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Rules of the road: A qualitative and quantitative synthesis of large wood transport through drainage networks

Natalie Kramer *, Ellen Wohl *

Dept of Geosciences, Colorado State University, Fort Collins, CO 80123, United States

A R T I C L E I N F O

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A B S T R A C T

To effectively manage wood in rivers, we need a better understanding of wood mobility within river networks. Here, we review primarily field-based (and some numerical) studies of wood transport. We distinguish small, medium, large, and great rivers based on wood piece dimensions relative to channel and flow dimensions and dominant controls on wood transport. We suggest further identification and designation of wood transport regimes as a useful way to characterize spatial-temporal network heterogeneity and to conceptualize the primary controls on wood mobility in diverse river segments. We draw analogies between wood and bedload transport, including distinguishing Eulerian and Lagrangian approaches, exploring transport capacity, and quantifying thresholds of wood mobility. We identify mobility envelopes for remobilization of wood with relation to increasing peak discharges, stream size, and dimensionless log lengths. Wood transport in natural channels exhibits high spatial and temporal variability, with discontinuities along the channel network at bankfull flow and when log lengths equal channel widths. Although median mobilization rates increase with increasing channel size, maximum mobilization rates are greatest in medium-sized channels. Most wood is transported during relatively infrequent high flows, but flows under bankfull can transport up to 30% of stored wood. We use conceptual models of dynamic equilibrium of wood in storage and of spiralling wood transport paths through drainage networks, as well as a metaphor of traffic on a road, to explore discontinuous wood movement through a river network. The primary limitations to describing wood transport are inappropriate time scales of observation and lack of sufficient data on mobility from diverse rivers. Improving models of wood flux requires better characterization of average step lengths within the lifetime travel path of a piece of wood. We suggest that future studies focus on: (i) continuous or high-frequency monitoring of wood mobility; (ii) monitoring changes in wood storage; (iii) using wood characteristics to fingerprint wood sources; (iv) quantifying volumes of wood buried within river corridors; (v) obtaining existing or new data from unconventional sources, such as citizen science initiatives, and (vi) creating online interactive data platforms to facilitate data synthesis.

1. Motivation

The need is strong to understand large wood transport dynamics in the context of flooding hazards (e.g., Mazzorana et al., 2012; Ruiz-Villanueva et al., 2013, 2014a; Lucía et al., 2015) and global nutrient fluxes (Bilby, 1981; Elosegi et al., 2007; Hilton et al., 2008; West et al., 2011; Wohl et al., 2012). By wood dynamics, we mean the processes associated with the recruitment, storage, and transfer of dead wood through drainage basins. Specifically, we focus on the transport of large wood (≥1 m in length and 10 cm in diameter).

Conceptual and quantitative models of river adjustment typically rely on two primary driving variables, water and sediment (Knighton, 1998). However, instream wood can be as important for channel change as sediment (e.g., Massong and Montgomery, 2000; Brooks and Brierley, 2002; Montgomery and Abbe, 2006; Le Lay et al., 2013). Early scientific and historical writings on wood were mainly inspired by awed observations of immense volumes of wood and associated channel change (Kindle, 1919; Kindle, 1921; Bevan, 1948; Triska, 1984). Reviews of historical accounts document the enormous quantities and landscape-scale impacts of wood from headwater channels to large rivers prior to extensive wood removal (Triska, 1984; Sedell et al., 1988; Wohl, 2014a) and most forested or historically forested catchments have vegetation- or wood-driven morphologies (Hickin, 1984; Collins et al., 2012; Gibling and Davies, 2012; Polvi and Wohl, 2013; Gurnell et al., 2015).

Despite this evidence for the importance of wood as a driving geomorphic variable, descriptions of geomorphic effects of wood on channel processes were largely absent in the mid-1900s (Hickin, 1984), when researchers were building foundational conceptual models (Grant et al., 2013; Wohl, 2014b) - such as graded rivers (Mackin,

* Corresponding authors.
E-mail addresses: n.kramer.anderson@gmail.com (N. Kramer), Ellen.Wohl@colostate.edu (E. Wohl).

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1948) and Lanes balance (Lane, 1955), and quantitative understanding of river systems - such as hydraulic geometry relations (Leopold and Maddock, 1953). The large-scale removal of wood from rivers during the 20th century (Montgomery and Piégay, 2003; Wohl, 2014a) likely led to a neglect of the geomorphic effects of wood on river process and form during this formative period of fluvial geomorphology.

As long as rivers are wood-depleted, models of river form adjusting primarily to sediment and water are adequate for managing rivers. However, in order to improve valued ecosystem services such as de-nitrification, sustainable fisheries, improved water quality, and enhanced physical and mental health of human communities (e.g., Wohl et al., 2015), managers now focus on reintroducing wood as engineered structures (Abbe and Brooks, 2011; Gallisdorfer et al., 2014), leaving mobile un-engineered wood in place on the floodplain (Piégay et al., 2005; Wohl et al., 2015), and managing riparian forests to increase the amount of wood that can be recruited (Kail et al., 2007; Wohl et al., 2015).

In Europe, afforestation of river corridors (Liébault and Piégay, 2002) has led to increased wood in transport, resulting in wood impoundments against bridge piers during floods (e.g., Lucía et al., 2015), increasing flood levels, and forcing large-scale channel changes beyond what can be predicted through existing models (Piégay et al., 2005; Ruiz-Villanueva et al., 2014b). Inability to plan for the impacts and hazards of large wood on channels is a management concern and stems largely from the fact that current models of river form and process used by managers do not include wood dynamics.

In the past few years, substantial progress in numerical simulation of wood transport has come from flume studies (Bertoldi et al., 2014; Davidson et al., 2015) and incorporation of wood modules into computer simulations, such as the *reach scale channel simulator* for habitat modelling (Eaton et al., 2012; Davidson and Eaton, 2015) and *iber wood* for hydrodynamic modelling of wood transport (Ruiz-Villanueva et al., 2014a, 2015c). Simulations from these models have led to better understanding of wood-related flooding hazards, channel change, and aquatic habitat. However, models are simplified versions of the complex interactions found in the field and they require information from field studies to constrain variables and assess reliability of scenario responses (Ruiz-Villanueva et al., 2015b). Recent rapid growth in numerical and modelling publications on wood transport is not matched by equivalent growth in field studies (Fig. 1).

In this paper, we first qualitatively and then quantitatively summarize, analyze, and synthesize literature on wood transport within the framework of a functional classification of small, medium, large, and great rivers (Table 1, Fig. 2). We focus on presenting a thorough review of case studies that have directly measured wood transport. We examine existing transport premises, present new conceptual frameworks

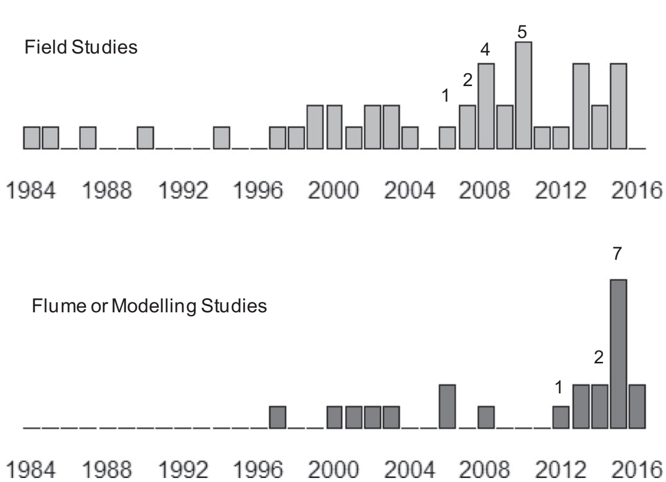

Fig. 1. Comparison of field and modelling publications that report direct measurement of wood transport by year. Bar heights equal total number of articles found.

Table 1
Functional classification of river size based on wood dynamics. Categorization based on characteristic dimensions of wood pieces relative to channel size and patterns of recruitment, storage, and transport of wood, after Keller and Swanson (1979), Church (1992), Nakamura and Swanson (1993), Piégay and Gurnell (1997), Gurnell et al. (2002), and Wohl (2016, this issue).

Small rivers	
Size	1st to 2nd order; key piece wood length > channel width; diameter of logs > flow depth
Recruitment	Characteristics of riparian woodland of overriding importance; hillslope instability, blowdown, snow avalanches, individual riparian tree mortality
Storage	Individual wood pieces form stable features that control sediment deposition, channel morphology, and gradient; pieces typically span and are suspended above the active channel; jams may be present, but most wood stored as individual pieces; distribution of wood close to random and governed by sites of input; wood causes local widening where channel boundaries are erodible; wood condition depends on input mechanisms and forest disturbance history; low mobility can result in high levels of wood decay
Transport	Wood not reorganized or transported except during unusual floods or debris flows with recurrence intervals > decadal; large pieces mostly immobile; long residence times regulated by decay and physical breakdown rather than fluvial transport
Medium rivers	
Size	2nd to 4th order; log diameter ~ flow depth; length of key logs > or ~ channel width
Recruitment	Hillslope, riparian, and bank source areas; tributary inputs; transport from upstream
Storage	Wood commonly stored in non-random, spatially discontinuous jams that partly or completely span the channel; jams comprised of mixed sizes of wood pieces, with larger key pieces trapping smaller, more mobile pieces; jams form at roughness elements such as boulders and planform irregularities; jams force bank erosion and avulsion, can create multithread planform; high inter-reach variation in wood loads; wood regulates sediment transport
Transport	Hydrologic regime is dominant control; drives periodic transport of stored and newly recruited pieces during high flows; key pieces and jams remain in place during smaller floods, accumulating smaller pieces; larger, more infrequent floods break up and rearrange jams
Large rivers	
Size	≥5th order; log diameter ≪ depth of flooded channel; all wood lengths < channel width; transition between medium and large rivers at channel widths ~20–50 m wide because longest wood piece lengths are in this range
Recruitment	Transport of wood from upstream, lateral channel erosion; exhumation of previously buried wood on floodplains
Storage	River morphology dictates wood storage sites; wood generally has less decay because of greater mobility; wood influences bar and channel sedimentation and regulates formation of secondary channels, channel planform, and widening of valley floor; reaches with greater sinuosity, more bars, and lower gradients typically have higher wood loads; wood accumulates within active channel at sites such as apex of bars, outer upstream facing margins of channel bends, backwaters, bank benches, and as individual pieces along channel margins during flood recession; large proportion of wood may be buried in floodplains and channel bars; wood accumulates on upstream side of living vegetation and influences morphologic evolution of stable vegetated islands and formation of multithread planform; wood does not form channel spanning jams, but can form channel spanning, dynamic wood rafts that persist for decades and cause channel avulsions
Transport	Wood exported downstream, laterally onto floodplains, or buried; wood exported regularly during high flow; amount of wood transfer highly variable and largely dependent on pattern of antecedent peak flows; high variability in water levels during flooding creates many opportunities for wood sequestration in long-term storage on the floodplain, causing large variability in wood residence time
Great rivers[a]	
Size	~10^6 km^2 or larger; mean annual discharge > 10^3 m^3/s; perennial flow; commonly have vast, seasonally inundated floodplains, great hydraulic diversity, large fine sediment loads, and deep channels
Recruitment	Mostly via inputs from upstream; local inputs include lateral exchange with floodplain, exhumation of buried wood, inputs from

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Table 1 (*continued*)

Small rivers	
	bank failures, and mass recruitment such as during hurricanes (Phillips and Park, 2009)
Storage	Pieces stranded along banks during receding flows; larger wood loads downstream from tributary junctions that deliver wood; floodplain accumulations at long lateral distances from channel; accumulations commonly decay in place or are partly buried; rafts that completely plug the channel are rare except where a multithread planform occurs
Transport	During most flows, rapid transfer of wood to deposition zones such as deltas, estuaries, or the ocean; lesser rapid fluctuations in discharge stage than large rivers create fewer opportunities for trapping of wood within channel or overbank deposition; wood transfer largely controlled by the spatial distribution and timing of wood recruitment from large tributaries; floodplain wood likely transported and redeposited within the floodplain rather than retransported to main channel; wood buried within channel bed may be transported downstream annually as part of the bed load

[a] Very little study has been done on wood in great rivers. This summary is based on our current understanding of wood dynamics in great rivers from personal field experience. The ideas presented should be tested and refined with further study.

of wood transport through drainage networks, and make suggestions for avenues of further research.

Although other reviews have included wood transport as a subcategory (Keller and Swanson, 1979; Harmon et al., 1986; Sedell et al., 1988; Gurnell, 2003; Le Lay et al., 2013; Wohl, 2016), this is the first review of which we are aware that focuses solely on transport. We intend the review to be a thorough summary to acquaint new wood researchers with the existing literature; a compilation of field-based constraints to compare to future numerical models; and as a collection of thought-provoking ideas intended to push researchers to develop new, testable hypotheses, thus rapidly advancing wood transport research.

2. Qualitative summary

Wood in storage is commonly referred to as *instream wood*. However, once wood becomes mobile, especially in larger channels, researchers tend to prefer the terms *floating wood* (e.g., MacVicar and Piégay, 2012; Ruiz-Villanueva et al., 2014b) or *drift wood* (e.g., Schmocker and Hager, 2011; Kramer and Wohl, 2014). Denoting wood as floating or drift (rather than instream) makes sense in the context of the transfer of wood through drainage networks, especially when wood is referenced along channels and in nonchannelized settings such as lakes, estuaries, or oceans (e.g., Kramer and Wohl, 2015).

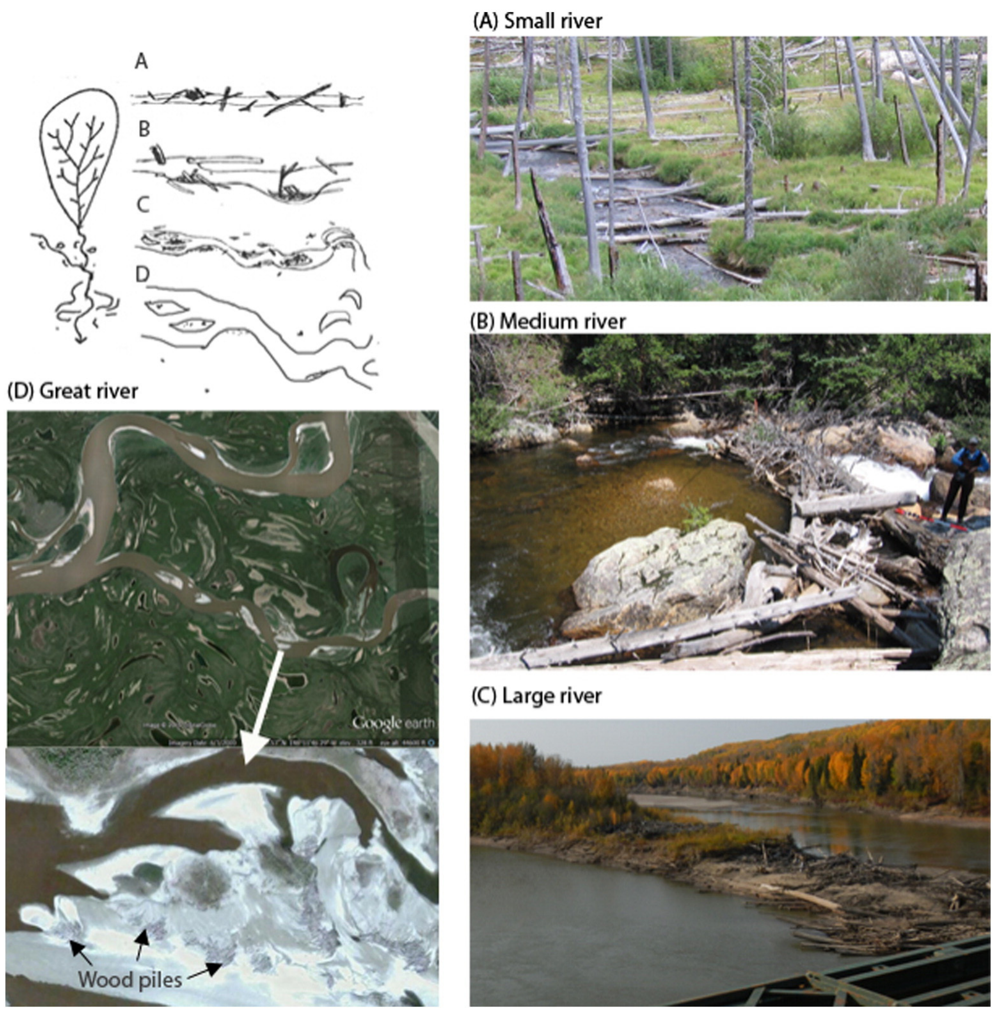

Fig. 2. Stream size with relation to wood storage patterns in a fluvial system. Schematic after Naiman et al. (2002), Keller and Swanson (1979), Le Lay et al. (2013), and Schumm (1977). (A) Random distribution of pieces on Ouzel Creek, Colorado, through a burned area (~6 m channel width, average piece length is 2.7 m with maximum pieces > width of channel). (B) Log jamming on North St. Vrain Creek, Colorado (~25 m channel width and average piece length is 3.3 m, maximum piece size < channel width). (C) Wood accumulations and vegetated island formation in Hyland River, British Columbia (channel width is ~100 m wide). (D) Burial of wood accumulations on side bars of the Yukon River, Alaska (~500 m channel width at 66.18510 N, −148.11925 E).

