The Natural Wood Regime in Rivers

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The natural wood regime forms the third leg of a tripod of physical processes that supports river science and management, along with the natural flow and sediment regimes. The wood regime consists of wood recruitment, transport, and storage in river corridors. Each of these components can be characterized in terms of magnitude, frequency, rate, timing, duration, and mode. We distinguish the natural wood regime, which occurs where human activities do not significantly alter the wood regime, and a target wood regime, in which management emphasizes wood recruitment, transport, and storage that balance desired geomorphic and ecological characteristics with mitigation of wood-related hazards. Wood regimes vary across space and through time but can be inferred and quantified via direct measurements, reference sites, historical information, and numerical modeling. Classifying wood regimes with respect to wood process domains and quantifying the wood budget are valuable tools for assessing and managing rivers.

Keywords: large wood, ecological integrity, geomorphic function, biodiversity, river corridor

Classic geomorphic conceptualizations of rivers focus exclusively on interactions between water and sediment (e.g., Lane's balance; Lane 1955). Although water has sometimes been accorded dominance as a driving force on river process and form, the importance of sediment supply is also widely recognized. Boundary resistance to erosion is a fundamental influence on river process and form, and in this context, the role of riparian vegetation is now well acknowledged, especially for low energy rivers (Gurnell et al. 2012, Gurnell 2014, Corenblit et al. 2015). Analogously, the effect of upland vegetation on sediment inputs to rivers is traditionally recognized for its role in limiting surface erosion and hillslope mass movement (e.g., Schumm 1968). The fundamental influence of vegetation as a geomorphic agent and as a source of wood to rivers is much less widely recognized in foundational literature, likely because of the long history of wood removal from river corridors by humans (Triska 1984, Montgomery et al. 2003, Wohl 2014). This last point is worth emphasizing: Historical descriptions of forested regions throughout the temperate latitudes indicate that orders of magnitude more wood were present in most forested river corridors prior to widespread deforestation and wood removal from river corridors for navigation and flood mitigation (Sedell and Froggatt 1984).

In the context of this increasing knowledge of flow, sediment, and vegetation interactions, long-held arguments for the importance of a natural flow regime are based on the understanding that the geomorphic and ecological integrity of a river depend on its natural dynamic character. The original conceptualization of this dynamic character emphasized the importance of variations in fluxes of water through time (Poff et al. 1997). The conceptualization of a natural sediment regime broadened the consideration of a river's dynamic character to reflect the importance of water and sediment interactions and sediment fluxes (Wohl et al. 2015). These two conceptual models recognize that centuries of human activities have created diverse changes in rivers, including alteration of natural flow and sediment regimes. These alterations have resulted in extensive ecological degradation and loss of biodiversity. Human activities on land and along rivers have also extensively changed and reduced important functions that include wood characteristics in river corridors. Alterations in the wood regime, however, are rarely recognized compared to the attention given to altered water and sediment regimes. In the present article, we argue that understanding the natural wood regime forms the third leg of a tripod supporting the physical processes underlying river science and management, along with the natural flow and sediment regimes. We define the wood regime in terms of the magnitude, frequency, rate, timing, duration, and mode of wood recruitment, transport, and storage.

Large wood traditionally refers to downed, dead pieces greater than 10 centimeter in diameter and 1 meter in length. Aggregates of smaller wood pieces (Culp et al. 1996, Galia et al. 2018) and living wood within the river corridor (Gurnell and Petts 2002, Gurnell et al. 2005, Opperman et al. 2008) also create important physical and ecological effects in river corridors. As a fundamental component of trees, wood contributes to the overall role of vegetation in driving forested river corridor form and function (Maser and Sedell

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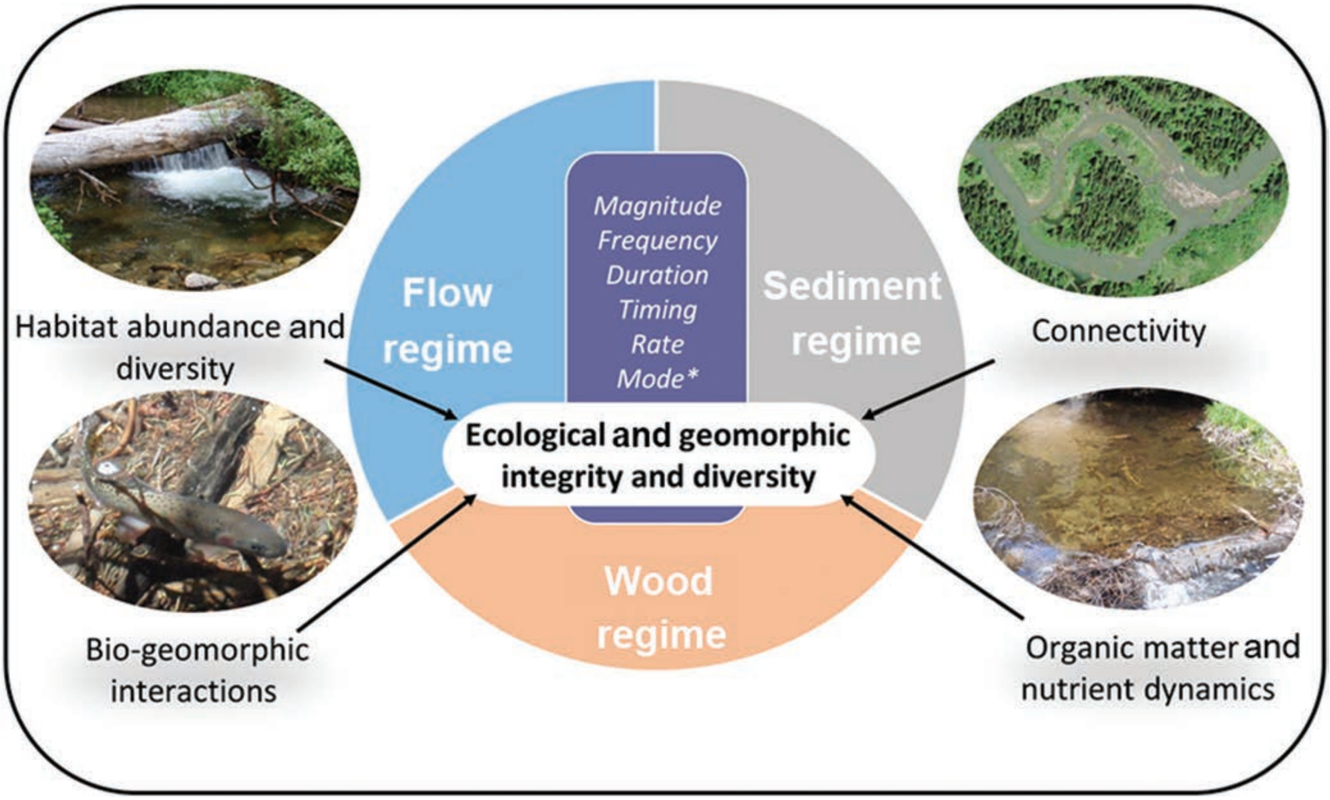

