountain basins: A quantitative estimation approach, *River Res. Appl.*, *97*, 81–97, doi:10.1002/rra.2614.
Ruiz-Villanueva, V., E. Bladé, M. Sánchez-Juny, B. Marti-Cardona, A. Díez-Herrero, and J. M. Bodoque (2014b), Two-dimensional numerical modeling of wood transport, *J. Hydroinfo.*, *16*(5), 1077, doi:10.2166/hydro.2014.026.
Ruiz-Villanueva, V., J. M. Bodoque, A. Díez-Herrero, and E. Bladé (2014c), Large wood transport as significant influence on flood risk in a mountain village, *Nat. Hazards*, *74*(2), 967–987, doi:10.1007/s11069-014-1222-4.
Ruiz-Villanueva, V., B. Wyżga, J. Zawiejska, M. Hajdukiewicz, and M. Stoffel (2015), Factors controlling large-wood transport in a mountain river, *Geomorphology*, doi:10.1016/j.geomorph.2015.04.004.
Ruiz-Villanueva, V., B. Wyżga, P. Mikuś, H. Hajdukiewicz, and M. Stoffel (2016a), The role of flood hydrograph in the remobilization of large wood in a wide mountain river, *J. Hydrol.*, doi:10.1016/j.jhydrol.2016.02.060.
Ruiz-Villanueva, V., B. Wyżga, H. Hajdukiewicz, and M. Stoffel (2016b), Exploring large wood retention and deposition in contrasting river morphologies linking numerical modelling and field observations, *Earth Surf. Processes Landforms*, doi:10.1002/esp.3832.
Ruiz-Villanueva, V., H. Piégay, V. Gaertner, F. Perret, and M. Stoffel (2016c), Wood density and moisture sorption and its influence on large wood mobility in rivers, *Catena*, *140*, 182–194, doi:10.1016/j.catena.2016.02.001.
Ryan, S. E., E. L. Bishop, and J. M. Daniels (2014), Influence of large wood on channel morphology and sediment storage in headwater mountain streams, Fraser Experimental Forest, Colorado, *Geomorphology*, *217*, 73–88.
Schenk, E. R., B. Moulin, C. R. Hupp, and J. M. Richter (2014), Large wood budget and transport dynamics on a large river using radio telemetry, *Earth Surf. Processes Landforms*, *39*(4), 487–498, doi:10.1002/esp.3463.
Scherer, R. (2004), Decomposition and longevity of instream woody debris: A review of literature from North America, in *Forest Land Fish Conference II Ecosystem Stewardship Through Collaboration*, *Proceedings Forest -Land-Fish Conf. II*, edited by G. J. Scrimgeour et al., pp. 127–133, Edmonton, Alberta.
Schmocker, L., and W. H. Hager (2010), Drift accumulation at river bridges, in *River Flow*, edited by A. Dittrich et al., Bundesanstalt für Wasserbau, Karlsrule.
Schmocker, L., and W. H. Hager (2013), Scale modeling of wooden debris accumulation at a debris rack, *J. Hydraul. Eng.*, *139*(8), 827–836, doi:10.1061/(ASCE)HY.1943-7900.0000714.
Schmocker, L., and V. Weitbrecht (2013), Driftwood, risk analysis and engineering measures, *J. Hydraul. Eng.*, 683–695, doi:10.1061/(ASCE)HY.1943-7900.0000728.
Sear, D. A., C. E. Millington, D. R. Kitts, and R. Jeffries (2010), Logjam controls on channel: Floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns, *Geomorphology*, *116*(3–4), 305–319, doi:10.1016/j.geomorph.2009.11.022.

Sedell, J. R., and J. L. Froggatt (1984), Importance of streamside forests to large rivers: The isolation of the Willammette River, Oregon, U.S.A., from its floodplain by snagging and streamside forest removal, *Int. Ver. Theor. Angew. Limnol.*, *22*, 1828–1834.

Sedell, J. R., P. A. Bisson, and F. J. Swanson (1988), What we know about large trees that fall into streams and rivers, in *From the Forest to the Sea: A Story of Fallen Trees*, *USDA Forest Service General Tech. Rep., PNW-229*, edited by C. Maser et al., pp. 47–82, Pacific Northwest Research Station, U.S. Forest Service, Portland, Oregon.

Seo, J. I., and F. Nakamura (2009), Scale-dependent controls upon the fluvial export of large wood from river catchments, *Earth Surf. Process. Landforms*, *34*(6), 786–800.