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Wood flux is governed by the unique interactions among hydraulics, wood pieces, and channel morphology, across space and time (Gurnell et al., 2015; Ruiz-Villanueva et al., 2015c). Thus, we summarize the existing knowledge of wood transport from field and numerical studies in three categories: flow characteristics (Section 2.1, Table 2), wood characteristics (Section 2.2, Table 3), and reach characteristics (Section 2.3, Table 4). Tables 2–4 are used to summarize the literature. In the following text, we propose a series of ideas, hypotheses, and suggested future research directions based on the findings from the papers presented in Tables 2–4. We summarize some of the main hypotheses presented in the following text in Table 5.

2.1. Flow characteristics

The primary flow characteristics that influence wood mobilization and transport include general shape of the hydrograph magnitude, duration, and rate of rise and fall and the sequence of flows through time (Table 2). Flow magnitude influences the areas inundated and the hydraulic roughness and retention capacity of the flooded area. Although wood discharge generally increases with water discharge on the rising limb, the relationship is nonlinear and highly variable (MacVicar and Piégay, 2012; Kramer and Wohl, 2014; Ruiz-Villanueva et al., 2014a; Ravazzolo et al., 2015b). This is logical, given the potential for multiple and complex interactions among piece size and shape, hydraulic forces, and channel characteristics such as boundary irregularities that can trap wood.

The rate of discharge increase may be important for estimating wood transport rates, and rapid changes in the hydrograph may account for much of the variability in wood discharge on the rising limb (Braudrick et al., 1997; Angradi et al., 2004; MacVicar et al., 2009). Some of the observed variability in wood transport may reflect wood input rates associated with processes such as bank erosion, floating of previously stable pieces, and piece-to-piece interactions among wood in transport (Braudrick et al., 1997; Keim et al., 2000; Bertoldi et al., 2014; Wohl, 2016). Thus, we propose that transport distance will be more limited for flashier floods because more wood will be mobilized in shorter amounts of time, leading to congested transport and increased wood deposition, especially as jams (Braudrick et al., 1997; Bertoldi et al., 2014). Higher densities of jams deposited near peak flows then limit transport distance of uncongested single pieces on the falling limb (Davidson et al., 2015).

We hypothesize that the duration of flows near or just under bankfull exerts the greatest influence on wood transport distance in meandering rivers. Transport capacity is likely maximized near bankfull when smaller-scale channel roughness features occupy a smaller proportion of the total flow and overbank roughness and wood trapping are not yet factors. Longer duration floods just under bankfull may also result in greater bank erosion from maximization of stream power directed at banks during these flows. Catastrophic bank failures during floods mostly occur on the falling limb (Rinaldi et al., 2008) or between long duration moderate floods (Luppi et al., 2009) from erosion of the bank on the outside of a bend (Pizzuto, 2009). Wood that enters the river from these bank collapses falls directly into the thalweg and moves longer distances downstream than previously fluvially deposited instream wood (MacVicar and Piégay, 2012). Consequently, transport distances may also be longer for flows with longer duration of stage just under bankfull on the falling limb.

Larger wood transport rates have been observed when water levels increase rapidly (MacVicar et al., 2009; Ruiz-Villanueva et al., 2016b), but not enough studies have focused on wood transport rates in relation to hydrograph characteristics, specifically rates of hydrograph rise and fall, to provide robust constraints, or thresholds for, initial, downstream, or lateral mobility. Thus, uncertainty remains regarding what types of flood hydrographs facilitate the greatest downstream versus lateral movements of wood and whether threshold rates of change in water discharge exist that dictate how and where wood will be deposited for

Table 2
Synthesis of main findings and references for influence of flow characteristics on wood transport.[a]

Flow characteristics
Magnitude
• Flow magnitude strongly influences whether wood is in transport because it dictates the flooded cross-sectional area, velocity, and depth of flow • The largest wood fluxes on rivers of all sizes occur during infrequent high flows • Background wood mobility rates under 30% exist for wood movement initiation in ordinary floods for many rivers • Wood transport responds non-linearly to increases in flow magnitudes and is highly variable • Hysteresis in wood transport: flows of equal magnitude transport much less wood on the falling limb than the rising limb • Wood mobilization threshold exists at magnitudes less than bankfull; before the threshold transport is negligible, after the threshold transport is possible and increases linearly with discharge until an upper wood transport threshold associated with overbank flows is reached, at which point wood transport suddenly decreases or levels off • Most wood is deposited near peak flow magnitude • Floods strand wood at discrete elevations and locations depending on stage height; elevations of stored wood can be used indirectly to assess wood flux for particular flows • Newly recruited wood can re-organize into jam stable states after only one bankfull flow; jams are re-mobilized and re-organized during exceptional flows • Wood transport velocity is more significantly related to log volume than magnitude of floods
Duration
• The amount of time between initiation of wood transport and peak flow is a better predictor of wood displacement downstream than magnitude of flow alone • Newly recruited wood during floods moves farther distances downstream than previously recruited wood
Rising and falling limbs
• Mobilization of wood occurs on the rising limb and is comparably negligible on the falling limb • New wood on the falling limb originates from morphological changes of the channel • Wood in transport on the falling limb is rapidly retained and entrapped • Flashier, more steeply rising hydrographs mobilize more wood • Transport and storage patterns respond nonlinearly to wood input rates (rate of rising limb), with a threshold input rate governing transition between congested and uncongested transport and corresponding depositional pattern as jams or single pieces (high or low wood loads) • Shorter pieces (i.e., broken pieces and branches) are transported earlier on the rising limb and follow a consistent relation with discharge; larger pieces are mobilized after small pieces and do not correlate well with discharge • Short pieces are transported on the rising and falling limbs, whereas the largest pieces are mainly transported on the rising limb
Flow history
• The amount of wood available for transport for any flood is a function of past flow history and non-fluvial recruitment since the last wood transporting flow • Flood peaks of similar magnitude will have varying wood loads based on their position in a sequence of floods • In small streams, the frequency of extreme events governs wood transfer downstream, with cycling of wood storage related to recurrence intervals of debris flows • In medium rivers, low recurrence, yearly flows re-organize individual pieces of wood into jam stable states, whereas exceptional floods re-organize jams • Newly recruited wood is less stable than previously transported wood • In large rivers, reach-scale wood storage can be highly variable year to year, and depends on flows during prior years

[a] Field references: Keller and Swanson (1979), Lienkaemper and Swanson (1987), Berg et al. (1998), Keim et al. (2000), Haga et al. (2002), Angradi et al. (2004, 2010), MacVicar et al. (2009), MacVicar and Piégay (2012), Bertoldi et al. (2013), Turowski et al. (2013), Kramer and Wohl (2014), Schenk et al. (2014), Iroumé et al. (2015), Jochner et al. (2015), Ravazzolo et al. (2015a,b), Kramer et al. (in press).
Modelling references: Braudrick et al. (1997), Bertoldi et al. (2014), Ruiz-Villanueva et al. (2014a, 2015c, 2016b), Davidson et al. (2015).

Table 3
Synthesis of main findings and references for influence of wood characteristics on wood transport.[a]

Wood characteristics
Anchoring
• How well a piece of wood is anchored is the most important variable governing initial wood mobilization; anchoring types include burial, bracing against other pieces or instream obstructions, ramping or bridging onto banks, roots of living vegetation growing from logs, rootwads • The single most important anchoring mechanism for initial mobilization of non-rooted pieces is burial • Bracing by other pieces of wood is more common and more effective at limiting mobilization than bracing against other in-stream elements, such as boulders • Wood loads and jams are related to spacing of mobile ramped pieces
Rootwads
• Presence of a rootwad limits travel distance and initial mobilization • Shorter pieces with rootwads may travel the shortest distances • Rootwads influence log steering in transport and pivoting during entrainment and entrapment
Length
• A length mobility threshold exists near or above bankfull width; wood less than bankfull width is more easily mobilized and travels farther • Piece length is a better predictor for whether a piece will move out of a reach than volume or diameter for nonbraided rivers • Shorter pieces (i.e., broken pieces and branches) are transported earlier on the rising limb because they are preferentially transported longer distances on the falling limb of previous floods and deposited at lower elevations • Shorter pieces of wood may not always move before longer pieces of wood due to shielding and bracing against larger pieces • In medium rivers, shorter pieces generally travel longer distances than longer pieces but there are instances when the longest pieces travel the longest distances • In large rivers, there is no consistent relation between transport distance and length of wood • In braided rivers, medium sized logs travel the farthest distances
Diameter
• A threshold for transport exists when flow depths = a critical floating depth related to the diameter and density; this is ~0.5 log diameter • Diameter is important for controlling the timing and elevation of wood deposition, especially in streams where inundated depth contracts rapidly with small changes in discharge, such as in broad braided rivers or floodplains • There is weak predictive power between log diameter and distance travelled in single thread channels and high predictive power in braided channels • Most instream logs float more than half way under water and are denser than in the forest environment
Orientation
• Single pieces with rootwads are commonly deposited oriented parallel to flow with the rootwad on the upstream side, which can then entrap more wood • Flume studies indicate perpendicular pieces are mobilized sooner than parallel pieces, while field studies indicate the opposite; natural complexities in piece shapes and anchoring are likely the source of the discrepancy. • Wood travels parallel to flow: unless interacting with other pieces (then perpendicular), ruddering from branches or rootwads, or travelling through velocity heterogeneities • Despite smaller forces acting on the parallel pieces, they are more mobile during floods than perpendicular or oblique pieces, which are commonly anchored or braced against other wood or banks • Loose unanchored pieces originally stored oriented at an angle to flow travel farther distances, most likely because once mobile they ferry across the current away from snags on the bank and enter the swifter velocities of the thalweg sooner
Species (also decay, density and branching complexity)
• Tree species is a master variable that governs many other mobility predictors (i.e., length, breakage, density, branching complexity, shape, rate of decay) • Field studies find species to be the best predictor of variance in transport distances • Travel distance decreases with increasing density • Density and shape strongly influence travel speed and entrapment during flood recession • Newly recruited green wood moves differently than fluvial wood due to differences in abrasion, water absorption, and buoyancy

[a] Field references: Harmon et al. (1986), Lienkaemper and Swanson (1987), Gippel et al. (1996), Piégay and Gurnell (1997), Berg et al. (1998), Jacobson et al. (1999), Keim et al. (2000), Haga et al. (2002), Lassettre and Kondolf (2003), Daniels (2006), Millington and Sear (2007), Warren and Kraft (2008), Wohl and Goode (2008), MacVicar et al. (2009), Cadol and Wohl (2010), Iroumé et al. (2010, 2015), Merten et al. (2011, 2013), MacVicar and Piégay (2012), Bertoldi et al. (2013), King et al. (2013), Beckman and Wohl (2014), Dixon and Sear (2014), Schenk et al. (2014), Shields et al. (2006), Ravazzolo et al. (2015a,b).
Modelling references: Bocchiola et al. (2006a,b), Braudrick and Grant (2000, 2001), Welber et al. (2013), Bertoldi et al. (2014), Davidson et al. (2015), Ruiz-Villanueva et al. (2015a, 2016a).

different channel types. Also, more work should be done to characterize the variability in speed of wood transport related to piece type and flow magnitude for diverse river morphologies. In meandering rivers, logs float with few obstructions; whereas in braided rivers, numerous obstacles cause logs to stop and be reentrained several times, reducing the average velocity. MacVicar and Piégay (2012) found that uncongested transport of logs moved at approximately the surface velocity of the water in a single-thread, meandering channel; whereas Ravazzolo et al. (2015b) found that wood moved at approximately half the celerity of peak flow for a braided, gravel-bed river.

Although higher floods mobilize wood that remains stable during lower floods (MacVicar and Piégay, 2012), the relationship between flood magnitude and large wood flux is highly variable (Kramer and Wohl, 2014; Iroumé et al., 2015; Kramer et al., in press) and depends on flow history (Haga et al., 2002; Kramer et al., in press). The lack of consistent relations between flow magnitude and large wood flux because of the influence of prior flows is analogous to the lack of consistent correlations between flow magnitude and channel morphologic change (Harvey, 1984; Desloges and Church, 1992; Cenderelli and Wohl, 2003). Because wood deposition mostly occurs near peak water discharge (MacVicar and Piégay, 2012; Ravazzolo et al., 2015b), we suggest that prior patterns of flood peak magnitudes may have high predictive power regarding how much wood is available for downstream transport in future floods. We hypothesize that the frequency of wood redistribution within the channel banks is largely scale-dependent, such that wood is redistributed more frequently with increasing river size. We predict that further research will reveal a discontinuity in transport flux through drainage networks simply because the frequency of redistribution and delivery is dissimilar between river types and sizes.

Turowski et al. (2013) have shown that for the steep, step-pool headwater Erlenbach River in Switzerland, coarse particulate organic matter (CPOM) transport rates (including finer material such as twigs, leaves, and large wood) consistently scale with discharge. Furthermore, they suggest that consistent power relations exist for transported piece size distributions of all organic matter and that if transport rates of finer fractions of CPOM can be monitored, transport rates of large wood could be estimated and vice versa. This idea holds some promise, as MacVicar and Piégay (2012) found that smaller pieces of large wood followed consistent relations with discharge on the rising limb of a flood, whereas larger pieces did not. Turowski et al. (2013) may have found more consistent relations between wood transport and discharge magnitudes compared to other large wood studies (MacVicar and Piégay, 2012; Kramer and Wohl, 2014) because they included the more abundant finer fraction of CPOM and/or because a stronger relation between discharge and wood export exists in steep headwater channels with limited floodplains. We suggest further testing the broad applicability of estimating wood discharge based on monitoring subsets of smaller size fractions that have consistent relationships with flood magnitudes, and then back-estimating quantity of larger wood based on known transported size distributions for a particular river.

Table 4
Synthesis of main findings and references for influence of reach characteristics on wood transport.

Reach characteristics
Channel morphology
• Wood will be routed more quickly and stored for less time in reaches that are confined versus unconfined, multi thread versus single thread, higher slopes versus lower slopes, flow regulated versus unregulated, smaller variability in channel depths of the flooded cross-section • Best predictors for wood mobility and transport distance change based on channel type; in reaches with high connectivity to floodplains, wood characteristics are better predictors, whereas in channelized reaches, hydrologic variables are better predictors • Wood transport distances and mobilization are substantially reduced on floodplains versus the main channel • For steep, coarse substrate, confined channels, roughness during low flows limits transport mobility and distance travelled; as flows overtop roughness elements, transport capacity increases, and wood flux is limited by supply • For alluvial channels with floodplains where low flow roughness is low, the duration and depth of flow over sand bars and supply of wood limit transport at flows under bankfull, whereas vegetated bars and floodplains limit transport as flows begin to overtop the regularly flooded channel • Degree of sinuosity may not limit transport distance
Wood abundance and jams
• Large wood and wood jams are commonly the dominant entrapment site for fluvially deposited wood • Wood pieces incorporated into jams are harder to mobilize than individual pieces • Storage frequency of jams decreases overall reach-scale mobility of wood • Single pieces of wood can travel past jams during moderate and high flow. • Channel spanning wood jams may have a limited impact on the travel distance of wood because most wood is transported during very high flows when jams are floated, water flows around them or over them, or the jams are transported • Log jams are frequently mobile and often exchange pieces or are transported and re-form in the same location with new pieces but similar structure • Most jams are mobilized by channel change during high flows or failure of key pieces due to breakage or decay • Jam frequency and location are related to long ramped pieces • Increased wood abundance in storage relates to increased wood recruitment during floods
Live-wood
• Living vegetation within the flow (live-wood) is extremely effective at trapping and anchoring wood, especially key pieces that later form jams • Floods create heterogeneity in riparian vegetation patterns based on locations of deposited wood piles that re-sprout or provide nursery sites for new live-wood
Forest disturbance history
• Forest disturbance history is closely related to dead and live wood abundance, which in turn influences mobility • Extreme floods in channels with high wood loads recruit more wood than floods in channels with low pre-flood wood loads • Wood mobilization is lower in old-growth reaches due to associated increase in channel complexity and supply of large key pieces that form jams • Wood is more mobile, with higher export rates and greater travel distances, in recently burned versus unburned catchments • Large, infrequent, catastrophic disturbances re-set the template for wood distribution patterns and channel change in subsequent years • Peak wood loads occur decades after catastrophic forest mortality events

[a] Field references: Murphy and Koski (1989), Benke and Wallace (1990), Young (1994), Piégay and Gurnell (1997), Berg et al. (1998), Jacobson et al. (1999), Johnson et al. (2000), Gurnell (2003), Wyżga and Zawiejska (2005), Shields et al. (2006), Pettit et al. (2006), Millington and Sear (2007), Oswald and Wohl (2008), Curran (2010), Sear et al. (2010), Iroumé et al. (2010), Wohl and Goode (2008), Wohl and Cadol (2011), Collins et al. (2012), MacVicar and Piégay (2012), King et al. (2013), Le Lay et al. (2013), Beckman and Wohl (2014), Dixon and Sear (2014), Boivin et al. (2015), Jackson and Wohl (2015), Lucía et al. (2015), Wohl (2016). Modelling references: Braudrick et al. (1997), Braudrick and Grant (2001), Bertoldi et al. (2014, 2015), Davidson et al. (2015), Ruiz-Villanueva et al. (2015b, 2016b).