Figure 1. Characteristics of the river corridor influenced by interactions among water, sediment, and wood. Characteristics listed around the margins (e.g., physical habitat template) are influenced by the presence of mobile and stored wood. In the central box,* Mode* *refers only to the wood regime.

1994). In the present article, the river corridor includes fluvially influenced portions of a valley floor, such as the active channel or channels, the floodplain and low terraces, the riparian zone, and the hyporheic zone. Explicit focus on river corridors, rather than channels, recognizes the vital importance of interactions between different portions of the valley bottom in the context of fluxes of water, sediment, and wood at network- to reach-scales (Hynes 1975). We consider a river corridor's wood regime to include all sizes and types of wood.

A rapidly growing literature documents the beneficial effects of wood on the geomorphology and ecology of rivers (figure 1, supplemental table 1). Wood affects channel and floodplain ecological function via controls on riparian plant community development and structure, aquatic habitat, the dynamics of particulate organic matter storage and processing, and the structure and production of biological communities. Wood influences longitudinal, lateral, and vertical fluxes of water, solutes, and mineral sediment—connectivity—within river corridors. Wood also changes channel and floodplain form, both when the wood pieces are mobile and when they are stored. Failure to adequately consider these effects distorts our understanding of river process and form. On the other hand, wood transport can create flood hazards associated with wood accumulation at structures such as bridges, where jams can create substantial bed scour and flooding. Because of hazards and other constraints, a natural wood regime may no longer be feasible in rivers with high flood risk. In these circumstances, a more pragmatic target wood regime should be identified and pursued to create at least some of the positive effects of wood in river ecosystems.

Analogous to natural and altered water and sediment regimes, we draw a distinction in this article between the natural wood regime and a target wood regime. A *natural wood regime* occurs where past and present human activities do not significantly alter the components of the wood regime. In many historically forested river corridors, however, human alterations of the mechanisms and magnitudes of the wood regime have been so sustained and intensive that it is no longer feasible to infer or restore a fully natural wood regime. Management can then be directed toward a *target wood regime*, in which wood recruitment, transport, and storage balance desired geomorphic and ecological characteristics within the current landscape constraints and with mitigation of wood-related hazards. Our objectives in this article are to define and characterize the wood regime and to provide perspectives on how to characterize and manage for natural and target wood regimes to increase geomorphic and ecological integrity of river corridors.

Table 1. Components of wood regimes with respect to recruitment, transport, and storage.

	Recruitment	Transport	Storage
Magnitude	Mass	Hypercongested/congested/semicongested/ uncongested	Abundant
	Individual		Minimal
Frequency	Frequent	Frequent	Frequent
	Infrequent	Infrequent	Infrequent
Duration	Short recruitment time (episodic)	Short transport time	Short residence time (mobile or quick to decay)
	Long recruitment time (continuous)	Long transport time	Long residence time (immobile or slow to decay)
Timing	Predictable	Predictable	Predictable
	Unpredictable	Unpredictable	Unpredictable
Rate	Rapid delivery	Rapid transport	Rapid change
	Slow delivery	Slow transport	Slow change
Mode	En masse	Floating (limited influence from obstructions)	Dispersed (ramp, bridge, parallel, oblique)
	Sliding/rolling	Deflecting (influenced by obstructions)	Concentrated (channel-spanning, partial, floodplain, raft)
	Falling (snapping, leaning)	Dragging (sliding, rolling)	Buried
	Biotic addition (beaver, human)		

The wood regime

Similar to flow and sediment regimes, a wood regime is temporally focused, with fluxes and storage of wood as the characteristics of interest. A wood regime may be most intuitively analogous to a sediment regime, because it exhibits many parallels to mineral sediment (Gurnell 2007). Wood, like sediment, can be stored in a river corridor for long periods, and therefore, the time interval is relevant to understanding the wood regime. Wood enters a river corridor and is moved by high flows and, in some steep mountain streams, by debris flows. The movement of wood, including recruitment to and transport along the river corridor, is commonly intermittent, with relatively long periods of locational stability between episodes of movement (Kramer and Wohl 2017). Wood characteristics continue to change both at rest and in transport, via processes of decay, abrasion, and breakage that are analogous to weathering, abrasion, and breakage of stationary mineral sediment, although rates of change in wood are likely to be faster than changes in sediment. Like sediment coming from uplands, the amount, piece size, morphology, and rate of change of wood can reflect processes and controls external to the river corridor, such as forest disturbance regime, forest composition, and forest successional processes. Finally, both movement and storage of wood influence river process and form and in turn riparian and aquatic habitat. The balance between wood recruitment, transport, and storage both reflects river corridor geometry, as geometry creates trapping sites for wood, and influences geometry, as stored wood influences processes such as sediment deposition and the formation of steps and pools, bars, and secondary channels (Keller et al. 1995, Wohl et al. 2018b).