Seo, J. I., F. Nakamura, D. Nakano, H. Ichiyanagi, and K. W. Chun (2008), Factors controlling the fluvial export of large woody debris, and its contribution to organic carbon budgets at watershed scales, *Water Resour. Res.*, *44*, W04428, doi:10.1029/2007WR006453.

Seo, J. I., F. Nakamura, and K. W. Chun (2010), Dynamics of large wood at the watershed scale: A perspective on current research limits and future directions, *Landscape Ecol. Eng.*, *6*, 271–287, doi:10.1007/s11355-010-0106-3.

Shields, F. D., Jr., and C. J. Gippel (1995), Prediction of effects of woody debris removal on flow resistance, *J. Hydraul. Eng.*, *121*(4), 341–354.

Shields, F. D., Jr., and R. H. Smith (1992), Effects of large woody debris removal on physical characteristics of a sand-bed river, *Aquat. Conserv. Mar. Freshwater Ecosyst.*, *2*, 145–63.

Shields, F. D., Jr., S. S. Knight, C. M. Cooper, and S. Testa (2000), Large woody debris structures for incised channel rehabilitation, in *Proceedings of ASCE 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management*, ASCE, Reston VA.

Shields, F. D., Jr., N. Morin, and C. M. Cooper (2004), Large woody debris structures for sand-bed channels, *ASCE J. Hydraul. Eng.*, *130*(3), 208–216.

Shmulsky, R., and P. D. Jones (2011), *Forest Product and Wood Sources: An Introduction*, 6th ed., Wiley Blackwell, U. K.

Simon, A., and A. J. C. Collison (2002), Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability, *Earth Surf. Processes Landforms*, *27*(5), 527–546.

Smikrud, K. M., and A. Prakash (2006), Monitoring large woody debris dynamics in the Unuk River, Alaska using digital aerial photography, *GISci. Remote Sens.*, *43*(2), 142–154.

Spänhoff, B., and E. I. Meyer (2004), Breakdown rates of wood in streams, *J. N. Am. Benthol. Soc.*, *23*, 189–197.

Steeb, N., D. Rickenmann, A. Badoux, C. Rickli, and P. Waldner, (2016), Large wood recruitment processes and transported volumes in Swiss mountain streams during the extreme flood of August 2005, *Geomorphology*, (August 2005). http://doi.org/10.1016/j.geomorph.2016.10.011.

Stoffel, M., M. Bollschweiler, D. R. Butler, and B. H. Luckman (2010), *Tree Rings and Natural Hazards: A State-of-the-Art*, 505 pp., Springer, Berlin.

Swanson, F. J. (2003), Wood in rivers: A landscape perspective, *Am. Fish. Symp.*, *37*, 299–313.

Swanson, F. J., and G. W. Lienkaemper (1978), Physical consequences of large organic debris in Pacific Northwest streams, *USDA Forest Service General Tech. Rep., PNW-69*.

Swanson, F. J., M. D. Bryant, G. W. Lienkaemper, and J. R. Sedell (1984), Organic debris in small streams, Prince of Wales Island, Southeast Alaska, *USDA Forest Service General Tech. Rep., PNW-166*.

Swanston, D. N., and F. J. Swanson (1976), Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest, in *Geomorphology and Engineering*, edited by D. R. Coates, pp. 199–221, Dowden, Hutchinson, and Ross. Inc, Stroudsburg, Pennsylvania.

Tabacchi, E., and A. M. Planty-Tabacchi (2003), Recent changes in riparian vegetation: Possible consequences on dead wood processing along rivers, *River Res. Appl.*, *19*(3), 251–263.

Tal, M., and C. Paola (2010), Effects of vegetation on channel morphodynamics: Results and insights from laboratory experiments, *Earth Surf. Processes Landforms*, *35*, 1014–1028.

Thévenet, A., A. Citterio, and H. Piégay (1998), A new methodology for the assessment of large woody debris accumulations on highly modified rivers (example of two French piedmont rivers), *Regulat. Rivers*, *14*, 467–483.

Tonon, A., L. Picco, D. Ravazzolo, and M. A. Lenzi (2014), Using a terrestrial laser scanner to detect wood characteristics in gravel-bed rivers, *J. Agric. Eng.*, *45*(4), 161–167.

Triska, F. J. (1984), Role of woody debris in modifying channel geomorphology and riparian areas of a large lowland river under pristine conditions: A historical case study, *Int. Ver. Theor. Angew. Limnol.*, *22*, 1876–1892.

Turowski, J. M., A. Badoux, K. Bunte, C. Rickli, N. Federspiel, and M. Jochner (2013), The mass distribution of coarse particulate organic matter exported from an Alpine headwater stream, *Earth Surf. Dyn.*, *1*, 1–11.