Table 5
Hypotheses regarding controls on wood mobilization and transport drawn from the literature review.

Hypotheses and associated assumptions
Flow characteristics -The duration of flows near bankfull exerts the greatest influence on wood transport
• transport capacity is likely maximized near bankfull • transport distances may be longer for flows with longer duration of discharge near bankfull -The frequency of wood redistribution within the active channel is scale-dependent, such that wood is redistributed more frequently with increasing river size Wood characteristics -Diameter is a strong predictor variable for wood mobility in reaches with high depth variability during wood-transporting flows. -Diameter becomes increasingly significant with greater proportion of flow depths near half the diameter of wood pieces -In small to medium rivers, orientation and position of wood do not strongly influence travel distance
• orientation and position are likely to be overshadowed by the influence of flood magnitude and reach-scale roughness elements that can deflect pieces -Wood that spends a greater portion of time oriented parallel to flow in small to medium rivers will spend more time in transport
• wood moving parallel to flow is less likely to become lodged or braced en route. Tree type is the most important global predictor variable for how wood moves through drainage networks • tree type significantly influences piece size, shape, and wood density -For a particular tree species, increasing density correlates positively with residence time and inversely with travel distance. -Wood pieces recruited from tree species that maintain a more complex, branched shape during river transport have lower mobility than pieces that weather to cylindrical shape Reach characteristics -Reach retention capacity is smallest within the range of discharges above a wood mobilization threshold and below bankfull stage (retention capacity is greatest for very low flows and overbank flows) -Log jam spacing only limits wood piece transport distance during low flows with limited wood mobility -During infrequent high flows when most wood is transported, the frequency and length of inundation during which living vegetation obstructs flow is a better predictor of wood mobility than the downstream spacing of log jams -Entrapment of wood by living vegetation may explain why wood flux peaks before water flux
• live wood can snare dead wood on the rising limb of the hydrograph before deposition at flood recession due to decreasing flow depths

2.2. Wood characteristics

Five characteristics of wood pieces exert an important influence on wood mobilization and transport: anchoring, length, diameter, orientation, and tree type (species, which governs decay rates, abrasion intensity, density, and branching complexity). Table 3 summarizes how these characteristics are linked to wood mobilization in the literature. Although burial is widely recognized as the most important anchoring mechanism (Berg et al., 1998; Wohl and Goode, 2008; Merten et al., 2011) and rootwads are often noted as substantially less mobile than pieces without rootwads (e.g., Braudrick and Grant, 2000; Bocchiola et al., 2006b; Daniels, 2006; Cadol and Wohl, 2010; Welber et al., 2013; Davidson et al., 2015; Iroumé et al., 2015), anchoring thresholds are not yet well understood. Information is very limited, for example, on the amount of burial needed to effectively keep pieces stationary for floods of variable magnitude and the stability of different types of rootwads. Surprisingly, Davidson et al. (2015) recently found that small pieces with simplified square rootwads in flumes were actually more stable than longer pieces with rootwads. We suggest further exploring the relative stabilizing effect and likelihood of subsequent jam formation for different types of rootwads from different species with varying levels of complexity and varying bole lengths Rootwads are commonly used in stream restoration projects (e.g., Shields et al., 2004). Thus, managers could use information on the minimum degree of root complexity and length required to meet stability criteria because of preference for smaller, less complex pieces that can more easily pass built structures if mobilized. Detailed field measurements of rootwads coupled with three-dimensional printing technology could be used to more accurately simulate wood characteristics in future flume experiments to test anchoring processes.

Case studies conducted on small to large rivers have found that longer pieces are either less likely to be moved during floods or are mobilized at higher discharges (Jacobson et al., 1999; King et al., 2013). A threshold for piece mobility exists based on the ratio of piece length to bankfull width, with logs less than bankfull width substantially more mobile than logs greater than bankfull width (Lassettre and Kondolf, 2003; Shields et al., 2006; Warren and Kraft, 2008; Wohl and Goode, 2008; Merten et al., 2011; MacVicar and Piégay, 2012; Dixon and Sear, 2014). Longer pieces are more likely to be braced or buried against channel margins, form key pieces in jams, and be anchored by rootwads, all of which give the longer pieces greater stability (Merten et al., 2011). However, much variability exists. For example, wood shorter than bankfull width does not always move when larger pieces become mobile (Warren and Kraft, 2008), and tracking studies of loose wood in large rivers have noted no relationship between size of wood and whether a piece is mobile during a flood (Schenk et al., 2014) or the timing of mobilization (Ravazzolo et al., 2015b). This lack of relationship between wood size and mobilization in large rivers is matched by observations in the flume that length does not influence threshold movement for logs shorter than bankfull width (Braudrick and Grant, 2000).

Case studies on medium rivers show that wood pieces shorter than bankfull width travel greater distances than longer pieces (e.g., Lienkaemper and Swanson, 1987; Berg et al., 1998; Daniels, 2006; Millington and Sear, 2007; Warren and Kraft, 2008; Iroumé et al., 2010; Dixon and Sear, 2014). However, transport distances are highly variable and the longest logs are capable of travelling the farthest distance despite their size (Dixon and Sear, 2014). Also, this relationship between piece length and travel distance does not consistently hold true for large rivers. Even though bigger pieces are less likely to be moved by floods (Jacobson et al., 1999), once mobilized, no consistent relation between transport distance and piece size is common (Jacobson et al., 1999; MacVicar and Piégay, 2012; Schenk et al., 2014; Ravazzolo et al., 2015b). One flume study simulating a large river showed that mobilization and travel distance actually increase with length (Davidson et al., 2015). Another flume study showed that travel distance peaks with medium sized logs that are long enough to steer off obstacles and have enough momentum to scrape past shallow depositional zones but are short enough not to be deflected by banks (Welber et al., 2013). Trends of decreasing transport with larger piece size are present in single-thread rivers, but the effects of log size on travel distance are more complicated in braided and multi thread channels of similar size (Welber et al., 2013; Ruiz-Villanueva et al., 2015c).

Existing observations leave several questions unanswered: If larger logs are mobilized later and are trapped sooner than shorter logs (MacVicar and Piégay, 2012), why can they have equal or longer transport distances? Is this solely because they travel at faster velocities or could this be a result of sampling bias because it is easier to tag, track, and identify larger pieces? Does a threshold piece size for equal downstream mobility exist? Does this threshold vary by stream and wood type? How does piece length impact the effectiveness of hydraulic steering to avoid obstacles and remain in swift current?

Diameter is more easily measured in the field than wood density and thus is often used in field studies of mobilization as a surrogate for flotation depth (i.e., buoyant depth), which flume studies indicate is an important variable in predicting wood mobilization and entrapment (Braudrick and Grant, 2000). For single pieces, diameter controls the timing and elevation of deposition on the falling limb of floods, especially for braided reaches or floodplains where the inundated depth alters rapidly with small changes in river stage (Bertoldi et al., 2013). As depths decrease, larger diameter pieces are slowed and stopped earlier on the receding limb (Bertoldi et al., 2013).

Although diameter can be the most important variable for mobility in braided channels (Welber et al., 2013), for single-thread channels, wood diameter appears to be a good predictor of mobilization only in the absence of other, more primary predictor variables such as anchoring and length (Haga et al., 2002). Field observations of natural wood in medium sized mountain and meandering channels have found no significant relationship (Iroumé et al., 2010) or weak predictive power (Dixon and Sear, 2014) between log diameter and distance travelled. Thus, although diameter appears to be important as a secondary threshold condition for initial mobilization, its influence on travel distance in these channels may be limited to conditions in which greater proportions of flow depth are similar to log diameter, such as during low flows, and through shallow braided or unconfined reaches.

A flume study of braided morphology has shown that wood mobility decreases at threshold flows equal to half the diameter of logs (Welber et al., 2013). This threshold is also supported by work in headwater rivers of Chile, which showed that the pieces moved in average floods had diameters less than half bankfull depth (Iroumé et al., 2015). Thus, we hypothesize that diameter is a stronger predictor variable for wood mobility in reaches with high depth variability during wood-transporting flows and that diameter becomes increasingly significant with greater proportion of flow depths near half the diameter. Although half-diameter appears to be equivalent to the flotation depth of wood, recent experiments examining relationships between water saturation, density, and buoyancy for instream wood suggest that most logs actually float more than halfway underwater (Ruiz-Villanueva et al., 2016a). Thus, the half-diameter threshold for wood mobility identified in the field and flume (Welber et al., 2013; Iroumé et al., 2015) may be more closely related to conditions when flow depths are slightly less than flotation depths.

Variability in results relating wood size to mobility likely result from: (*i*) Equal mobility conditions when small pieces are shielded from movement by larger instream structures (such as boulders and larger logs or logjams). This scenario is similar to the concept of armouring in gravel- and cobble-bed streams (Parker and Toro-Escobar, 2002). (*ii*) Local anchoring or bracing of pieces in natural channels exerting greater controls on wood mobilization than wood size (MacVicar and Piégay, 2012). (*iii*) Smaller pieces preferentially transported earlier on the rising limb of floods because they are transported longer during the falling limb of prior floods and stranded at lower bank heights (MacVicar and Piégay, 2012). (*iv*) Flashy hydrographs mobilizing wood in short time intervals, potentially reducing any significant differences in initial mobilization between large and small pieces (Ravazzolo et al., 2015b). (*v*) Variability in piece shapes and densities (Merten et al., 2013). (*vii*) Local and reach scale variability in channel retentiveness and characteristics (Wyżga and Zawiejska, 2005; Wohl and Cadol, 2011).

Flume studies indicate that pieces perpendicular to flow are less stable than those oriented parallel to flow (Bocchiola et al., 2006a), but this relationship is unclear in the field (Iroumé et al., 2015). In natural channels, individual loose pieces of wood are commonly deposited along channel margins parallel to flow, whereas wood oriented perpendicular is usually anchored or braced. This complicates field mobility studies on log orientation. If flow is sufficient to float most loose, unjammed wood on the channel margins, a greater amount of wood oriented parallel may be floated simply because there are greater amounts of loose, easily transported pieces with this orientation.

The orientation of pieces greatly impacts drag force, which impacts when a piece is mobilized, and its downstream velocity (Gippel, 1995). Thus, orientation should play a role in total travel distance of a

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piece of wood during floods. However, the influence of floating wood piece orientation on travel distance is not well characterized in the field. Video monitoring of a large river found that uncongested wood transport is oblique to flow, commonly zig-zagging across the channel (MacVicar et al., 2009). This is in disagreement with flume studies that show uncongested transport parallel to flow (Braudrick and Grant, 2001; Welber et al., 2013). Flume studies typically use smooth dowels; whereas wood pieces in natural channels have irregularities in shape that could work as passive rudders, making parallel travel less likely in natural settings.

We could not find any studies that investigated travel orientation in small to medium channels. We hypothesize that, for these channels, orientation and position of wood in the river are not dominant explanatory variables for travel distance because they are likely to be overshadowed by the influence of flood magnitude and reach-scale roughness elements that can deflect pieces. However, if orientation does play a role in these streams, we hypothesize that wood that spends a longer portion of time oriented parallel to flow will travel longer because the wood is less likely to become lodged or braced en route. This may be one reason why shorter wood travels longer distances; shorter wood pieces are generally more similar to cylindrical rods, and their small size allows them to spend more time travelling parallel to flow and less time being deflected by instream roughness elements.

Species and level of decay dictate how prone wood pieces are to breaking en route and can impact travel distances by changing the size and shape of pieces (Lassettre and Kondolf, 2003; Wohl and Goode, 2008; MacVicar and Piégay, 2012; Merten et al., 2013). Preliminary findings from the few studies to explicitly look at influences of density, tree species, and shape on travel distance suggest that tree type is one of the best predictors of downstream transport distance (Merten et al., 2013; Schenk et al., 2014; Ravazzolo et al., 2015b; Ruiz-Villanueva et al., 2016a). We hypothesize that tree type is the most important global predictor variable for how wood moves downriver and through drainage networks, explaining variance associated with transport distance, residence times, travel paths, and depositional patterns.

Recent advances have been made in understanding how wood density relates to water content and buoyancy (e.g., Ruiz-Villanueva et al., 2015a) and how variation in buoyancy among and within different species relates to travel distance (Ruiz-Villanueva et al., 2016a). However, more work is needed on how water content of logs changes as they travel through drainage networks and how this relates to depositional patterns such as the probability of becoming buried, which can lead to longer residence times. We hypothesize that, for a particular tree species, increasing density (from increasing water content) correlates positively with residence time and negatively with travel distance. In relation to wood type, we also hypothesize that wood pieces recruited from tree species that maintain a more complex, branched shape during river transport have lower mobility than pieces that tend to approximate cylinders.

2.3. Reach characteristics

Although general patterns relate hydrology (see Section 2.1) and wood characteristics (see Section 2.2) to wood mobility, these relations are highly variable (Welber et al., 2013; Iroumé et al., 2015) and significant differences in mobility and deposition exist among contrasting channel types, sizes, and forest disturbance regimes (Young, 1994; Wyżga and Zawiejska, 2005). Much of this variability is likely related to local channel and floodplain characteristics that promote reach-scale retention (Braudrick and Grant, 2001; Wyżga and Zawiejska, 2005; Pettit et al., 2006) because, during floods, wood is preferentially deposited and stored in hydraulically rougher (Ruiz-Villanueva et al., 2015b), unconfined (Dixon and Sear, 2014; Lucía et al., 2015) reaches.

The degree of channel roughness is commonly described using relationships between wood characteristics and channel morphology (Braudrick and Grant, 2001), abundance of dead wood and jams (Beckman and Wohl, 2014), and presence of live-wood within the flow (Jacobson et al., 1999). Forest history governs the recruitment of new wood (King et al., 2013) and catastrophic events can drastically change wood loads, channel morphology, and distribution of live wood (Johnson et al., 2000; Pettit et al., 2006; Oswald and Wohl, 2008). Thus, we have grouped reach-scale characteristics that govern wood transport into five categories: channel morphology, wood abundance and jams, live wood, and forest disturbance history (Table 4).

Wood pieces not travelling in the thalweg, long compared to bankfull width, or thicker than flow depth, are more likely to interact with in-channel obstructions, channel margins, and the floodplain, limiting mobility and transport distances (Braudrick et al., 1997). The proportion of wood carried in the thalweg versus near-bank regions for different levels of flow and diverse river types is unknown. Preliminary studies suggest that, in large and great rivers, wood is predominantly carried in the thalweg for flows less than bankfull (MacVicar et al., 2009; MacVicar and Piégay, 2012; Kramer and Wohl, 2014). However, as water levels reach overbank flows, wood is quickly routed to and trapped on the floodplain (MacVicar and Piégay, 2012). For flows that exceed bar heights on gravel-bed braided rivers, GPS tracking of log paths during transport showed that most logs are transported above bars rather than travelling in the thalweg, and as flows begin to recede, wood is quickly deposited (Ravazzolo et al., 2015b).

Reach characteristics contributing to wood retention change as flood magnitude increases (MacVicar and Piégay, 2012; Ruiz-Villanueva et al., 2015b) because deposition is dominantly controlled by the availability and type of trapping sites at peak flow (Millington and Sear, 2007; MacVicar and Piégay, 2012). For steep, confined, small- to medium-sized, mountain channels, retentiveness is highest at lower flows and decreases as flood magnitude increases (Wohl and Goode, 2008; Wohl and Cadol, 2011). However, floods with peak flows greater than bankfull will be more effective at trapping wood than floods below bankfull because wood is more likely to interact with roughness elements such as riparian vegetation and shallow depths in overbank areas (Wohl et al., 2011; MacVicar and Piégay, 2012). For any stream reach, we hypothesize that reach retention capacity is smallest within the range of discharges above wood mobilization thresholds and under bankfull, and retention capacity is greatest for very low and overbank flows.

Retention rates of reaches have been estimated using exponential decay models of transport distances for experimentally introduced leaves (Larrañaga et al., 2003) and small dowels ≤ 1.06 m in length and ≤0.035 m in diameter (e.g., Millington and Sear, 2007). Whether these models can be scaled up to model large wood retention has yet to be tested, but emergent properties such as congested transport (Braudrick et al., 1997) are unlikely to be adequately represented in experimental additions of small materials.