The analogies between sediment and large wood regimes should not overshadow the importance of recognizing large wood as distinctive and equal in importance to water and sediment as a component of river geomorphic process and form. A natural wood regime commonly shows substantial variation through time (figure 2) and across a river network (figure 3) that may not parallel those of water and sediment. The natural wood regime for a river segment or river network reflects the distinctive characteristics of that ecoregion, including the tree species present and available for recruitment and the associated size and physical complexity (e.g., branching) of recruited wood, as well as the rates of decay and breakage that influence wood transport and storage. The natural wood regime also reflects the distinctive physical characteristics of a river network or portion of a network, including the disturbance regime (e.g., blight and insect infestations, tropical cyclones, debris flows, landslides, ice storms, snow avalanches, wildfires) that influences wood recruitment, the natural flow and sediment regimes that govern wood transport and modification while in storage (e.g., via wetting and drying or abrasion), and the geometry of the river corridor that governs the presence and connectivity of portions of the valley bottom outside of the active channel, from which wood can be recruited and in which wood can be stored.

Sediment and wood regimes have previously been conceptualized in the form of a budget in which storage results from the difference between inputs and outputs within a defined area over a specified time interval. Wood budgets have been developed for application to time spans ranging from centuries (Benda and Sias 2003) to a single flood (Lucía et al. 2015, Comiti et al. 2016; supplemental text 1). Although we recognize the usefulness of a budget as a means

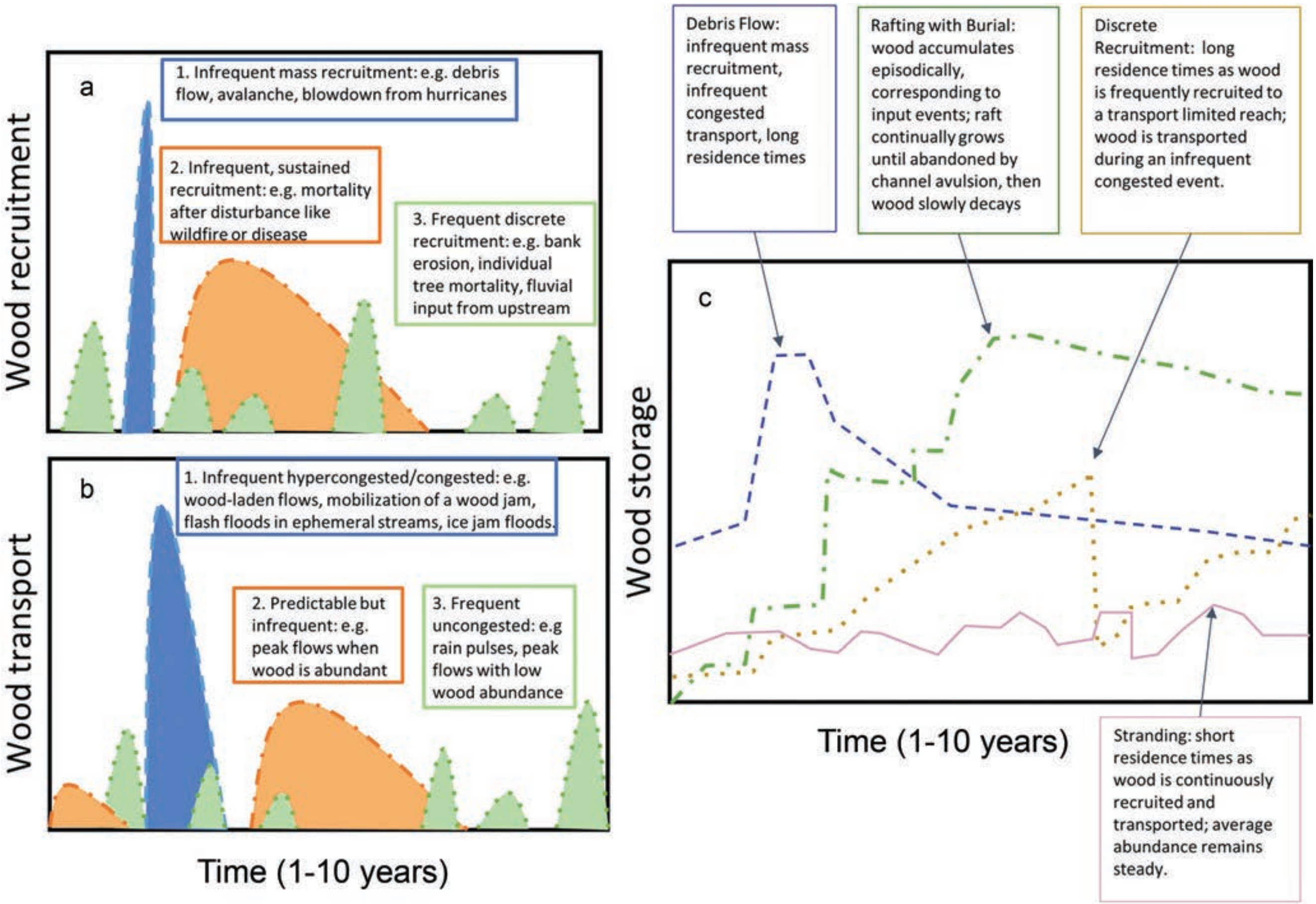

Figure 2. Hypothetical examples of wood recruitment (a), transport (b), and storage (c) regimes through time. Regimes are illustrative: Substantial variability may exist that is not represented in the present article. Wood storage reflects combined interactions between different recruitment and transport regimes. We present expected patterns of storage regimes through time associated with four of the example process domains in figure 3.