Uchiogi, T., J. Shima, H. Tajima, and Y. Ishikawa (1996), Design methods for wood-debris entrapment, *Proc. Int. Symp. Interpraevent Garmisch Partenkirchen*, *5*, 279–288.

Ulloa, H., A. Iroumé, L. Mao, A. Andreoli, S. Diez, and L. E. Lara (2015), Use of remote imagery to analyse changes in morphology and longitudinal large wood distribution in the Blanco River after the 2008 Chaitén volcanic eruption, southern Chile, *Geogr. Ann.*, *1*, –19, doi:10.1111/geoa.12091.

van Der Nat, D., K. Tockner, P. J. Edwards, and J. V. Ward (2003), Large wood dynamics of complex Alpine river floodplains, *J. N. Am. Benthol. Soc.*, *22*(1), 35–50.

Van Dijk, A. I. J. M., H. E. Beck, R. S. Crosbie, R. A. M. de Jeu, Y. Y. Liu, G. M. Podger, B. Timbal, and N. R. Viney (2013), The millennium drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy and society, *Water Resour. Res.*, *49*, 2729–2746, doi:10.1002/wrcr.20123.

Västilä, K., and J. Järvelä (2014), Modeling the flow resistance of woody vegetation using physically based properties of the foliage and stem, *Water Resour. Res.*, *50*, 229–245, doi:10.1002/2013WR013819.

Västilä, K., J. Järvelä, and J. Aberle (2013), Characteristic reference areas for estimating flow resistance of natural foliated vegetation, *J. Hydrol.*, *492*, 49–60.

Vaz, P. G., E. C. Merten, D. R. Warren, C. T. Robinson, P. Pinto, and F. C. Rego (2013), Which stream wood becomes functional following wildfires?, *Ecol. Eng.*, *54*, 82–89, doi:10.1016/j.ecoleng.2013.01.009.

Veblen, T. T. (1986), Age and size structure of subalpine forests in the Colorado Front Range, *Bull. Torrey Bot. Club*, *113*, 225–240.

Waldner, P., C. Rickli, D. Köchlin, T. Usbeck, L. Schmocker, and F. Sutter (2007), Schwemmholz. Ereignisanalyse Hochwasser 2005 – Teil 1: Prozes se, Schäden und erste Einordnung (in German). Bundesamt für Umwelt BAFU, Eidgenössische Fors chungsanstalt, in *Umwelt-Wissen*, vol. 0825, edited by W. S. L. G. R. Bezzola and C. Hegg, pp. 181–193, Bundesamt für Umwelt BAFU, Bern, Switzerland.

Wallace, J. B., and A. C. Benke (1984), Quantification of wood habitat in subtropical coastal plain streams, *Can. J. Fish. Aquat. Sci.*, *41*, 1643–1652.

Wallerstein, N. P., and C. R. Thorne (1996), Debris control at hydraulic structures in USA and Europe, US Army Corps of Engineers, Contract Report CHL-97-4. [Available at http://chl.erdc.usace.army.mil/%5CMedia%5C7%5C5%5C6%5CCHL-CR-97-4.pdf.]

Warren, D. R., and C. E. Kraft (2008), Dynamics of large wood in an eastern U.S. mountain stream, *For. Ecol. Manage.*, *256*, 808–814.

Webb, A. A., and W. D. Erskine (2003), Distribution, recruitment, and geomorphic significance of large woody debris in an alluvial forest stream, Tonghi Creek, southeastern Australia, *Geomorphology*, *51*, 109–26.