Wood transport dynamics on floodplains are less understood than transport in channels, particularly with respect to the timing and transfer of wood between channels and floodplains. Limited studies suggest that, despite having higher initial mobility, floodplain wood does not move very far and floodplains are a net sink for wood that becomes an important part of the floodplain ecosystem (Benke and Wallace, 1990).

Large wood, channel-spanning jams, and wood rafts can be very efficacious at trapping wood and when present are commonly the dominant entrapment site for fluvially transported wood (Pettit et al., 2006; Millington and Sear, 2007; Warren and Kraft, 2008; Beckman and Wohl, 2014; Dixon and Sear, 2014; Wohl, 2014a; Boivin et al., 2015; Iroumé et al., 2015; Jackson and Wohl, 2015) and smaller coarse particulate matter (Jochner et al., 2015). Higher amounts of wood in storage, especially as jams, have been related to higher amounts of wood recruited during floods (Johnson et al., 2000), lower wood export rates (Bertoldi et al., 2014; Davidson et al., 2015), and longer residence times (Wohl and Goode, 2008). However, several studies highlight that jams are frequently mobilized, often reforming in the same locations with new pieces (Piégay and Gurnell, 1997; Gurnell et al., 2002; Wohl and Goode, 2008; Curran, 2010; Sear et al., 2010; Collins et al., 2012; Dixon and Sear, 2014). Pieces that are trapped within and behind jams can be released and replaced by other pieces during high flows, so that the overall architecture of the jam appears similar even though the internal pieces are different (Lienkaemper and Swanson, 1987; Dixon and Sear, 2014). Direct observations indicate that entire logjams can be floated up and then set back down during high flows (S. Gregory, pers. comm., July 2015) or can break apart as individual basal wood pieces break or are dislodged (Wohl and Goode, 2008). Although factors such as proportion of channel cross-sectional area obstructed by the jam, potential for overbank flow and dissipation of hydraulic force (Wohl, 2011), porosity of the jam, and cause of jam formation likely influence the relative stability of individual jams, little is known of the relative importance of diverse processes by which jams become mobile.

Because the storage frequency of large pieces of in-channel wood has a negative relationship to piece mobilization (Merten et al., 2011; Wohl and Beckman, 2014; Davidson et al., 2015), channels with more stored wood and greater numbers of jams have so far been assumed to have lower overall wood mobility and to transport wood shorter distances (Warren and Kraft, 2008). However, destruction and reformation of jams in the same location may create the impression that a reach is transport limited because of a high density of wood in storage, when in fact the site favors repeated formation of jams. Thus, field observations made during low flow of changes in wood storage may not actually reflect how much wood moved during a flood because overall storage values within a reach can remain the same despite high wood flux (Lienkaemper and Swanson, 1987; Keim et al., 2000; Wohl and Goode, 2008; Dixon and Sear, 2014). And, although jams and large key pieces of wood form obstacles, they do not impede the ability of some pieces to flow over, around, or through the jams during high flows (Lassettre and Kondolf, 2003; Millington and Sear, 2007; Warren and Kraft, 2008; Dixon and Sear, 2014; Schenk et al., 2014). Several questions remain, such as: what storage density of wood is needed to greatly impact overall wood mobility within a reach; what is the impact of removing wood from streams on the downstream transport of other pieces of wood; and can turnover of wood be estimated based on storage density?

The proportion of the channel cross-sectional area obstructed by a jam, as well as the porosity of the jam, likely influences the ability of individual wood pieces to move downstream past the jam. Jams can also cause avulsion during high flow (Keller and Swanson, 1979; O'Connor et al., 2003; Collins et al., 2012; Phillips, 2012), creating a transport bypass chute for wood. We suggest that the presence of jams does not necessarily cap wood transport distances at one to two jam spacing intervals, as previously presumed (Warren and Kraft, 2008) and modelled (Martin and Benda, 2001; Lassettre and Kondolf, 2003). We hypothesize that logjam spacing may only limit transport distances during low flows with limited wood mobility. This is supported by observations by (Lassettre and Kondolf, 2003), who found that jams only impede wood travel distance for floods with recurrence intervals < 6–15 years. Relationships between transport distance and jam spacing remain unclear for varying flow magnitudes and should be an avenue of future research. Complicating analysis of jam mobility and jam influence on piece transport in the existing literature is that the word *jam* is used to refer to 2–3 pieces of wood in contact (e.g., Wohl and Cadol, 2011; Bertoldi et al., 2013), as well as large, channel-spanning structures (e.g., Beckman and Wohl, 2014), and commonly the criteria for designating a jam are not clearly stated.

Of particular importance to trapping efficacy during major floods is the presence of rooted living vegetation (*live-wood* after Opperman et al., 2008) within the flow and on banks (Jacobson et al., 1999; Pettit et al., 2006; MacVicar and Piégay, 2012; Bertoldi et al., 2015; Ravazzolo et al., 2015b). Living vegetation is particularly effective at trapping mobile wood in overbank areas (Wohl et al., 2011) and on mid-channel bars (Jacobson et al., 1999). We hypothesize that during infrequent high flows when most wood is transported, the frequency and length of inundation during which living vegetation obstructs flow is a better predictor of wood transport distance than the downstream spacing of logjams. Furthermore, the abundance and distribution of specific live wood species that are singularly effective trappers (Jacobson et al., 1999) may account for most of the variance. If this is the case, then a large river with flow paths that route wood over vegetated bars and floodplains and through overbank channels may be more transport limited than medium channels with a high density of logjams, even though channel widths on the large river are greater than log lengths.

We also hypothesize that entrapment of wood by living vegetation may be the reason why wood flux peaks before water flux (MacVicar and Piégay, 2012; Ruiz-Villanueva et al., 2016b), because live wood can snare dead wood on the rising limb of the hydrograph before deposition during flood recession due to decreasing flow depths. If this is true, then the lag between the wood flux peak and the discharge peak could be used as a measure of overall entrapment efficiency of that channel for a particular flood. Episodic reorganization of wood and mass deposition of wood from exceptional flooding can have lasting effects on channel morphology and overbanks and greatly impact the availability, mobility, and transport paths of wood (Oswald and Wohl, 2008).

Fluvially deposited wood piles create heterogeneity in riparian vegetation patterns by providing nursery sites for new live-wood and by creating hard points, protecting new growth from rapid erosion of banks and bars at lower flows (Hickin, 1984; Collins et al., 2012; Gurnell et al., 2015). Even where input and transfer of fluvial wood are rare and wood piles rapidly decay or burn, their influence on vegetation germination can be substantial (Pettit et al., 2006). Thus, flooding disturbance history can have a feedback loop governing forest structure, heterogeneity, and age, which in turn influence wood loading, channel complexity, and wood transport. Flume studies show a threshold response in patterns of wood storage (Bertoldi et al., 2014) and wood transport to input rates of wood (Braudrick et al., 1997). These results suggest the possibility of using estimates of wood input rates from episodic events, such as floods or hillslope failures, to predict different alternate stable states of reach-scale wood transport (congested versus uncongested) and wood storage patterns (single piece versus jam dominated).

Although channels draining old-growth forests tend to have lower wood mobility than younger forests attributed to higher instream wood loads (Gurnell, 2003; Iroumé et al., 2010; Collins et al., 2012; Beckman and Wohl, 2014; Jackson and Wohl, 2015), some field studies of transport distances in relation to forest history yield mixed results, with Berg et al. (1998) documenting greater transport distances in an old-growth watershed compared to a logged watershed and Young (1994) and King et al. (2013) documenting greater export in burned watersheds compared to unburned watersheds. Differences between disturbance types and subsequent impact on transport dynamics in channels likely influence these contrasting findings.

Legacy impacts from past land use also influence contemporary wood transport. Studies from forest ecology indicate that rates of wood recruitment vary on time frames from decades to centuries (Murphy and Koski, 1989; Wohl, 2016). Two centuries or more are commonly required to reach old-growth forest conditions and peak wood loads occur decades after catastrophic forest mortality events such as pine beetle outbreaks (Bragg, 2000). Consequently, observed wood transport could reflect past rather than current conditions of the watershed (Wohl and Cadol, 2011), but the effect on interpretation of wood transport processes remains unclear.

3. Quantitative summary

Field researchers have made advances in understanding wood transfer and transport through natural drainage networks during the last 40 years, but this has been on a case-by-case basis and generalizations

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have not yet been drawn from the data. In this section, we focus on analyzing and synthesizing field measurements of wood transport in order to highlight general patterns of wood mobility across diverse sizes and types of rivers. Appendix A provides a summary of field-derived empirical equations.

3.1. Methods

We conducted a literature search for field studies that measured the mobility of wood via change in storage in a reach (Eulerian) and studies that measured the travel distance of wood pieces (Lagrangian). Henceforth, we use the term *initial mobility* to refer to observations of change in storage, *downstream mobility* to refer to data that record travel distance, and *mobility* to refer generally to both categories. In the literature, the term *mobility* is used interchangeably when referring to initial mobility of wood in storage and downstream transport mobility of floating wood. This ambiguity can create confusion. We distinguish between initial and downstream transport mobility because factors that influence initial mobilization may not be as important for transport of the same piece downstream.

We only included studies with direct mobility measurements in the field. We did not include studies that back-calculated mobility from wood budgets or recruitment measurements or results from numerical models. We located 40 studies with such measurements in a broad range of peer-reviewed publications (17 journals), as well as one technical report and two theses. About 57% of studies came from physical science publications, while about 43% came from ecology- and forestry-related publications. The largest proportion of studies from a single journal was 20% in *Geomorphology*, followed by 10% in *Earth Surface Processes and Landforms* and in *River Resources Research*. Table 6 summarizes the studies by continent and by number of data values contributed from each study. We did not conduct a full quantitative analysis on total wood flux because this information was very limited; most flux values were back-calculated rather than directly measured; and reconciling values from different studies proved too difficult because of different reporting metrics. Wohl (2016, this issue) summarizes some wood flux values, but a more thorough compilation of wood budget fluxes would be useful.

Wood mobility is typically monitored via tagging pieces or remote sensing of large accumulations along a reach (Δx) and then noting how much and how far this wood moved within a given time frame (Δt), typically one year. Consolidating data from many disparate sources on wood mobility proved difficult. Most studies do not report the same values because study questions differ. For example, some studies investigated jam mobility, whereas others looked at mobility of loose pieces. Some studies analyzed only wood that was exported, whereas others considered only newly recruited wood.

From each initial mobility study, we recorded what was measured (typically # pieces or volume of wood), as well as the following categories (if reported): the starting amount in storage (*start*), the amount that left the reach (*left*), the amount that entered the reach (*came*), the amount that stayed (*stayed*), and the final value in storage (*end*). When possible, the stayed variable was subdivided into an amount that stayed but moved within the reach (*repositioned*), and the amount that was immobile (*immobile*). For comparison with the widely used wood budget equation (Benda and Sias, 2003), *came* is Q_i and/or L_i, *left* is Q_o and/or L_o. *Start*, *end* and *repositioned* are all different forms of S_c. When studies did not differentiate between pieces that were repositioned locally versus pieces that were exported downstream, we assumed that the pieces were exported downstream. When a study differentiated between repositioned pieces and exported pieces, the authors distinguished two populations of mobile wood, one that moved minimal distances and was locally retained and one that was exported longer distances downstream. In most cases, we were able to back-calculate categories not supplied. Sometimes we calculated values based on a starting value and a reported % mobilized. If we were unable to back-calculate based on given information, the category was left empty.

Table 6
Summary of field studies by location used in the quantitative analysis of wood mobility; $\#T_d$ are the number of downstream travel distances and $\#M_i$ are the number of initial mobility measurements used from each study at each location.

Location	River	$\#T_d$	$\#M_i$	Study
North America				
California	Central Sierra Streams	2	23	Berg et al. (1998)
California	Soquel Creek	–	2	Lassettre and Kondolf (2003)
California	Sacramento River	6	6	MacVicar et al. (2009)
Colorado	5 Rocky Mountain Streams-Colorado	–	48	Wohl and Goode (2008)
Georgia	Oggeechie River	–	7	Benke and Wallace (1990)
Illinois	Poplar Creek	1	1	Daniels (2006)
Illinois	Upper Mississippi Missouri Ohio Rivers	–	6	Angradi et al. (2010)
Minnesota	Streams draining into Lake Superior	–	1	Merten et al. (2010)
Minnesota	Streams draining into Lake Superior	1	–	Merten et al. (2013)
Mississippi	Little Topshaw Creek	–	4	Shields et al. (2008)
New York	Rocky Branch	1	3	Warren and Kraft (2008)
North Carolina	Lower Roanoke	2	1	Schenk et al. (2014)
North Dakota	Upper Missouri	–	1	Angradi et al. (2004)
Oregon	Bark Buttermilk and Hudson Creeks	–	8	Keim et al. (2000)
Texas	San Antonio River	–	1	Curran (2010)
Washington	Salmon Creek	–	4	Bilby (1984)
Washington	Various	–	1	Grette (1985)
Washington	Queets River	1	–	Latterell and Naiman (2007)
Washington	Streams in Lookout Basin	1	5	Lienkaemper and Swanson (1987)
Wyoming	Crows and Jones Creek	2	4	Young (1994)
Central and South America				
Costa Rica	6 Costa Rican Streams	–	12	Cadol and Wohl (2010)
Chile	Vuelta de la Zorra	1	1	Iroumé et al. (2010)
Chile	Vuelta de la Zorra	–	1	Ulloa et al. (2011)
Chile	Buena Esperanza and Tres Arroyos	3	4	Mao et al. (2013)
Chile	4 Chilean Mountain Streams	–	18	Iroumé et al. (2015)
Chile	Blanco River	–	4	Ulloa et al. (2015)
Europe				
Basque	12 Iberian Streams	–	19	Diez et al. (2001)
Basque	Agueara Basin	–	4	Elosegi et al. (1999)
England	Highland Water	1	4	Dixon and Sear (2014)
England	Main Highland Water	–	1	Piégay and Gurnell (1997)
England	Upper and Main Highland Water	–	2	Gurnell (2003)
England	Upper Highland Water	–	9	Millington and Sear (2007)
France	Ain River	–	11	MacVicar et al. (2009)
France	Ain River	–	4	MacVicar and Piégay (2012)
Italy	Tagliamento River	–	3	Bertoldi et al. (2013)
Italy	Tagliamento River	1	–	Ravazzolo et al. (2015a)
Italy	Tagliamento River	–	8	van der Nat et al. (2003)
Italy	Piave River	1	1	Pecorari (2008)
Switzerland	Erlenbach River	1	–	Jochner et al. (2015)
Africa, Asia and Australia				
Namibia	Kuisab River	1	2	Jacobson et al. (1999)
Japan	Oyabu Creek	4	4	Haga et al. (2002)
Australia	Daly and Katherine Rivers	–	1	Pettit et al. (2013)

In addition to these values, we recorded potential explanatory variables: stream width (w), recurrence interval of largest event in Δt (RI), fraction bankfull of largest event in Δt (F_b), maximum log length in storage (L_{max}), study time frame (Δt), and reach length (Δx). We chose not to focus on diameter because the range of flows and channel types would hide any relationships related to diameter. Also, diameter was not as consistently reported as length. When available, we used reported bankfull widths; otherwise, we used reported width, reported mean or median width, or used the center of a given range. We were not overly concerned about the mix of types of width values because the error introduced from this is much smaller than the range of stream widths (1.5 m–927 m). When possible, we used the fraction bankfull reported for each study. If this value was not reported, we calculated the value based on reported discharge values for floods and bankfull or we estimated the value based on text descriptions, assigning a value of 0.5 for low flows, 1 for near bankfull flows, 1.5 for overbank flows, and 2 for very high flows. In some cases, too little information was given to determine fraction bankfull and this category was left blank. We did not attempt to estimate recurrence intervals and only used values for this category when reported. The final data set included 36 studies with 229 data entries (Supplemental data file *initialmobility.csv*). Channel widths (w) ranged from 1.5 to 927 m (median (M) = 7.2, $n = 223$), RI from 0.29 to 50 yr (M = 1.5, $n = 44$), F_b from 0.4 to 5.4 (M = 1, $n = 169$), L_{max} from 1 to 60 m (M = 20, $n = 229$), Δt from 0.01 to 13 years (M = 1, $n = 211$), and Δx from 0.04 to 240 km (M = 100 m, $n = 193$).

We computed dimensionless wood lengths as L_{max}/w (henceforth L^*). The L^* values ranged from 0.02 to 11 (M = 3, $n = 223$). Based on data availability, we simply used the maximum length of wood found in storage for the river to calculate L^*. When maximum log lengths were not reported, we used maximum log lengths from other wood studies on the same river or from similar regions. We chose not to use average length of wood because the size of the largest pieces reflects key pieces for jams and accumulations that moderate wood mobility. Another option would have been to use riparian tree heights, but these are commonly larger than wood found in the stream because most trunks break during the recruitment process. Maximum wood length might not be the best metric to calculate L^* because maximum length can be highly variable, depending on how many pieces are measured. No studies have thoroughly investigated how L^* should be calculated, so uncertainty remains regarding which log lengths should be used for comparison with stream width to maximize predictive power on wood mobility. Should maximum log length in storage be used, or L_{90} or L_{85} (analogous to D_{90} or D_{85} in sediment research)? We recommend that future studies more fully characterize the distribution of log lengths in storage. Additional reporting of other size fractions such as L_{90} and L_{85} might provide better metrics than L_{max} to use in calculations of L^*. Also, channel width is generally assumed to be width at bankfull, but there is no reason to limit L^* to just one width and this metric could be calculated at various stages of flooding.