of quantifying the wood regime, in the present article, we use the framework of a wood regime to emphasize temporal fluctuations in wood dynamics.

The natural flow regime focuses on water flux. Poff and colleagues (1997) used systematic records of stream flow to quantify characteristics of magnitude, frequency, duration, timing, and rate of change in water discharge. Although time-series data are particularly useful in characterizing natural flow regimes, analogous data are much more limited for sediment regimes (Wohl et al. 2015) and few exist for wood regimes. In addition, the details of how wood is recruited to and stored within a river corridor strongly influence the wood regime. Given this, we propose that six components within each of the processes of wood recruitment, transport, and storage are required to describe the wood regime at a site (table 1):

Magnitude refers to the relative or absolute volume or mass of wood recruited, transported, or stored. *Frequency* refers to how often wood is recruited, mobilized and transported, or deposited in storage. *Duration* refers to the length of time over which recruitment events occur, or wood is transported or stored. *Timing* refers to when wood is recruited, transported, and stored, with respect to either seasonal patterns or components of the flow regime (e.g., recruitment during the rising limb and flood peak, deposition of wood during the recessional limb). *Rate* refers to the flux (mass or volume per unit of time) at which wood is recruited or transported or the flux of wood mass lost by decay, breakage, and abrasion during storage. *Mode* refers to the process by which wood is recruited and transported and the location and form (e.g., jams or dispersed pieces) of wood storage within the river corridor.

The six aspects of the wood regime outlined above can have varying degrees of importance relative to one another depending on environmental conditions and reasons for which this framework is being used. For example, comparing wood storage duration with the rate of wood mass loss by decay, breakage, and abrasion can indicate how changes in the frequency of wood transporting flows (e.g., by dams or diversions) might affect wood stored downstream.