Welber, M. (2013), Morphodynamics and driftwood dispersal in braided rivers. PhD Thesis, University of Trento, Italy, Department of Civil, Environmental and Mechanical Engineering.
Welber, M., W. Bertoldi, and M. Tubino (2013), Wood dispersal in braided streams: Results from physical modeling, *Water Resour. Res.*, *49*, 7388–7400, doi:10.1002/2013WR014046.
Wilcox, A. C., and E. Wohl (2006), Flow resistance dynamics in step-pool stream channels: 1. Large woody debris and controls on total resistance, *Water Resour. Res.*, *42*, W05418, doi:10.1029/2005WR004277.
Wohl, E. (2011), Threshold-induced complex behavior of wood in mountain streams, *Geology*, *39*(6), 587–590, doi:10.1130/G32105.1.
Wohl, E. (2013), Floodplains and wood, *Earth Sci. Rev.*, *123*, 194–212.
Wohl, E. (2014), A legacy of absence: Wood removal in U.S. rivers, *Prog. Phys. Geogr.*, *38*(5), 637–663, doi:10.1177/0309133314548091.
Wohl, E., and D. Cadol (2011), Neighborhood matters, patterns and controls on wood distribution in old-growth forest streams of the Colorado Front Range, USA, *Geomorphology*, *125*(1), 132–146, doi:10.1016/j.geomorph.2010.09.008.
Wohl, E., and J. R. Goode (2008), Wood dynamics in headwater streams of the Colorado Rocky Mountains, *Water Resour. Res.*, *44*, W09429, doi:10.1029/2007WR006522.
Wohl, E., and K. Jaeger (2009), A conceptual model for the longitudinal distribution of wood in mountain streams, *Earth Surf. Processes Landforms*, *34*(3), 329–344, doi:10.1002/esp.1722.
Wohl, E., and D. N. Scott (2016), Wood and sediment storage and dynamics in river corridors, *Earth Surf. Processes Landforms*, doi:10.1002/esp.3909.
Wohl, E., F. L. Ogden, and J. Goode (2009), Episodic wood loading in a mountainous neotropical watershed, *Geomorphology*, *111*(3-4), 149–159, doi:10.1016/j.geomorph.2009.04.013.
Wohl, E., D. A. Cenderelli, K. A. Dwire, S. E. Ryan-Burkett, M. K. Young, and K. D. Fausch (2010), Large in-stream wood studies: A call for common metrics, *Earth Surf. Processes Landforms*, *625*, doi:10.1002/esp.1966.
Wohl, E., S. Bolton, D. Cadol, F. Comiti, J. R. Goode, and L. Mao (2012), A two end-member model of wood dynamics in headwater neotropical rivers, *J. Hydrol.*, *462-463*, 67–76, doi:10.1016/j.jhydrol.2011.01.061.
Wohl, E., B. P. Bledsoe, K. D. Fausch, N. Kramer, K. R. Bestgen, and M. N. Gooseff (2016), Management of large wood in streams: An overview and proposed framework for hazard evaluation, *Am. Water Resour. Assoc.*, *52*(2), 315–335.
Wyzga, B., and J. Zawiejska (2005), Wood storage in a wide mountain river: Case study of the Czarny Dunajec, Polish Carpathians, *Earth Surf. Processes Landforms*, *1494*, 1475–1494, doi:10.1002/esp.1204.
Wyżga, B., and J. Zawiejska (2010), Large wood storage in channelized and unmanaged sections of the Czarny Dunajec River, Polish Carpathians: Implications for the restoration of mountain rivers, *Folia Geogr.*, *XLI*, 5–34.
Wyzga, B., J. Zawiejska, P. Mikus, and R. J. Kaczka (2015), Contrasting patterns of wood storage in mountain watercourses narrower and wider than the height of riparian trees, *Geomorphology*, *228*, 275–285.
Young, M. K., D. Haire, and M. A. Bozek (1994), The effect and extent of railroad tie drives in streams of southeastern Wyoming, *Western J. Appl. For.*, *9*, 125–130.
Young, W. (1991), Flume study of the hydraulic effects of large woody debris in lowland rivers, *Regul. Rivers Res. Manage.*, *6*, 203–211.
Zabel, R. A., and J. J. Morrell (1992), *Wood Microbiology*, Academic, New York.
Zanoni, L., A. M. Gurnell, N. Drake, and N. Surian (2008), Island dynamics in a braided river from an analysis of historical maps and air photographs, *River Res. Appl.*, *24*, 1141–1159.

Erratum

In the originally published version of this article, there were errors that affected authorship as well as the manuscript's reference section.

Co-author Angela Gurnell's name should have been printed as Angela M. Gurnell.

The following reference was cited in text but was omitted from the reference list: Steeb, N., Rickenmann, D., Badoux, A., Rickli, C., & Waldner, P. (2016). Large wood recruitment processes and transported volumes in Swiss mountain streams during the extreme flood of August 2005. *Geomorphology* (August 2005), doi:10.1016/j.geomorph.2016.10.011.

The following references were originally published incorrectly: Harmon M.E., Franklin J.F., Swanson F.J., Sollins P., Gregory S.V., Lattin J.D., Anderson N.H., Cline S.P., Aumen N.G., Sedell J.R., Lienkaemper G.W., Cromack K., Cummins K.W. (1986), Ecology of coarse woody debris in temperate ecosystems. *Adv. Ecol. Res.* 15: 133–302. Ravazzolo, D., L. Picco, L. Mao, and M. A. Lenzi (2015a), Instantaneous movements of logs during floods in the Piave River, *Proceedings of the Wood in World Rivers Conference*, Padova, Italy, July 2015.

These errors have since been corrected, and this version may be considered the authoritative version of record.