In order to compare studies, we calculated the % net change in storage ((end-start)/start), redeposition rate (% end value that came), remobilization rate (% start value that left), stability rate (% of start that stayed or was repositioned), reposition rate (% start value that was repositioned), and % total mobile pieces (100 ∗ (came + left + repositioned) / (start + came)) in Δt. We suggest that % total mobile pieces as defined here is the best overall metric for mobility because this includes imported, exported, and locally transported wood as a fraction of all the wood that moved through storage during Δt. In many studies, it is unclear whether mobilized pieces were locally mobile or left the reach because no differentiation is made between repositioned pieces and downstream mobile pieces. The most commonly reported mobility variable was the remobilization rate because most studies were focused on exploring factors that influenced the relative stability of wood already in storage, not fluvial redeposition of previously transported or newly recruited wood.

We analyze transport distance by stream size using all reported values for distance travelled: minima, maxima, means, and medians (Supplemental data file *distance.csv*). We used all reported values in order to assess range of variability within travel and because travel distance from field data is limited. Although we would have liked to compare transport distance to transported wood lengths and diameters, many studies did not report transported log dimensions separately from stored wood dimensions. Thus, we were unable to extract this information for enough studies to achieve meaningful results.

3.2. Results

To obtain an overall sense for initial mobility during varying flows, we plotted % mobility values against fraction bankfull and against recurrence interval (RI) of the highest flow within the study period (Fig. 3). Most of the data are from flows under twice bankfull. Of the studies that reported RI, most were ≥1 year and <10 years. There is a strong stepped threshold for maximum mobility at bankfull discharge or the yearly recurrence interval. Below bankfull or for minor floods with less than yearly RI, the maximum possible mobility of stored wood is ~30%. For bankfull or higher discharges, maximum possible mobility jumps to ~80%. These thresholds bound a mobility envelope for stored wood. The outliers not contained within this envelope include mobility measurements after large morphological changes (van der Nat et al., 2003) or measurements of mobilization of newly recruited wood on an actively eroding meander bend (MacVicar et al., 2009) and in a braided river (Bertoldi et al., 2013).

The 30% percent low flow maximum mobility threshold (Fig. 3) is slightly lower than typical values for % of wood stored as individual pieces and % of wood in the regularly flooded channel (Table 7). This is expected because some of the individual pieces are probably above bankfull and some of the pieces below bankfull are probably within stabilizing jams or anchored. Comparing loose, unattached single pieces at varying stage heights to low flow mobility rates would be useful. If a consistent relationship holds, it may be possible to determine yearly, low flow, background wood flux based on wood elevations, akin to base flow on hydrographs.

To relate mobility to change in storage (ΔS), we plotted the % total mobility in relation to net change in storage (Fig. 4). Our compiled data show that a net change in storage of zero is associated with the widest range in mobility from zero to ~80–90%. A definable lower threshold for % total mobility based on % net change in storage is apparent in Fig. 4. This lower bound resembles a funnel that meets at a point and is nearly symmetrical for negative and positive net change for lower rates of mobility. This means that, on average, rivers are in equilibrium with wood inputs equal to outputs. This observation is also supported by Fig. 3, which shows little difference in the ranges of % mobility of wood that *came* or *went*. However, mobility between 30 and 80% is more commonly related to larger net gains in storage than net loss (Fig. 4). This probably reflects the influence that high flows have on recruitment of new wood. All mobility rates under maximum thresholds are possible for all flows (Fig. 3). The largest flows do not always transport the most wood from a reach and can even have zero mobility because mobility depends not only on absolute flow magnitude, but also on deposition patterns set by the sequence of prior high flows (e.g., Haga et al., 2002) and reach-scale biogeomorphic characteristics. Low reach-scale remobilization rates can occur alongside high reach-scale redeposition rates, or vice versa, resulting in increasing or decreasing trends in total reach wood storage. Whether a reach has net increasing or net decreasing trends in stored wood impacts wood export yields for future floods. The asymmetry toward net accumulation of wood in storage for events with >30% mobility (Fig. 4) could reflect larger scale patterns of global wood accumulation in rivers as a result of afforestation, effects of disturbances such as fire on wood loads, or decreasing frequency of high peak flows from flow regulation.

To understand mobility across stream sizes, we plotted percent initial mobility and transport distance against channel width and L^* (L_{max}/w) (Fig. 5). The explanatory variables w and L^* were plotted on a log scale as well as untransformed to better display the results from the 900-m range in channel widths. Maximum potential wood mobility

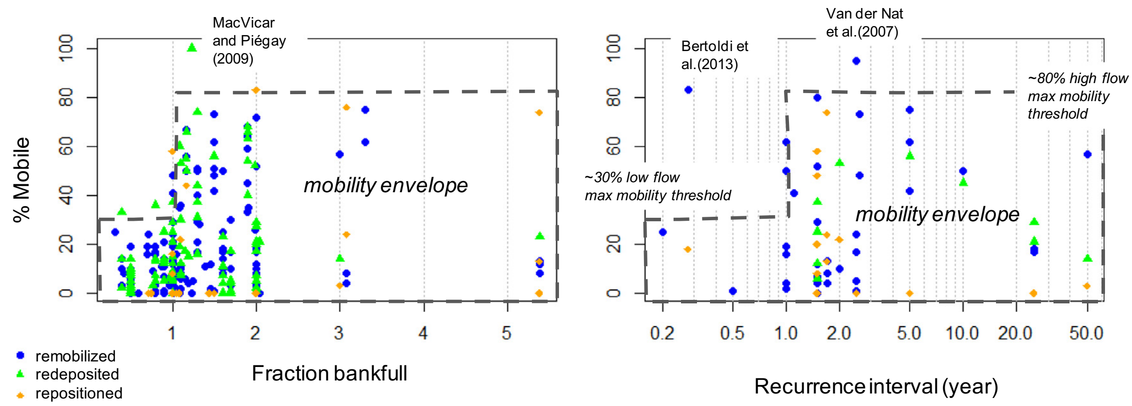

Fig. 3. Mobility of wood in relation to flow. Left: Mobility related to fraction of bankfull from the highest discharge in the study period. Right: Mobility related to highest recurrence interval flood within study timeframes. Dashed lines annotate possible mobility thresholds outlining a mobility envelope. Data are provided in the supplemental file *initialmobility.csv*.

(drawn as the upper dashed threshold in Fig. 5) increases as channels become wider up to ~3 m, at which point maximum mobility stabilizes at ~80–90% up to ~20 m channel width, then decreases until channels are >100 m wide, beyond which mobility likely stabilizes again, although we lack the data to definitively show this.

If L^* is used rather than absolute stream widths, this relationship of increasing maximum mobility from small to medium channels ($L^* < 5$), constant maximum mobility for medium channels ($5 \geq L^* \geq 1$), and then decreasing mobility for large channels ($L^* < 1$) becomes more clear, with fewer outliers (Fig. 5). Outliers not contained within the mobility envelope (Fig. 5) are from a study of remobilization of recently recruited wood from a volcanic eruption (Ulloa et al., 2015), mobilization of wood from one actively eroding meander bend (MacVicar and Piégay, 2012), and remobilization of wood due to large morphological changes in braided rivers (van der Nat et al., 2003; Bertoldi et al., 2013).

The braided river data may be plotting outside mobility envelopes because of inappropriate values for stream width used in the calculation of L^*. The estimated channel width carrying water was not reported for different flows, so we had to use the channel width of the entire valley bottom. Channel widths change substantially with small changes in stage along braided rivers. As a result, many of these outlier values may actually plot closer to a medium-sized river for low flows, large river for high flows, and possibly a great river for extremely high flows. Also, diameter is an important mobility variable in braided systems where depth and width change rapidly with small fluctuations in flow (Welber et al., 2013). Thus, similar graphics as in Figs. 3 and 5 that replace L^* with a dimensionless log diameter, D^* (Diam/flow depth), may highlight mobility patterns in braided rivers and on floodplains that we were unable to capture in this analysis.

Transport distances plotted against channel width and L^* fall into two main groups, which are depicted as two separate shaded boxes on Fig. 5, corresponding to medium and large rivers. A discontinuity exists between 0.5 and 1 L^*, when typical maximum log lengths are less than the channel width but greater than half the channel width. This discontinuity occurs at the transition between medium and large rivers (between ~20 and 50 m channel width). The mean recovery rate from studies for tracked wood was ~50–70% and ranged as low as 0% for studies that reported transport distance at reach length. Even though not all wood was recovered, and thus maxima are not true maxima, transport distances appear to be about two orders of magnitude higher for large rivers than for medium rivers. The median travel distance (calculated from all reported values: max, means, and mins) for each group is drawn as a solid black line on Fig. 5 (bottom row) and is close to 100 m for small-medium rivers and one to two orders of magnitude higher for large rivers. The one outlier is from experimental release and tracking of smaller pieces of wood in a cleaned mountain channel with no obstructions (Haga et al., 2002). Because of the small size of wood pieces used in the experiment, this study plots as a medium river when plotted by channel width, but a large river when considering the size of wood in the experiment in relation to channel width.

Table 7
Case study values for percent pieces in storage that could be potentially mobile in lower flows. % Ind. is the percent of wood surveyed as individual pieces, and % ubf is the percent of wood in the regularly flooded channel between low flow and bankfull.

River (reference)	% Ind.	%ubf
East Fork (Berg et al., 1998)	23	–
Empire (Berg et al., 1998)	<1	–
Lavezolla (Berg et al., 1998)	27	–
Badenaugh (Berg et al., 1998)	2	–
Sagehen (Berg et al., 1998)	25	–
Pauley (Berg et al., 1998)	9	–
Veulta de la Zorra (Ulloa et al., 2011)	50	47
Pichún (Ulloa et al., 2011)		20
Tres Arroyos (Mao et al., 2013)	88	–
Sacramento (MacVicar et al., 2009)	66	40
Kuisab River (Jacobson et al., 1999)	54	–
Lower Roanoke (Schenk et al., 2014)	50	44
Kochino-tani Creek (Haga et al., 2002)	66	–
Crows Creek (Young, 1994)	25	55
Jones Creek (Young, 1994)	37	41
Upper Missouri (Angradi et al., 2004)	39	–
Upper Missouri (Angradi et al., 2010)	86	30
Mean	43	40
St. dev	27	21

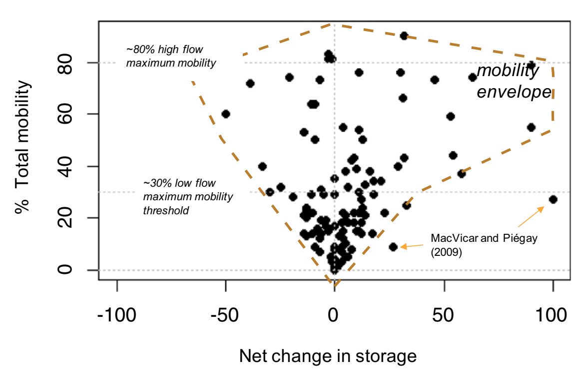

Fig. 4. Total mobility of wood in relation to percent net change in storage. Dashed line defines a mobility envelope, marked outliers are discussed in the text. Low and high flow thresholds are from Fig. 3. Total mobility was calculated as the amount of wood that was mobile (redeposited, remobilized and repositioned) divided by the total amount of wood in storage within the timeframe (original amount plus the amount that was newly deposited). Data are provided in the supplemental file *initialmobility.csv*.

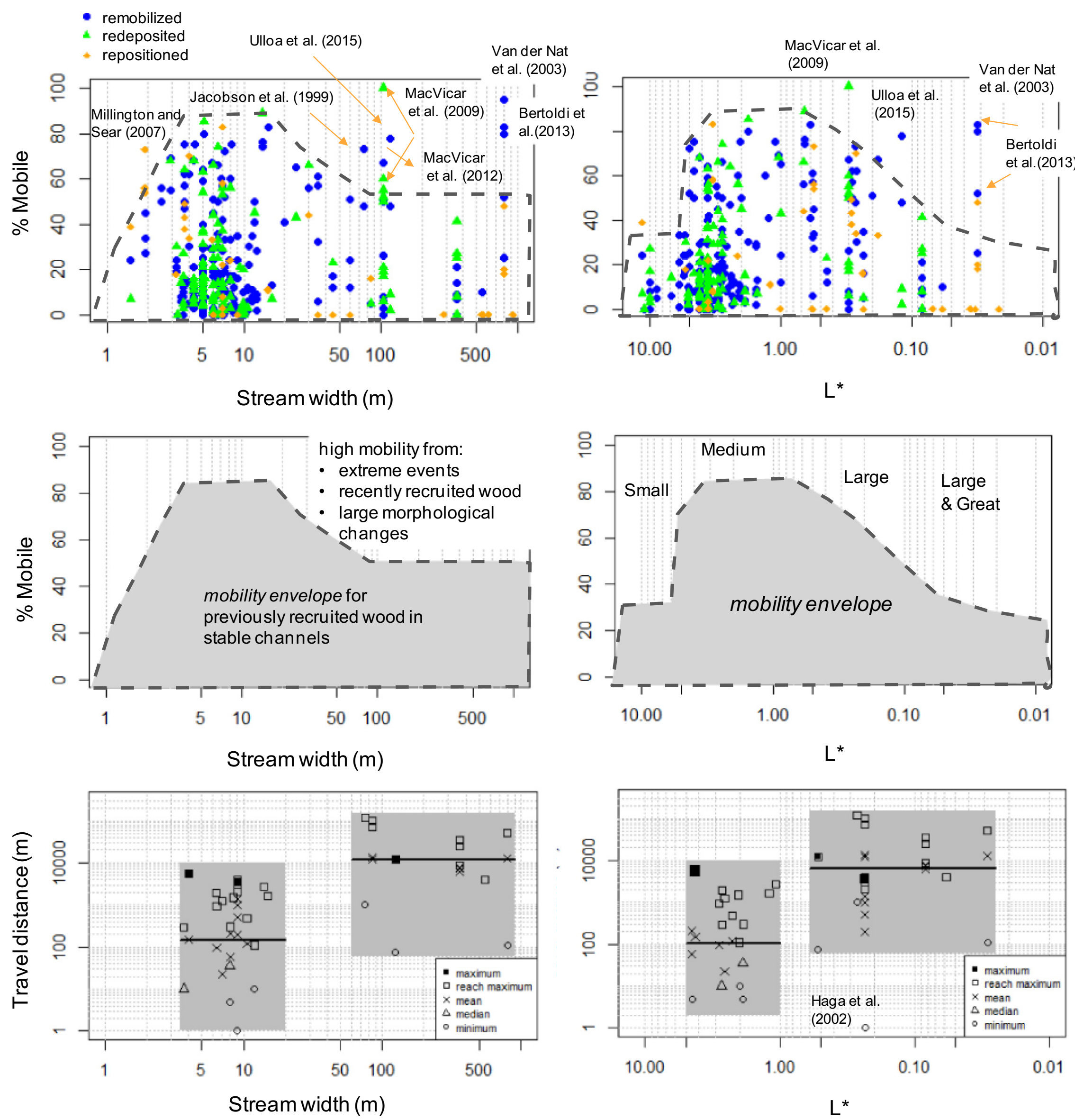

Fig. 5. Mobility of wood in relation to stream size as width (left) and dimensionless length, L^* (right). L^* is maximum wood length in storage divided by channel width. Log scales are used to better show patterns across the wide data range. Top row: presentation of initial mobility data; dashed lines define mobility envelopes. Middle row: interpretation of initial mobility data. Bottom: presentation of downstream mobility data. Solid lines mark the median transport value within each shaded grouping. Marked outliers outside of mobility envelopes are discussed in the text. Data are provided in the supplemental files *initialmobility.csv* and *distance.csv*.

One analysis that we would like to conduct is to compare flow (as RI or fraction bankfull) to the ratio: L_{max} of transported wood/L_{max} of wood in storage. Unfortunately, few studies reported the length characteristics of transported wood and the length characteristics of wood in storage in a manner that facilitated comparison. Or, studies did not include values of flows that transported wood compared to either bankfull or to the gage record. We recommend that future studies of wood mobility report size characteristics of transported wood, size characteristics of the nontransported wood, and recurrence interval or proportion of bankfull for flows.