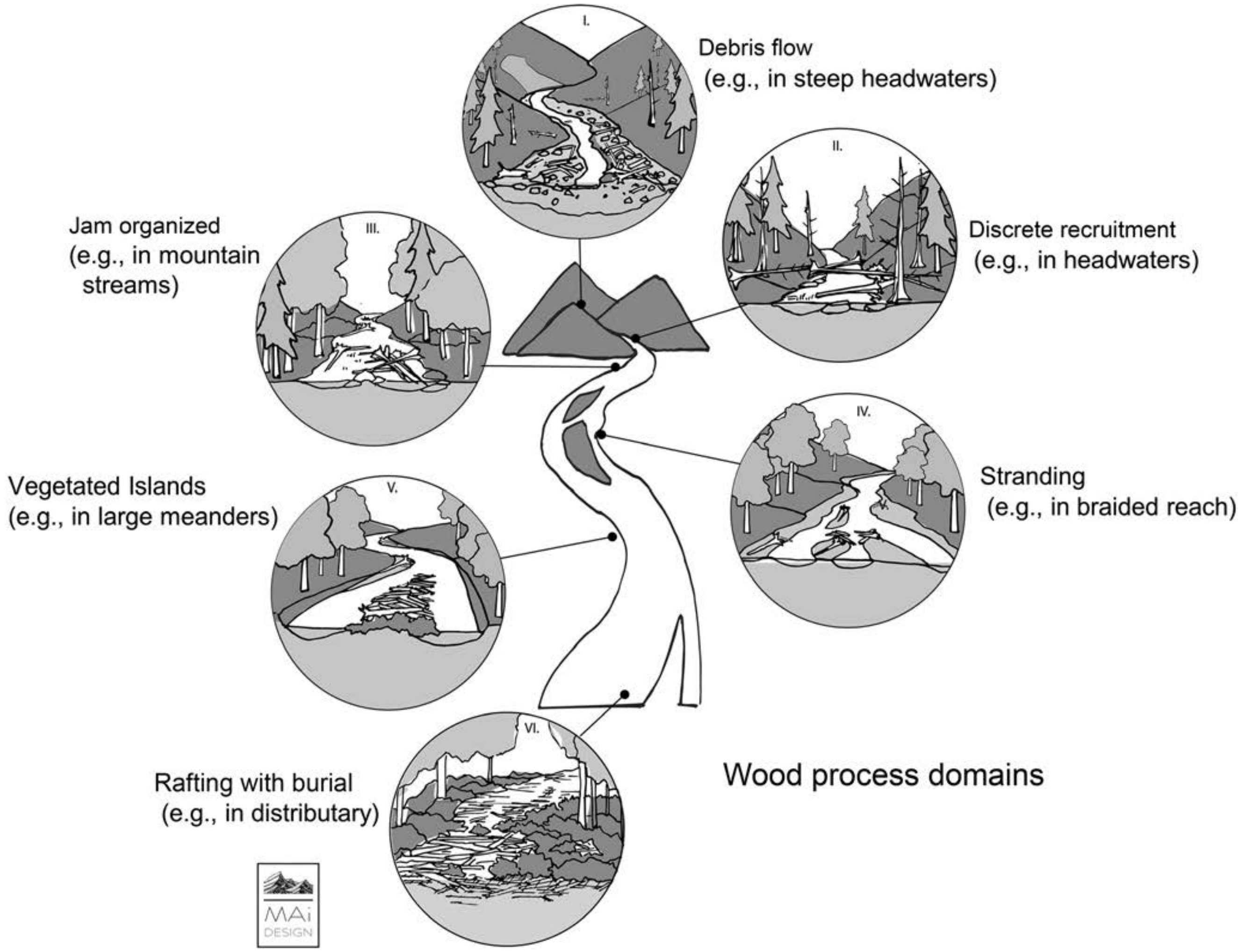

Figure 3. Hypothetical wood process domains along a river continuum. Each example domain has defining wood regime characteristics (table 1) that result in a distinct regime over a specified time (figure 2). Domains depicted are not intended to present a complete representation of all process domains and are not necessarily mutually exclusive. Furthermore, each domain does not necessarily encompass all components of the regime. Debris flow: Wood is delivered infrequently en masse with long to permanent residence times. Discrete recruitment: Recruitment of individual trees left dispersed in situ, over time leads to abundant storage because of limited transport capacity. Jam organized: Flow is sufficient and frequent enough to mobilize and deflect pieces over short transport durations into concentrated jam features. Stranding: Dispersed wood is stranded on bars and margins as flows recede, transport timing and duration are predictably associated with flow level and frequency. Vegetated islands: Wood is frequently floated and transported for long durations until concentrated at deposition sites, such as the heads of islands, facilitating revegetation and island expansion. Rafting with burial: Large concentrated rafts obstruct channels, long residence times interact with depositional environments to facilitate abundant accumulation, revegetation, and wood burial. Illustrations by MAi Design llc (www.maisierichards.com).

Alternatively, comparing the timing of recruitment events to the timing of wood transporting flows can yield insights into the mechanisms of wood storage. Although the wood regime should always be considered holistically, because many aspects are interrelated, some aspects of the wood regime or interactions between aspects may be disproportionately important for a given management or research scenario.

In the following sections, we discuss sources of spatial and temporal variability in each of the components of a wood regime and review methods used to quantify each component.

Recruitment

Spatial variations in recruitment reflect variations in forest characteristics and processes that move wood into river corridors. Forests are characterized by primary productivity and associated forest stand density, tree diameter and height, species (which influences wood density, piece form or branching, decay rate, and resprouting of deposited pieces), all of which differ substantially among bioclimatic regions and within a river catchment if the catchment spans sufficient elevational or latitudinal range (e.g., Wohl 2011). Recruitment mechanisms also vary spatially as connectivity between different portions of the river corridor and hillslopes, as well as wood transport and forest disturbance, vary downstream. Individual tree mortality, mass movements, and avalanches may be particularly important sources of lateral wood inputs in low-order, confined channels (Keller et al. 1995, May and Gresswell 2003), for example, whereas bank erosion is likely to become progressively more important as a source of lateral wood recruitment in partly confined and unconfined river segments (Lassettre et al. 2008, Lucía et al. 2015, Ruiz-Villanueva et al. 2018). Human alterations may also influence the spatial extent and age of forests, as well as the dominance of different recruitment processes, heterogeneously throughout watersheds.

Temporal variation in wood recruitment reflects the varying importance of different mechanisms and magnitudes of recruitment. Over time intervals of decades to centuries, wood recruitment may be dominated by episodic recruitment of forest patches associated with severe storms (Phillips and Park 2009) or hillslope instability (May and Gresswell 2003), for example, but recruitment of individual trees via both continual and episodic bank erosion appears to be particularly important at shorter time intervals along downstream portions of many channels (e.g., Piégay et al. 2017). A wood budget provides a useful framework for explicitly identifying spatial and temporal variation in diverse forms of wood recruitment (e.g., Benda and Sias 2003, Wohl 2011).

Wood recruitment to a river corridor can be quantified using at least two approaches. Direct measurements commonly cover only short periods such as a single large storm or flood (e.g., Comiti et al. 2016) or at most a few decades (Boivin et al. 2015). Numerical models typically focus on either forest dynamics over decades to centuries and the resulting magnitude and frequency of wood recruitment (Gregory et al. 2003) or on the potential for recruitment during a single storm or flood in relation to factors such as volume of standing wood and processes that recruit that wood to the river corridor (e.g., landslides; Mazzorana et al. 2011).

Transport

The portion of the wood regime that characterizes transport is the most similar to the characterization of the natural flow regime. Although the characteristics of flow are the first-order controls on wood transport, spatial and temporal variation in channel and floodplain geometry, sediment inputs and mobility, wood piece size, and wood storage (e.g., dispersed pieces versus jams) all influence wood transport. Distinctly different conditions may characterize wood entrainment, or the initiation of motion, and wood transport. The relative importance of downstream transport or deposition on the channel margins or floodplain varies with factors such as channel size (Gurnell 2003), channel–floodplain connectivity (Wohl et al. 2018a), local flow width and depth, and flow regime (Kramer and Wohl 2017). Temporal factors such as stage of the flood hydrograph (MacVicar and Piégay 2012, Kramer and Wohl 2017) and recent history of high flows also influence mobilization and transport of wood. The first significant flood after recruitment, for example, can play a disproportionately large role in wood dispersal relative to subsequent flows (Millington and Sear 2007). Wood transport magnitude–frequency relationships could be useful to understand wood regimes, but appropriate data series of wood flux in relation to stream discharge are just starting to be developed for a few rivers (Kramer and Wohl 2017).

Direct measurements of wood transport and input–output fluxes are rare but can be undertaken using field measurements at a station (Turowski et al. 2013), time-lapse photography of a channel (e.g., MacVicar and Piégay 2012, Benacchio et al. 2017), or archived airborne imagery at coarser, but more extensive scales and longer periods (e.g., Senter et al. 2017). Numerical models are also used to examine transport over diverse time scales and hydraulic conditions (e.g., Lancaster et al. 2001, Mazzorana et al. 2011, Ruiz-Villanueva et al. 2014).

Storage

Magnitude, duration, and mode of wood storage have received more attention than any component of wood recruitment and transport. Magnitude of wood storage is commonly quantified as volume of wood per spatial unit (e.g., cubic meters wood per hectare of surface or per unit length of channel) and is referred to as wood load (Van der Nat et al. 2003). Compilations of published wood loads indicate enormous variability within and between river networks, with ranges of 10 to approximately 50 cubic meters per hectare for unmanaged floodplains (Lininger et al. 2017) and 0 to approximately 5000 cubic meters per hectare for unmanaged channels (Ruiz-Villanueva et al. 2016, Wohl et al. 2017).

Most studies focus on wood load in relation to drainage area or bankfull channel width, both within a river network and between networks (e.g., Gurnell 2003, Fox and Bolton 2007, Ruiz-Villanueva et al. 2016, Wohl et al. 2017). Although significant trends exist between channel wood load and predictor variables such as drainage area or bankfull width within a region, relationships are highly variable and break down when applied to data from multiple regions (Gurnell 2013, Wohl et al. 2017). In addition, insufficient data on floodplain wood loads exist to allow analyses of the entire river corridor (Lininger et al. 2017).

Insight into past wood loads under natural wood regimes can be obtained from modeling, reference sites, and historical records. Numerical (e.g., Lancaster et al. 2001, Mazzorana et al. 2011, Ruiz-Villanueva et al. 2014) and stochastic (e.g., Eaton et al. 2012) models have been developed to quantitatively estimate wood deposition and storage over diverse time scales.

Reference sites are otherwise analogous sites in which the multiple factors that influence the wood regime have not been substantially altered by human activities. Because of the significant temporal and spatial variability in processes influencing the wood regime, inferences from sites disturbed minimally by humans probably provide at best a first-order approximation and are most useful when they are based on regional, rather than site-specific averages (e.g., Richmond and Fausch 1995, Fox and Bolton 2007).

Historical information can provide particularly useful qualitative (or, rarely, quantitative) insight into magnitude of river corridor wood storage in regions such as North America, Australia, and New Zealand prior to European settlement. Probably the most striking example is the Great Raft on the Red River, in Louisiana (Triska 1984). More commonly, historical accounts provide qualitative insight into the effects of loss of stored wood on flooding, navigation, and river corridor processes (e.g., Sedell and Froggatt 1984, Harmon et al. 1986, Wohl 2014; supplemental text 2).

Duration of wood storage within the active channel or floodplain can vary enormously, from less than 1 year to more than 10,000 years (Nanson et al. 1995, Wohl 2013, 2017). Factors controlling duration include wood piece size relative to channel size, position of wood within the river corridor and accumulation in jams, tree species, climate, degree of saturation of wood, and flow and sediment regimes (Le Lay et al. 2013, Ruiz-Villanueva et al. 2016). Because of the potential for trapping among the trunks of living trees (Wohl et al. 2018a) or burial during overbank or lateral accretion (Guyette et al. 2008, Collins et al. 2012), floodplain wood can have longer storage times than wood within the channel. Rates of decay in relation to tree species, size and stability of wood piece, and climatic conditions have also received limited attention (Harmon et al. 1986), but clearly vary significantly between regions (Wohl 2017), varying from 50 to 100 years for complete decay in dry climates to from 10 to 100 years in humid temperate climates and less than 10 years in the humid tropics.

Mode of wood storage has been examined as dispersed versus concentrated (logjams) wood pieces (e.g., Kraft et al. 2011) over varying lengths of channel. Spatial variations in logjams occur at the network-scale, such as *in situ* jams in headwater channels versus transport jams in larger channels (Abbe and Montgomery 2003), as well as at the reach scale, with preferential formation of jams in portions of the channel such as bars and islands (e.g., Piégay 1993). Similarly, floodplain wood can be concentrated in jams across the floodplain or predominantly along the floodplain margins (Wohl et al. 2018a). Although it remains difficult to precisely predict the size and residence time of individual jams, the locations within the river corridor that tend to accumulate jams can be predicted with reasonable accuracy.

Feedback loops within wood regimes

Interactions among recruitment, transport, and storage create nonlinear effects both within the wood regime and for the geomorphic and ecological effects of wood. Rapid recruitment via bank erosion can facilitate formation of closely spaced channel-spanning logjams that limit subsequent wood transport (Oswald and Wohl 2008). Wood jams create higher wood loads than dispersed pieces and wood jam spatial density regulates the efficiency of a reach at trapping wood in transport (Scott and Wohl 2018, Wohl et al. 2018b). The ability of some wood species to regenerate extends residence times through root anchorage, whereas the regenerating aboveground biomass acts as an additional retention structure for other wood pieces (Gurnell et al. 2001). Storage influences the rate and magnitude of wood decay by controlling the exposure and potential abrasion and decomposition of wood pieces (Merten et al. 2013). Wood decay also influences transport and storage as decaying wood pieces break or abrade and, therefore, become more easily mobilized (Merten et al. 2013).