The transition between medium and large rivers is usually placed at $L^* = 1$. Our plots of % mobility against L^* (Fig. 5) reveal that most observations of mobilization have been conducted in medium-sized rivers with maximum log length between two and five times channel width. Our plots of % mobility and transport distance suggest that the transition between medium and large rivers occurs between $L^* = 1$ and $L^* = 0.5$. Although maximum initial mobility may be maximized for medium channels (Fig. 5), median mobility measurements increase with increasing channel size (Fig. 6), increasing from 9% in small channels ($n = 23$) to 14% in medium channels ($n = 136$), 32% in large channels ($n = 45$), and 80% in braided large rivers (although this sample size is small, $n = 5$).

Several field studies have empirically modelled probability of movement and downstream transport, and we summarize their approaches and equations in Appendix A. The probability of movement typically is modelled from change in storage using logistic functions with wood characteristics as explanatory variables (Lassettre and Kondolf, 2003; Wohl and Goode, 2008; Merten et al., 2010). Variables typically include length or length related to bankfull width, categorical variables for anchoring or rootwads, and diameter related to flow depth. Numerical simulations of wood flux based on physical modelling of a 10 year flood on the Czarny Dunajec in Poland present transport ratios (the amount of wood exported divided by the amount imported) as linear functions of wood volume, effective depth, and dimensionless wood length (L^*), as well as exponential functions of wood density separately for single- and multithread reaches (Ruiz-Villanueva et al., 2015c).

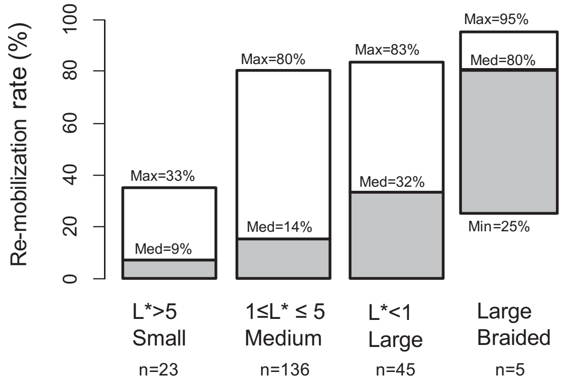

Fig. 6. Remobilization rates by stream class. Extent of bars is the range of the data. The shaded grey portion extends from the minimum to the median values.

Nonlinear functions of transport ratios related to varying discharge are also presented in which Ruiz-Villanueva et al. (2015c) show that the transport ratio response is different between more (RI < 10–15 years) and less frequent events. Iroumé et al. (2015) found linear relationships between percent mobility of stored pieces and flow characteristics such as the unit stream power at maximum stage height and the ratio of maximum stage over bankfull stage.

Transport distance has been modelled using exponential functions to reach retention rates (Millington and Sear, 2007) and water depth at peak flow (Haga et al., 2002). Transport distance has also been modelled as a function of jam spacing (Martin and Benda, 2001; Lassettre and Kondolf, 2003), although this may have limited application to low flow conditions when jams are completely obstructing the channel and are not mobile.

Although variables modelled in empirical field-derived equations for wood mobility (Appendix A) can be similar, most of the studies listed modelled different response variables (wood velocity, percent mobile, probability of key piece mobility, travel distance) because each study was focused on different goals. To facilitate comparison of mobility between case studies and between rivers of differing size, we suggest that field scientists focus effort on empirical formulation of % mobility and travel distance. As we have shown in Section 3, % mobility can be calculated in many ways (e.g., % start that left, % end that came). We suggest developing equations of mobilization that predict the % of starting value that leave the reach or are repositioned within the reach because this will facilitate estimation of wood flux from measured storage values. However, we highly recommend always reporting the raw volume or count values of changes in storage so that other researchers can recalculate mobility in other forms.

4. Discussion

4.1. Mobile wood and management

The origin of instream wood research as a discipline can be traced back to the Pacific Northwest (Oregon, Washington, and British Columbia) during the mid-1970s to early 1990s, where government foresters and fish ecologists became interested in the role of wood for improving fish habitat. Early research into wood transport was primarily motivated by the desire to understand the stability of wood in streams because investigators thought that the longevity of instream wood influences the quality of fish habitat (Anderson and Sedell, 1979; Keller and Swanson, 1979; Hogan, 1984; Harmon et al., 1986; Bilby and Ward, 1989; Nakamura and Swanson, 1993).

But even the largest pieces of wood and jams in natural channels can move. When engineered structures are anchored in mobile systems, restoration projects are sometimes declared unsuccessful over timeframes of 5+ years because most of the wood structures are destroyed by large floods or bank erosion (e.g., Shields et al., 2006). Engineered wood structures can be ecologically significant even if they do not stay in place (Choné and Biron, 2015). In a compelling paper on wood mobility and ecological function, Daniels (2006) found that although wood in a low gradient meandering river was too mobile to have more than a short-term impact on the morphology or hydraulics of the channel, wood did directly impact bed storage of organic material in a manner that outlasted the residence of the wood and provided valuable ecosystem services to benthic communities. Thus, the mobility of wood allows patchy deposition of nutrient-rich organic material to cover a greater spatial extent of the stream bed. If wood is always anchored in place, then organic material deposition is limited to those areas near anchored wood.

Although rehabilitation with anchored wood may be appropriate for reaches in which wood is naturally less mobile, anchored wood is inherently flawed for reaches in which natural processes facilitate the regular and episodic transfer of wood over time periods shorter than those of desired beneficial ecological outcomes. Wood naturally moves downstream or laterally onto floodplains, so the best and most cost effective management practice is to ensure that the stream has a supply of new wood, preferably including some large pieces, via upstream recruitment from riparian forests, and then allow the river to redistribute and repeatedly mobilize the wood (Kail et al., 2007).

If management strategies are adopted to increase unanchored wood loads, there are concerns that the mobile wood will endanger instream structures and increase flood damage from clogging. These concerns have merit because higher wood loads can facilitate more recruitment during floods (Johnson et al., 2000). However, field evidence indicates that increased amount of wood in storage along a reach does not translate to increased wood against bridges, as presumed, but instead may decrease the hazard of wood clogging by increasing the likelihood that the pieces will be trapped on log jams and complex channel margins before accumulating against structures (Lassettre and Kondolf, 2003; Mao et al., 2013). Most wood comes from pieces recruited from upslope landslides and bank failures during a flood, not from previously transported fluvial wood (Lassettre and Kondolf, 2003; Lucía et al., 2015). Thus, the common management practice of removing instream wood may actually facilitate the downstream mobility of these newly recruited pieces, rapidly delivering them to the first available obstruction: often bridges, weirs or other built structures. Rather than removing wood, Lassettre and Kondolf (2003) recommended that the most economical option would be to replace culverts and bridges with structures designed to pass wood typical for a stream.

4.1.1. Storage patterns and transport processes

Stored wood characteristics have been used to develop wood budgets to infer wood flux and transport distance (e.g., Martin and Benda, 2001) because the pattern of wood stored in river networks is assumed to reflect input and transport processes (Keller and Swanson, 1979; Davidson et al., 2015). As we have shown and others have noted (e.g., van der Nat et al., 2003), flows under bankfull generally transport <30% of the stored wood, roughly corresponding to available loose wood positioned under bankfull stage (Fig. 3, Table 7). However, the linkages between wood transport and wood storage are poorly defined and complex and thus the interpretation of wood transport only through patterns in storage is limited. Video monitoring of wood in active transport on the Ain River, a large meandering river in France, has shown that estimates of wood export derived solely from storage and recruitment characteristics may be underestimating actual wood flux by two to ten times (MacVicar and Piégay, 2012).

The main shortcoming is that storage characteristics only provide a snapshot of conditions based on the time interval monitored, limiting inferences regarding short- or long-term temporal fluctuations in transport from seasonal resurveys of storage. Another problem is substantial variability on the reach scale caused by increases or decreases in channel retentiveness and trapping sites both longitudinally along a river

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and with changing flow stage (Bertoldi et al., 2013). For example, Iroumé et al. (2010) found that, for low order, mountain headwater channels in Chile, wood movement (% pieces mobilized) only occurred in a few reaches. Also, a large discontinuity in wood storage and transport processes exists between flows that access floodplains and those that do not (MacVicar and Piégay, 2012; Dixon and Sear, 2014). Thus, when estimating wood flux from field measurements, results can be highly dependent on design and spatial and temporal extent of sampling.

The largest advances in linking transport processes to wood export and storage characteristics have been made in flumes with simplified wood and mobile banks. These flume experiments have expanded the understanding of linkages between input rates and storage regimes (Braudrick et al., 1997; Bocchiola et al., 2008; Bertoldi et al., 2014), entrapment processes related to the interaction of channel form with wood and flow characteristics (Braudrick and Grant, 2001; Bocchiola et al., 2006a; Welber et al., 2013), and how live wood moderates and controls storage and export (Bertoldi et al., 2015). Although these physical models are useful, they are simplifications of the complex interactions found in the field. The combination of infrequent, complex field observations coupled with frequent yet simplified scaled measurements in flumes and models yields the biggest advances, as in Ruiz-Villanueva et al. (2016b).

4.2. Regular and episodic transfer of wood

Wood transfer is both regular and episodic. Jochner et al. (2015) described a four end-member conceptual model linking combinations of continuous recruitment and export with episodic recruitment and export. Even in the Pacific Northwest, which is known for more stable logjams, there are high rates of movement, especially for the smaller fractions of large wood, such that wood flux is a constant process (Keim et al., 2000). Juxtaposed on this constant flux is large-scale, episodic flux of the biggest jams and largest pieces during floods with long recurrence intervals.

We have conceptualized regular versus episodic flux of wood in storage in Fig. 7. The stepped profile of wood storage in the diagram relates to small episodic delivery and export of wood and the large steps represent rarer episodic wood fluxes. Small channels have large episodic wood flux but minimal to no yearly regular flux; whereas larger river have more frequent regular flux but smaller scale episodic flux attributable to the increased sites of deposition on floodplains during large flows. Plots such as Fig. 7 for different timescales could illuminate links between wood storage and flux through time and help to characterize variability in wood storage as a function of time, as done by Kramer et al. (in press). Developing such plots would involve continued monitoring of known sites of wood retention via cameras (minutes to days), field revisits (months to years), and satellite or remote imagery analysis (years to decades). Especially useful would be measuring the flow stage or discharge so that sudden changes in wood storage could be more easily linked to hydrology.

Most studies are yearly resurveys that include multiple high flows rather than investigating the impact from one flood, which is problematic for relating wood to flow because wood movement is an episodic, flood-driven process. Thus, there is a disconnection between how mobilization is measured and the process that drives mobilization. Some studies have used cameras or GPS trackers to monitor change in storage at finer timescales (Bertoldi et al., 2014; Ravazzolo et al., 2015b) and others have made efforts to return to field sites during (Schenk et al., 2014) or immediately after floods (Dixon and Sear, 2014). We recommend that more investigators attempt to differentiate wood mobility for each wood-transporting flow rather than simply finding the yearly averaged change in storage.

Our quantitative analysis shows that when flows are sufficiently high, large amounts of wood are episodically recruited to or exported from reaches, with potential for about 80–90% turnover for remobilization of fluvial wood (Fig. 3). The highest turnover rates are for new recruits and in areas with large morphological changes (see Section 3). However, for a typical year, there also appears to be a background flux of wood for low flows that is at maximum ~30% of the total amount of wood in storage (Fig. 3). Additional data collection focused on the goal of separately measuring smaller-scale yearly flux versus flux from more rare, episodic large flows with potential for high flux would be useful, as would constraining thresholds (for volume of export and for recurrence interval) between the two types of wood transfer. Consistent low-flow flux rates may be related to elevations of loose wood below bankfull. If this relationship holds true, then wood stored within the low flow channel could potentially be used universally to obtain rough estimates of background wood exported from basins. On top of this background rate, episodic flux could be estimated or modelled based on characteristics of flow, wood, and the channel reach.

Despite having high interannual variability, most systems appear to be in dynamic equilibrium with regard to wood storage and export (conceptualized in Fig. 7). Commonly, wood mobilization studies note that wood mobilized out of a reach or buried is replaced with new wood so that the total storage volumes remain nearly the same with little net change from year to year (Benke and Wallace, 1990; Marcus et al., 2002; van der Nat et al., 2003; Wohl and Goode, 2008; Schenk et al., 2014). Thus, remote sensing studies that only record changes in total volumes within a reach may report low mobility because of little net change in volume, when in fact there was high mobility in piece to piece exchange not identifiable from greater observation distances (e.g., Curran, 2010).

4.3. Wood transport capacity

The phrase *transport capacity* is used liberally in wood research to refer to reaches that do not store large amounts of wood. The most general definition of capacity is the original given by Gilbert and Murphy (1914): 'the maximum load a stream can carry (35). With regard to wood, transport capacity is determined by the effectiveness of a reach at retaining wood for a particular flow (Marcus et al., 2002). At low

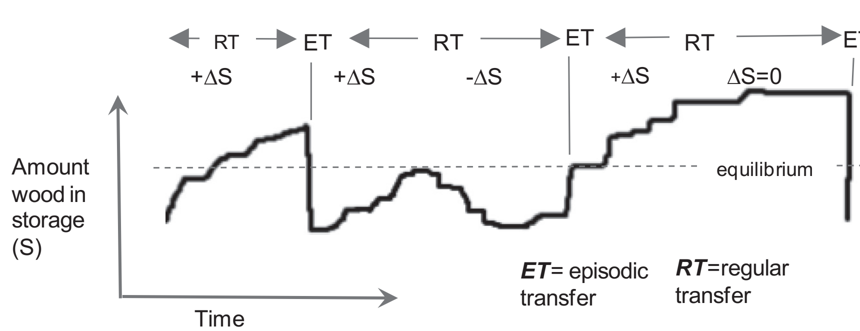

Fig. 7. Conceptual model of dynamic equilibrium of wood in storage (*S*) through time. Stepped profile reflects alternating smaller scale regular transfer (RT) and large-scale episodic transfer (ET) of wood.

flows, many reaches are transport limited and cannot pass wood, especially wood of large sizes. At high flows when wood transport occurs, in almost all cases, rivers can pass most of the wood supplied, so that all but small natural rivers are commonly supply limited at peak wood flux. As flood waters recede, transport capacity decreases.

The rate and timing of decreased transport capacity on the falling limb depend not only on the steepness of the falling limb but also on reach and wood characteristics. Blanket statements that refer to reaches as having low transport capacity are not particularly helpful because transport capacity is not a fixed quantity (Lisle and Smith, 2003) but is dependent on wood supply, water levels, and channel retentiveness. Much research on sediment dynamics has focused on better understanding the transition between a particle moving as bedload or suspended load, or immobile to mobile during discharge pulses in flumes and natural settings. Similarly, developing relationships between water levels and channel retentiveness for wood pieces of varying sizes as rivers transition from supply limited to transport limited on the falling limbs of floods would be useful. Basically, when and where does wood transition from immobile to mobile and back to immobile?

Borrowing from bedload research, we have constructed two conceptual models showing transport regimes of wood related to water stage. In Fig. 8 (top), we diagram theoretical thresholds for wood movement regimes for a single log as a function of transport stage (ratio of water stage over stage at incipient motion (H_t/H_i)) on the rising limb of a hydrograph. In Fig. 8 (bottom), we depict hypothetical mobility regimes related to discharge as a fraction of bankfull (Q_t/Q_{bf}).

Transport regimes in Fig. 8 (top) include (i) moving in contact with the channel, (ii) deflecting against channel boundaries, and (iii) unimpeded floating. Mobility regimes in Fig. 8 (bottom) include immobile, partially mobile, and fully mobile wood loads. Again borrowing from sediment research, we define immobile, partially mobile, and fully mobile as <10%, 10–90%, and >90% mobilization of wood in storage, respectively. These categories can also be conceptualized based on downstream movement as *not moved*, *locally repositioned*, and *exported downstream*. These conceptual models could easily be tested, developed, and refined. They can also be used for visual display of differences in threshold position as piece sizes change or for different hydrologic or channel conditions.

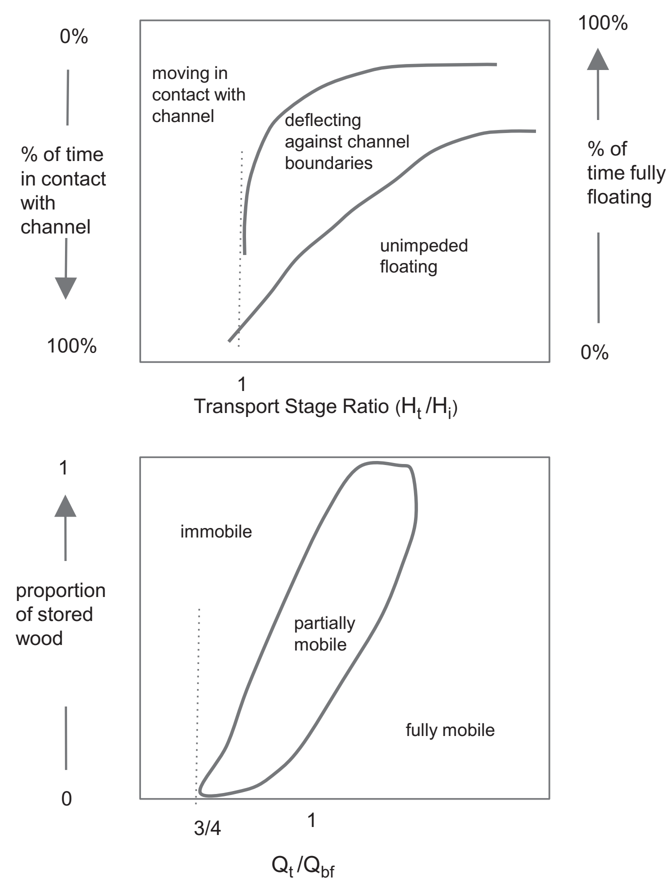

Fig. 8. Conceptual transport regimes and thresholds as functions of flow. Models inspired by data supported conceptualizations of bedload particles by Haschenburger (2013). Top: Movement regimes of single logs as a function of transport stage (stage height at time t (H_t)/stage height at initial mobilization (H_i)). At the threshold for movement (1), there is a sharp decrease in the time that wood spends in contact with the bed and the time that it spends floating starts to increase. As stage increases, wood spends more time floating and less time deflecting off of channel features. In this figure, logs do not float for 100% of the time because sometimes logs become beached for shorter amounts of time before continuing downstream. Bottom: Mobility regimes as a function of discharge at time t (Q_t) relative to bankfull (Q_{bf}). Position of thresholds depicted could change depending on patterns of antecedent floods, recruitment events, flow stage, and changing channel characteristics. Mapping how thresholds change for changing conditions may be a fruitful endeavor.

4.4. Downstream wood transport

The downstream transport distance of a sediment particle is commonly described as path length, which is the total lifetime streamwise displacement of particles, composed of multiple step lengths separated by rest periods (Haschenburger, 2013). Analogous to this is the spiralling metaphor for wood movement introduced by Latterell and Naiman (2007) and revitalized in the recent review by Wohl (2016, this issue). The spiral metaphor describes the lifetime transport of wood as a series of spirals along a path: The spirals represent rest periods, and the width of the spirals depict residence time. The distance between spirals is the step length between resting locations. We have redrawn the spiral metaphor in the context of a fluvial system in Fig. 9 to show hypothetical differences in rest periods from small to great rivers and downstream mobility on floodplains. Quantifying and contrasting the density functions of step lengths and rest periods for different rivers and through basin networks could be a useful manner in which to identify longitudinal and regional patterns in wood mobility.

The length of wood is arguably the most important control on how wood behaves (where it is stored and when it is mobilized). Diameter (or flotation depth) is also an important variable when flow depths are similar to flotations depths (see Section 2.2). In our quantitative analysis, we used L^* (length of wood/channel width) to place channels into woody dynamic size categories of small, medium, large, and great (Fig. 5). The L^* proved to be a useful dimensionless metric that allowed for easy comparison of wood mobility metrics across stream type and size. However, as discussed in Section 3, more work needs to be done to determine which length of wood should be used in the L^* equation to maximize predictability of wood mobility. Should this be L_{max} or a smaller size fraction like L_{90} or L_{85}? Also, MacVicar and Piégay (2012) suggested using $\phi = log_2\ (L)$ to define wood size classes, as done by Cadol and Wohl (2010) and Iroumé et al. (2010), and as used to define sediment size categories. Although this idea has not thus far garnered much support from field scientists, the base 2 log transform of wood lengths has proven useful when modelling and explaining wood mobility.

Despite the importance of rootwads for limiting mobility and transport distances (Wohl and Goode, 2008; Davidson et al., 2015), almost no information exists relating rootwad size, type, and shape characteristics to mobility beyond noting presence or absence. One exception is a recent flume study that suggests that shorter bole lengths on pieces with rootwads actually increases stability over longer lengths (Davidson et al., 2015), but this is yet to be corroborated in the field.

Investigators commonly assume that the transport of wood increases as the widths of channels increase relative to the length of wood, and therefore larger rivers have greater transport capacity than smaller rivers. Although potential transport distance appears to be two orders of magnitude greater for channels wider than maximum

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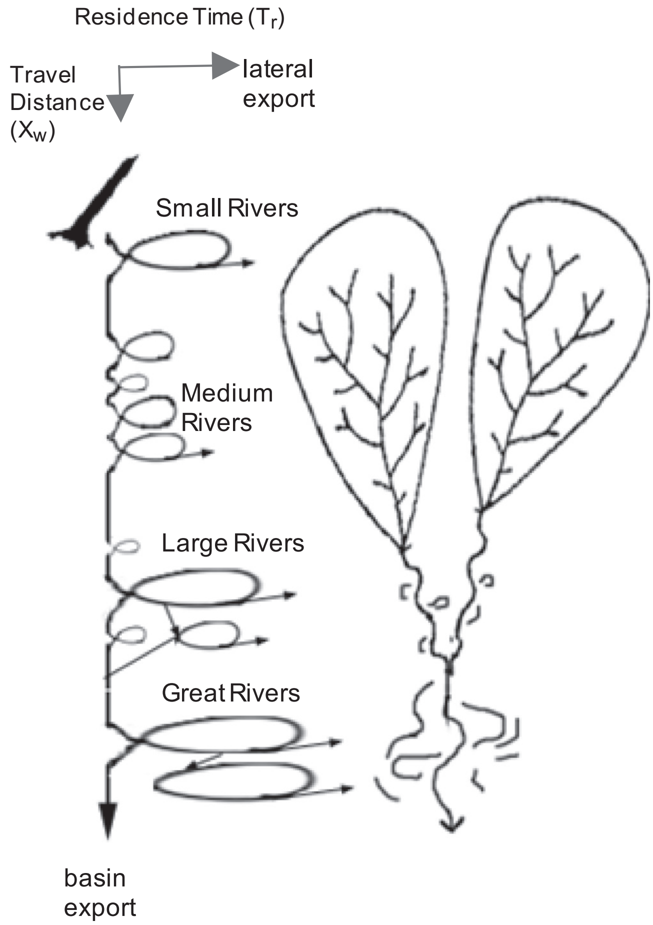

Fig. 9. Conceptual model of the spiralling movement of large wood through a fluvial system. Size of loops represent residence times at a single location before reentering transport. Connected loops to the side of the main vector represent downstream transport on a floodplain. The lifetime for a piece of wood from its starting location in the channel to its final resting place is the sum of all the residence times and the travel time (most likely very small compared to rest periods). The distance travelled is the sum of all the step lengths. Throughout the lifetime of the wood piece, from source to sea, the piece undergoes vertical, lateral, and downstream exchanges. Along any spiral, a piece of wood may decay in place, ending its path. Diagram after Latterell and Naiman (2007) and Schumm (1977).

log lengths (Fig. 5), potential mobilization of wood in storage between channel sizes is nuanced. Median values of mobilization increase with increasing channel size, which suggests that larger channels do transport higher proportions of stored wood more regularly than smaller channels (Fig. 6). However, event-based turnover of stored wood is maximized in medium channels (Fig. 5). Lower maximum mobilization rates on large rivers compared to medium rivers seem reasonable because the stored wood in larger rivers is more likely to be partially buried or scattered on floodplains at farther distances from the main channel. Medium-sized channels are typically more confined than large or great rivers, with smaller floodplains and coarser substrate. Consequently, most of the stored wood in medium rivers is closer to the thalweg, where flow velocities are the greatest and less opportunity for anchoring via burial or by instream live-wood. We suggest that the live-wood growing on islands, bars, and frequently inundated floodplains likely counterbalances the increased conveyance of wood in larger rivers.

Unfortunately, general ignorance of the relative importance of factors influencing downstream transport of mobilized wood exists due to the scarcity of studies that actually track transport of wood during floods. We found 17 studies that tracked wood via tagging, RFID, or tethered GPS boxes. Of these, only two actually tracked all wood regardless of how far each piece travelled (Dixon and Sear, 2014; Ravazzolo et al., 2015b). Two other studies had 100% recovery for a year because they were able to recover the one piece that moved during lower-than-average flows (Pecorari, 2008; Schenk et al., 2014). Because maximum transport distances were commonly bounded by study reach lengths, reported mean transport distances do not reflect the entire transported population.

4.5. Functional classification from wood dynamics

In this paper, we have used functional guidelines to differentiate small, medium, large, and great rivers based on wood dynamics (Table 1, Fig. 2). Originally introduced by researchers in the Pacific Northwest (Keller and Swanson, 1979; Nakamura and Swanson, 1993) and succinctly summarized by Church (1992), this functional classification of streams has been utilized in Europe (Piégay and Gurnell, 1997; Gurnell et al., 2002) and more recently revitalized in the context of relative importance of inputs and outputs in wood budgets (Wohl, 2016, this issue). Categorizing rivers based on wood characteristics is justified for forested channels because the geomorphology of these channels is wood-driven (Le Lay et al., 2013) and, as channel size increases, the behaviour of wood also changes (Church, 1992; Gurnell et al., 2002; Wohl, 2016) (Table 1).

Because channels are not subdivided into these categories based solely on their size but on the patterns and functions of wood within them, Church (1992) makes the point that a small river could behave like a large river if all the wood being transported is less than the width of the channel. However, referring to headwater reaches as large when they do not carry larger pieces of wood is confusing and not visually intuitive. Because the names of these functional categorizations are small, medium, large, and great, there will always be a propensity to classify them into these categories strictly by channel size rather than by incorporating wood dynamic process domains as originally intended.

Although the functional wood dynamic classification (Table 1) connects certain wood process regimes to sizes of channels and thus enables testing of general network trends, it fails to capture spatial and temporal network heterogeneity. For example, a small creek may have some reaches that are like a small channel (recruitment-dominated) and others that behave like a medium channel (jam-dominated). In addition to referring to rivers by size class to convey scale, we suggest classifying rivers by process domains related to definable regimes of wood dynamics. Universal, succinct process domain categories are useful to facilitate comparison among studies, to explore the temporal-spatial distribution and heterogeneity within channel networks, and to identify sets of predictive equations that perform better under different regimes.

One option is to designate process domain names that refer to the dominant storage, transport, and recruitment regimes. Davidson et al. (2015) described two storage regimes, a randomly distributed, newly recruited state and a self-organized jam, stable state. Braudrick et al. (1997) described three transport regimes: congested, semi-congested, and uncongested flow. We suggest that primary reach-scale wood process domains are recruitment-dominated regimes, jam-dominated regimes, flow-dominated regimes, and burial/exhumation-dominated regimes. Additional process domains are also possible. For example, flash-flood-dominated regime might be the best category for desert ephemeral channels. Jochner et al. (2015) present a compelling, four end-member conceptual model of wood regimes as event-driven export (continuous recruitment, episodic export), event-driven delivery (episodic recruitment, continuous export), fully episodic (episodic recruitment and export), or fully continuous (continuous recruitment and export).

Reach-scale process domains likely transition through time from one regime to another because of fluctuations in flow and changes in morphology, disturbance, or system wide trajectories caused by regional drivers such as climate change or alterations of land use. Once a consistent set of process domains is defined, this can be used as a tool to explore and map temporal and spatial transitions between process domains.

4.6. A discontinuous network - the traffic metaphor

Wood dynamics are different for differently sized streams, and delivery of wood from one part of a stream network to another is a discontinuous or episodic process, as depicted in Figs. 7 and 9. Thus, we propose that an apt metaphor for wood transport is vehicle traffic. Just as hydrology, wood characteristics, and biogeomorphic reach characteristics control the movement of wood through stream networks (Gurnell et al., 2015), motivation to travel, type of vehicle, and road conditions govern how people travel through road networks.

If hydrologic conditions do not meet base thresholds, little to no wood flux occurs, which is analogous to the underlying motivations that govern when and how far people will travel (i.e., wood transport mobilization and travel distance) and when and where they are stationary (i.e., wood residence time). Sometimes, special events cause extra, congested traffic. This is similar to high wood congestion caused by large disturbances. More commonly, daily routines and work commutes govern traffic conditions. This is similar to regular background wood flux from normal yearly floods. Travelling at night is less common and only under special circumstances will drivers be on the road during this time. This is similar to lack of wood flux during low flows unless wood is newly delivered from a localized bank failure.

Wood characteristics can be thought of as the type of vehicle in which one is travelling. The vehicle governs which paths or road can be taken and the speed of travel. Someone on a motorized scooter will take different paths than other vehicles, just as a small piece without a rootwad may take a different path than larger pieces with rootwads. However, in some conditions, such as a traffic jam, everyone travels the same speed, which equates to fully congested wood transport.

Traffic conditions and movement are not only governed by the motivation (hydrology) and the vehicle (wood characteristics), but the state of the roads, which controls how fast or how slow a destination is reached. Road conditions are similar to how biogeomorphic characteristics of reaches, such as presence of live-wood, degree of confinement, channel planform complexity, density of logjams, access to floodplains, and other factors that can limit or increase the distance and rate of movement of wood downstream.

We have conceptualized this metaphor in Fig. 10 as a flow chart of stoplights. Whether a piece of wood will be moved at any given moment can be predicted by whether the piece meets minimum mobility thresholds that allow it to go forward (green), possibly move or progress slowly (yellow), or stop (red). We first assess hydrologic conditions for transport to determine whether wood meets minimum thresholds for mobility prior to assessing wood or reach characteristics. If a piece of wood has potential to be transported based on hydrology, then the unique interactions between its characteristics and the channel are assessed. Thus, for any moment of time, a snapshot can be used to assess where individual wood pieces are located and whether they are likely to move based on the hydrologic, wood, and channel *traffic conditions* (see Fig. 10). Assessments made over the course of a flood can be used to provide estimates of the overall efficiency of wood movement for specific floods. We recognize that this model is a simplification of the complex interactions involved. However, we consider the model a useful framework for modelling and exploring temporal variations in wood flux.

4.7. Moving forward

The main limitations to describing wood transport are inadequate observation timescales and lack of sufficient mobility data from diverse rivers and regions that also capture variability between reaches. These are similar hurdles to quantifying bedload. Bedload transport equations do not perform well for coarse-grained substrate with poor sorting because they fail to integrate spatial and temporal complexities that influence grain entrainment (Haschenburger, 2013).

In order to improve models of wood flux on local and regional scales, we need better characterization of average step lengths within the lifetime travel path of a piece of wood (see Fig. 9), and we need a better

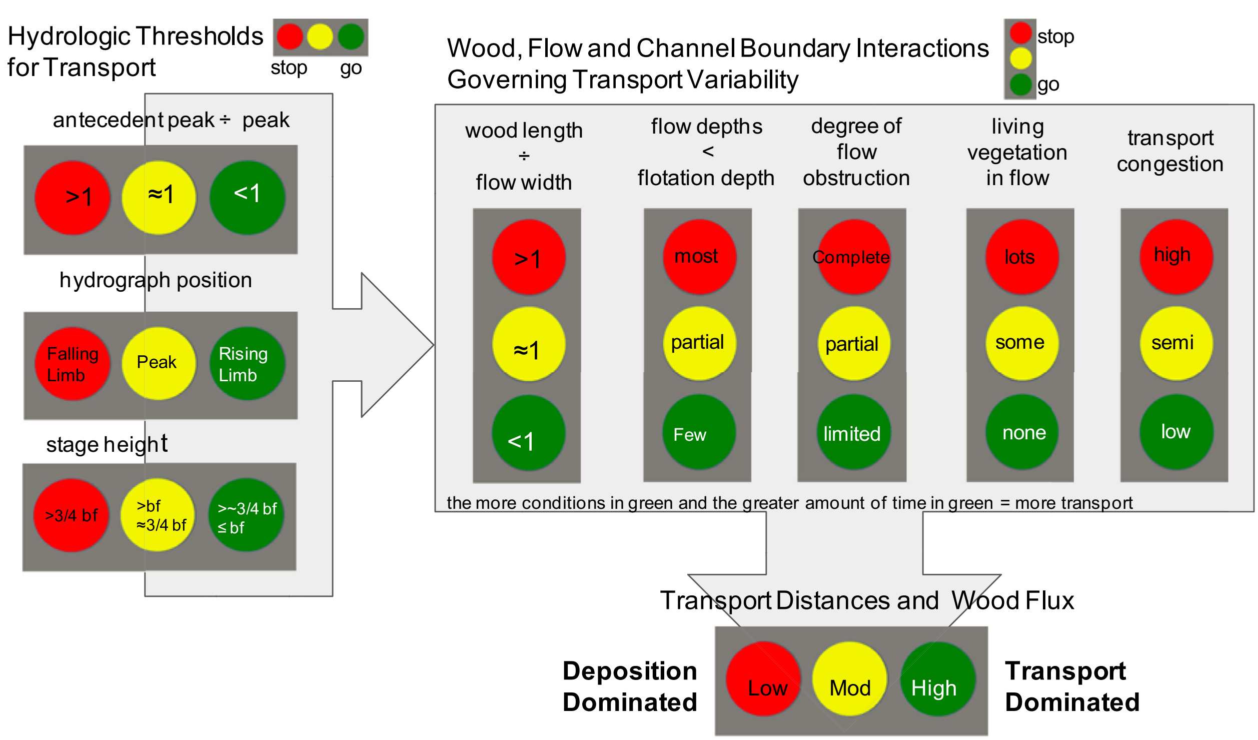

Fig. 10. Conceptual model of wood movement through drainage networks as a traffic stop light metaphor. Fully described in Section 4.6. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

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understanding of how changes in storage through time are related to variability in wood flux and hydrology. Efforts to better define entrainment and entrapment conditions and thresholds will be extremely useful, especially focused on individual flows or patterns over decades. A wider range of flow observations for diverse rivers will help to link reach-scale processes with network-scale processes.