Feedback loops also create nonlinear physical and ecological effects associated with wood. Logjams can cause greater bed scour and deposition of fine sediment than an equivalent volume of dispersed wood pieces (Wohl 2017). Wood stored along the inside of a meander bend may facilitate greater sediment deposition than wood stored along the outside of the bend (Zen et al. 2017). Channel-spanning logjams that are closely spaced downstream can facilitate formation of secondary channels that significantly increase habitat abundance and biological productivity per unit length of valley (Herdrich et al. 2018, Venarsky et al. 2018).

The presence of these and other feedback loops between mobile and stored wood and river corridor process and form highlight the importance of considering wood in the context of an integrated wood regime that includes diverse aspects of recruitment, transport, and storage. Feedback loops are particularly important in creating nonlinear behavior in river corridors, including alternative states mediated by the presence or absence of wood (supplemental text 3; Collins et al. 2012, Livers et al. 2018). Multiyear monitoring of storage from ground-based measurements or airborne imagery can show the potential variability in magnitude, duration, and mode of wood storage at one location and can inform transport dynamics by tracking wood that is imported into the storage zone, remains in storage, or is exported downstream (Boivin et al. 2015; figure 4). This type of monitoring may be particularly effective at identifying feedback loops and thresholds.

Target wood regimes

In the following sections, we review how insight gained from natural wood regimes and understanding of river corridors can be used to identify target wood regimes that balance the benefits derived from wood in river corridors against the potential hazards created by wood. The first steps in this process are characterizing the contemporary wood regime, identifying differences between the natural and contemporary wood regime, and differentiating wood process domains within a river network.

Characterizing contemporary wood regimes

Direct measurements and numerical and stochastic models can be used to characterize the different components of

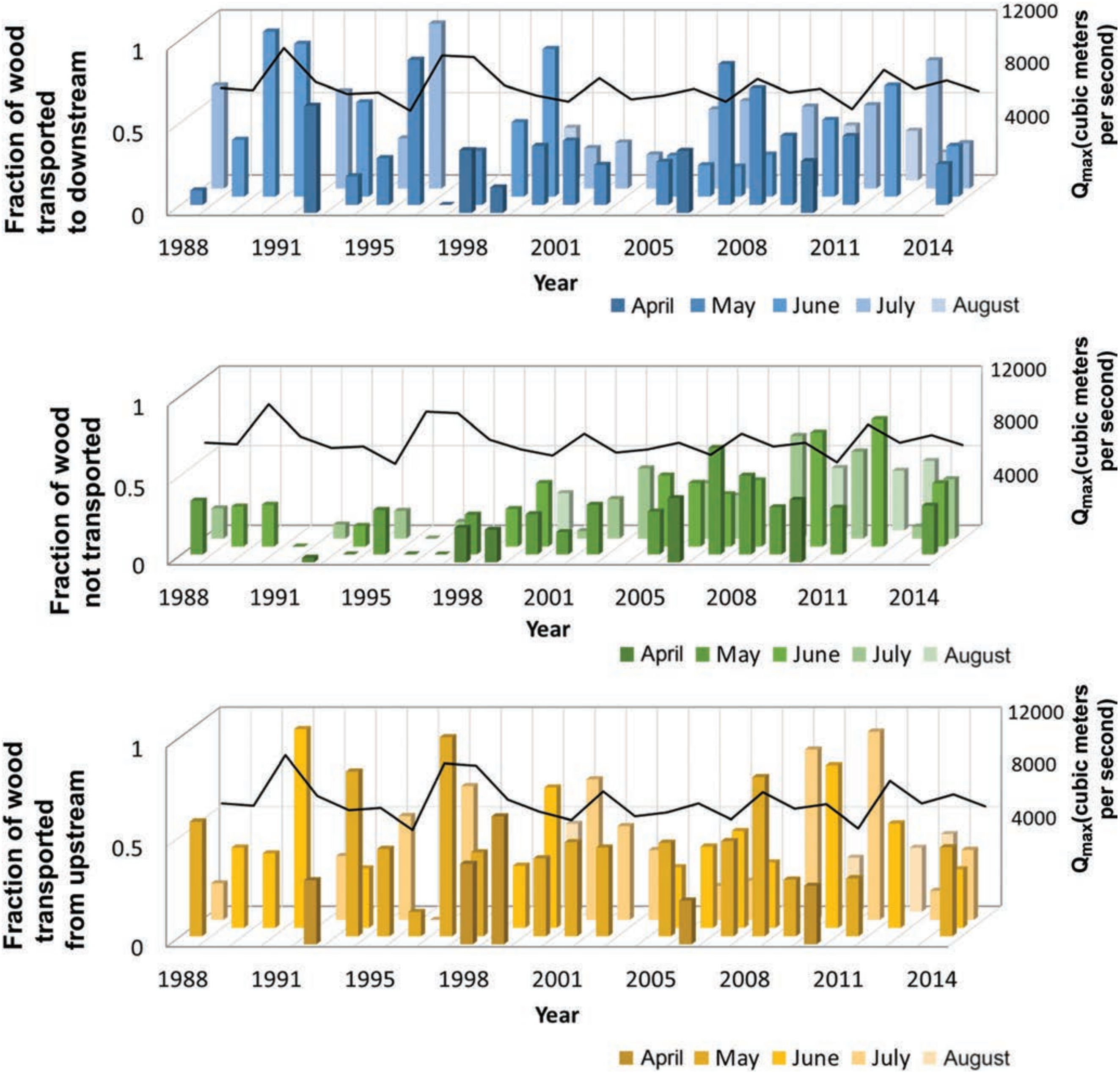

Figure 4. Time series showing fluctuation in proportion of wood entering storage, remaining in storage, or leaving storage from 1988 to 2014 within wood jams on islands in the Slave River, northern Canada (data from Kramer and Wohl 2017). Maximum peak discharge for each year on the y***-axis, indicated by the black line, is the same for all plots.***

contemporary wood regimes, as was discussed in the preceding sections. However, until more data are available to accurately parameterize mechanistic, multiscale models of wood regimes across regions (Scott and Wohl 2018), characterizing wood regimes over broad spatial scales will remain difficult. Current efforts can best describe individual segments of river corridor that are defined on the basis of consistent characteristics of flow, sediment, and wood regimes, as well as channel and floodplain morphology.