A general approach that will lead to efficient quantification of wood transport is to design studies to constrain thresholds between transport regimes for different channel sizes, channel morphologies, hydrology, and wood characteristics. Until recently, most field studies that included wood transport data treated wood transport as a secondary study goal after description of wood storage, wood recruitment, or ecological impact. As more researchers make wood movement their primary focus, these thresholds will be rapidly identified. We have presented several conceptual frameworks that may prove useful to guide such work (Figs. 8–10).

Below, we summarize some specific suggested approaches for acquiring data to achieve broader spatial and temporal coverage of wood dynamics.

- *Monitor wood in action*. This can be done at a station by monitoring passage via automatic video monitoring (e.g., MacVicar and Piégay, 2012), coarse interval timelapse cameras (e.g., Kramer and Wohl, 2014; Kramer et al., in press), or radio tags (e.g., Schenk et al., 2014). The downstream movement of logs can by tracked with GPS (e.g., Ravazzolo et al., 2015b) or by actively following radio tags during flooding via boat or aircraft (e.g., Schenk et al., 2014).
- *Monitor change in storage at known retention sites at varying timescales* (e.g., Wohl and Goode, 2008; Moulin et al., 2011; Bertoldi et al., 2013; Schenk et al., 2014; Boivin et al., 2015).
- *Use wood characteristics to fingerprint wood source*. This can help identify wood-contributing subbasins and travel distances. Moulin and Piégay (2004) were very successful in making inferences about wood flux at basin scales based on the characteristics of wood trapped in a reservoir.
- *Quantify the amount of buried wood*. Buried wood has been identified successfully using acoustic bathymetry (White and Hodges, 2003) and ground penetrating radar (Kramer et al., 2012; Valdebenito et al., 2016), but values of wood buried in stream beds are largely unquantified. Buried wood is an important component of wood flux because, in rivers with sediment loads capable of easily burying wood, at least the same amount or more that is exported may be buried. For example, three-quarters of the wood exported from the Lower Roanoke River to the ocean in North Carolina was buried or decomposed en route (Schenk et al., 2014).
- *Use remote sensing techniques* to assess change on larger spatial and longer temporal scales (e.g., Bertoldi et al., 2013; Atha, 2014; Ulloa et al., 2015; Kramer et al., in press).
- *Conduct stratigraphic and/or other analysis of wood deposited in basins and floodplains* to obtain long-term (decade to millennial scale) records of wood flux from watersheds (Guyette et al., 2008; Seo et al., 2008; Seo and Nakamura, 2009; Fremier et al., 2010; Boivin et al., 2015; Kramer and Wohl, 2015).
- *Use already existing data from unconventional sources*. Hidden data within government agencies, individual scientists, or private companies that have never been published or otherwise made easily available but that can be acquired if requested is often quite useful. Heidorn (2008) calls these *dark data*. For example, Moulin and Piégay (2004); Seo et al. (2008); and Fremier et al. (2010) successfully used reservoir debris extraction records to indirectly estimate basin wood flux. In addition to finding and using dark data, a vast amount of unconventionally collected data is freely available on the internet. Wood researchers have yet to take advantage of this. Numerous posted photos and videos of rivers that include wood could be utilized to expand the geographic extent of studies. Videos of wood transport, especially wood transport from ice-jam flooding, flash flooding in deserts, and catastrophic flooding could be analyzed to estimate wood flux during rare events. Some internet contributors have YouTube (www.YouTube.com) channels devoted to chasing flash floods. Also, with the increased use of small waterproof action cameras, outdoor recreation enthusiasts are posting to the internet continuous footage of their excursions down sections of rivers in remote regions. Reports of changes in wood are commonly posted to online whitewater kayaking forum boards on sections of rivers that are regularly navigated. Finding ways to automatically and easily curate and utilize these data is a worthy research endeavor.
- *Participate and use Web 2.0 and create and utilize citizen science initiatives*. Web 2.0 refers to the part of the internet that is interactive, such as social media and citizen science platforms (e.g., www.citsci.org, www.crowcrafting.org). Citizen science refers to the use of non-scientists to help collect, process, or analyze data. Although citizen science initiatives have been utilized in ecology, medicine, and astronomy (e.g., bird surveys, gene mapping, star classification), they have been underutilized by large instream wood researchers (we came across none). In a short review of the use of citizen science, Silvertown (2009) made the point that Almost any project that seeks to collect large volumes of field data over a wide geographical area can only succeed with the help of citizen scientists (469). Citizen science could be used, not only to collect data from diverse regions, but also to validate and train automatic image processing routines.
  Web 2.0 not only opens up real-time interaction between scientists and non-scientists, but can facilitate data collection and curation from diverse individual scientists globally to reduce the amount of ‘dark data and facilitate synthesis between studies. This has already been done in medical fields to advance treatment for particular diseases by synthesizing and collecting information on case studies from doctors practicing independently (e.g., Butzkueven et al., 2006). A large but highly rewarding project would be to develop an online interactive river wood data platform where field scientists and managers could add and contribute their data while interacting with each other. This would facilitate better curation of metadata, common reporting of metrics, access to dark data, and international collaborations across disciplines.
- *Compile quantitative reviews* that integrate case study information for basin- and reach-scale wood flux, wood recruitment rates, residence times, and storage patterns.

5. Conclusion

We propose that the stop and go, the jamming and unjamming, or the discontinuity of wood flux is the most important aspect of the wood regime for river morphology, dynamics, and biota, rather than wood stability. Therefore, wood transport dynamics need to be incorporated into conceptual and quantitative models of river systems, riparian ecosystems, and nutrient routing. This requires substantial effort to obtain an equivalent working knowledge of wood transport as currently exists for sediment transport (e.g., Haschenburger, 2013; Kuhnle, 2013). This paper contributes to this effort by summarizing existing transport premises and ideas from prior studies, synthesizing quantitative results on wood transport from field studies, and presenting knowledge gaps, conceptual models, and hypotheses that can be used to design future field, flume, and modelling studies. In an era in which new remote technologies and new sources of data are increasingly accessible and applicable to research on wood in river corridors, we anticipate that studies of wood transport in rivers are poised to yield significant insights on wood dynamics and river ecosystem management.

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Appendix A. Equations of wood mobility

A.1. Transport distance based on exponential scaling by reach retention rates (Millington and Sear, 2007)

$$P_d P_0 e^{-kd}$$

where, P_d = # pieces that moved distance d in meters, P_0 = initial # of pieces introduced, k = per meter retention rate. $1/k$ represents the mean travel distance in m. Equation used in experimental addition of small dowels (≤1.06 m in length and ≤.035 m in diameter) released in Highland Water, a small, meandering, natural channel in England.

A.2. Transport distance as an exponential function of water depth at peak flow (Haga et al., 2002)

$$y_1 = 0.52e^{12.75x}, R^2 = 0.58 (n = 60)$$
$$y_2 = 0.45e^{13.01x}, R^2 = 0.65 (n = 37)$$
$$y_3 = 0.26e^{13.97x}, R^2 = 0.71 (n = 9)$$
$$y_4 = 3.84e^{8.32x}, R^2 = 0.61 (n = 15)$$

where y_i is travel distance for a series of flow events and x is an estimate of water depth at peak flow. Equations derived from experimental release of logs (Length = 1.7 m ± 0.4 Diam = 14 cm ± 4) stripped of irregularities in a 5500-m-long section of the gravel-cobble bedded Oyabu Creek in Japan with no boulders or instream wood to block travel; bankfull width = 9 m; gradient = 4.0; size of released logs not representative of maximum riparian heights (20–30 m); riparian tree species were beech (*Fagus crenata*), oak (*Quercus mongolica*), Japanese cherry birch (*Betura grossa*), fir (*Abies firma*), and hemlock (*Tsuga sieboldii*).

A.3. Transport distance as a function of jam spacing (Martin and Benda, 2001)

$$\xi = L_j \frac{T_p}{T_j} \beta^{-1}$$

where, ξ is the transport distance over a lifetime of a piece of wood, L_j is the distance between transport obstructing jams, T_p/T_j is the longevity of wood over longevity of jams and β is the transport-obstructing effectiveness of jams. Theoretical quantitative equation based on interjam spacing and degree of channel obstruction for 28 reaches ranging from 3.3 to 23 m in width within the Game Creek watershed in southeast Alaska; assumed that transport distance is limited to interjam spacing, did not directly measure distance; tree species are western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), Sitka alder (*Alnus sinuate*), and salmonberry (*Rubus spectabilis*).

A.4. Stochastic models of travel distance and mobility of individual pieces (Lassettre and Kondolf, 2003)

$$T_d = L_j MF[\ln(RI)]$$
$$P_m = m_1 + m_2 MF + m_3[\ln(RI)]$$
$$MF = \frac{1}{1 + e^{m_1 + m_2 \frac{L}{w_{bkf}} + m_3 D + C_1 + C_2 + C_3 + C_4 + C_5}}$$

where, MF is a mobility factor with values between 0 and 1, P_m is probability of movement and T_d is travel distance. RI is recurrence interval, m_1, m_2 and m_3 are constants, L is the length of a piece of wood, $\overline{D}$ is average diameter of a piece of wood, w_{bkf} is the channel width at bankfull, and C_i are categorical variables of decay class by species, species, stability by type, rootwad presence, and cut. Empirical equations developed for individual pieces of wood in central California in meandering sections of Amaya Creek (w_{bkf} = 6 m) and East Branch Soquel Creek (w_{bkf} = 12 m) characterized by channel-spanning log jams; stream wood included big leaf maple (*A. macrophyllum*), red alder (*A. rubra*), tanoak (*Lithocarpus densiflora*), coast redwood (*S. sempervirens*), and Douglas-fir (*Psuedotsuga menziesii*); maximum log length was 60 m; assumed wood moved only the average jam spacing (L_j) for yearly occurring floods; travel distance was adjusted upwards for more mobile pieces and to account for the fact that wood could pass jams by a multiple of MF and the natural log of the return period (RI).

A.5. Empirical logistic model of key piece mobility based on wood characteristics (Wohl and Goode, 2008)

$$P_m = 1/(1 + e^{-x})$$
$$x = 1.4 + 0.52L^*_{log} + 0.05D^*_{log} - 0.02C_1 - 0.13C_2 + 0.20C_3, R^2 = 0.47$$

where P_m is probability of key piece mobility, L^* is the piece length divided by average reference channel width, and D^* is the dimensionless annual peak flow depth divided by piece diameter. Categorical variables C_1, C_2, and C_3 are whether a key piece is a bridge, unattached or ramped, respectively. Developed using five high elevation streams of the Rocky Mountains in Colorado after 10 years of repeat surveys; channel widths ranged from 4.3 to 6.5 m, maximum wood length was 18 m; and instream wood was mostly conifers: Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine (*Pinus contorta*).

A.6. Empirical linear relationships for percent mobility based on flow characteristics (Iroumé et al., 2015)

$$M_{\%} = -4.2 + 0.0065\omega[H_{max}], R = 0.62 (n = 17)$$
$$M_{\%} = -14,514 + 20(H_{max}/H_{Bk}), R = 0.60, (n = 17)$$

where $M_{\%}$ is percent mobility, $\omega[H_{\max}]$ is unit stream power for maximum stage height in N/m^3, and H_{max}/H_{Bk} is ratio of maximum stage height over stage height at bankfull. Fitted for forested mountainous headwater rivers in Chile; channel widths range from 5 to 13 m, maximum length of instream wood was 25 m, and wood type is dominated by native coihue (*Nathofagus dombeyi* and *nervosa*) and tepa (*Laureliopsis philippiana*), as well as plantations of eucalyptus (*Eucalyptus globulus*) and pine (*Pinus sp.*); results showed wide scatter, with increasing variance among higher values of the explanatory variable.

A.7. Empirical exponential relationship between wood volume and wood velocity (Ravazzolo et al., 2015b)

$$v_w = 0.71V_w^{0.22}, R^2 = 0.87 (n = 5)$$

where v_w is wood velocity in m/s and V_w in m^3 is wood volume. Equation was developed using data from five logs with GPS tags and tracked during a flood in the large, 800 m wide, bar-braided Rio Tagliamento in northeastern Italy; in-stream wood is at maximum 25 m in length and primarily alder (*Alnus incana*), poplar (*Popoulas nigra*), and willow (*Salix alba*).

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A.8. Logistic model of mobilization based on wood characteristics (Merten et al., 2010)

$$P_{mob} = e^x/(1+e^x)$$
$$x = 0.39{-}2.64\beta_1 + 0.86\beta_2{-}1.52\beta_3{-}0.77\beta_4{-}0.80\beta_5{-}0.09\beta_6{-}1.59\beta_7$$
$$n = 865, P{<}0.001, Nagelkerkes R^2 = 0.39$$

where P_{mob} is the probability of mobilization, β_1 = burial, β_2 = effective depth, β_3 = length ratio, β_4 = bracing, β_5 = rootwad presence, β_6 = downstream force ratio, β_7 = draft ratio. Developed using data from instream large wood within the channel from nine forested streams draining into the north shore of Lake Superior, Minnesota; piece lengths 3.8 ± 3 m and diameters 0.18 ± .13 m; no tree species specified; flow depths ranged from 0.53 to 2.48 m, velocity from 0.86 to1.92 m/s, stream power from 15 to 252 N/m s, slopes from 0.001 to 0.02, bankfull widths from 3.4 to 24 m and peak flow from 2.1 to 54.7 m^3/s; data collected during year of extreme drought.

A.9. Transport ratio as a function of wood characteristics and discharge for single thread (T_{rS}) versus multithread (T_{rM}) reach (Ruiz-Villanueva et al., 2015c)

as a function of wood Volume (V_w);

$$T_{rS} = 0.31V_w^{-0.29}, R^2 = 0.56$$
$$T_{rM} = 0.03V_w^{-1.25}, R^2 = 0.33$$

as a function of wood diameter (D_w) and mean water depth (W_{depth});

$$T_{rS} = -0.18(D_w/W_{depth}) + 0.32, R^2 = 0.93$$
$$T_{rM} = -0.49(D_w/W_{depth}) + 0.58, R^2 = 0.94$$

as a function of wood length (L_w) and channel width (w);

$$T_{rS} = -2.19(L_w/w) + 0.92, R^2 = 0.91$$
$$T_{rM} = 2.40(L_w/w) + 0.12, R^2 = 0.82 for L_w/w{<}0.12$$
$$T_{rM} = -2.91(L_w/w) + 0.77, R^2 = 0.73 for L_w/w{>}0.12$$

as a function of wood density (ρ_w);

$$T_{rS} = 3.278e^{-3.89}\rho_w, R^2 = 0.98, n = 4$$
$$T_{rM} = 1.036^{-1.83}\rho_w, R^2 = 0.84, n = 5$$

as a function of discharge (Q);

$$T_{rS} = -0.12 + 0.004Q, R^2 = 0.91, for Q{<}100, RI = 10$$
$$T_{rS} = -0.25 + 0.001Q, R^2 = 0.44, for Q{>}100, RI{>}10$$

OR

$$T_{rS} = -1.96 + .35Q^{0.11}, R^2 = 0.91$$
$$T_{rM} = -0.17 + 0.005Q, R^2 = 0.97, for Q{<}110, RI{<}15$$
$$T_{rM} = 0.3 + 0.001Q, R^2 = 0.55, for Q{>}110, RI{>}15$$

OR

$$T_{rM} = -2.12 + 1.32Q^{0.13}, R^2 = 0.95$$

The transport ratio, T, is the amount exported divided by the total amount imported to the reach. These series of equations developed from numerical simulation using *Iber Wood* computer model and simulating wood and channel characteristics from field data collected from the Czarny Dunajec River in the Polish Carpathians; simulated multi- and single-thread reaches; tree species included large alders (*Alnus incana*), large willows (*Salix fragilis* and *S. alba*) and young willows (*S. purpurea* and *S. eleagnos*); wood lengths ranged from 1 to18 m, mean = 12.5 m, widths from 0.05 to 0.8 m, mean = 0.23 m and density from 0.4 to 0.95 g cm^{-1}, mean = 0.56 g cm^{-1}; results are from simulation of 10-year flood (Q = 105 m^3/s) and used mean values except for the variable for which the relationship was modelled.

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geomorph.2016.08.026.

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