A primary management challenge is that of comparing expected wood regime in natural conditions versus contemporary wood regime. The contemporary wood regime in many river networks is affected by flow regulation, land use in recruitment zones, vegetation and wood removal, or river engineering. One strategy for comparison is to consider basin-scale magnitude of wood recruitment, transport, and storage according to an expected maximum based on reference or historical conditions, and then assess the differences between observed and natural conditions (Ruiz-Villanueva et al. 2016, Senter et al. 2017). Observed differences can then be linked to changes in process, form, and function within the river corridor, and management

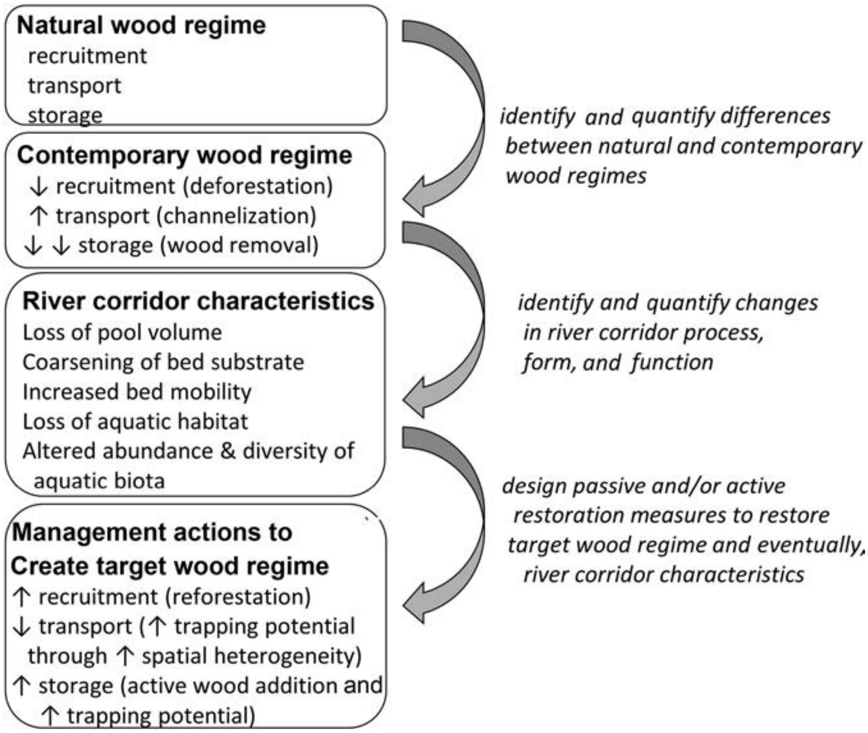

Figure 5. Flow chart outlining suggested procedure for developing a target wood regime. In this hypothetical example, the contemporary wood regime differs from a natural wood regime. Reduced recruitment because of deforestation and declining wood supply and increased transport because of channelization and loss of wood-trapping potential within the channel result in greatly decreased wood storage in the river corridor and associated alteration in river corridor characteristics. Management actions that restore wood supply through reforestation and increase trapping potential by enhancing the physical complexity of the channel and floodplain geometry can reduce wood transport and increase storage, helping to restore lost river form and function.

actions can be designed to enhance wood-related benefits (figure 5).

An ever-present challenge is that wood regimes at regional scales are idiosyncratic compared with water regimes, which can be inferred regionally with relatively straightforward models such as regional rating curves for discharge. Part of the idiosyncrasies of wood regimes are that many rivers, especially in human-altered watersheds, are supply limited with respect to wood. Even in unaltered watersheds, the details of the wood regime are strongly influenced by the location, age, and species characteristics (e.g., shape and size) of trees. These types of constraints presently prevent us from reaching the same level of quantitative accuracy that can be developed for water and sediment regimes. However, wood process domains can be used to spatially differentiate significant aspects of the wood regime within and among river networks.

Wood process domains

A geomorphic process domain is a spatially identifiable area characterized by distinct suites of processes (Montgomery 1999, Polvi et al. 2011). Wood process domains are parts of the river network with similar wood regime patterns (Wohl 2011; figure 3), but the criteria used to distinguish process domains can vary on the basis of the component of the wood regime that is of most interest. Process domains can be used to distinguish high-relief portions of a network in which channels are confined and well connected to adjacent hillslopes, for example, so that hillslope instability dominates large wood inputs (May and Gresswell 2003). In lower relief portions of the network, partly confined to unconfined channels can have predominantly autochthonous wood recruitment from the floodplain (Wohl et al. 2018b). Process domains can be useful in differentiating wood-transport-limited and supply limited portions of the network (Wohl and Jaeger 2009). Process domains can also be designated on the basis of portions of the river network in which channel physical complexity or fluvial transport of wood onto floodplains enhances storage (Wohl et al. 2018b) versus portions of the network in which minimal wood is stored.

Managing for target wood regimes

Integrated models of wood recruitment, transport, and storage do not yet exist for most regions of the world. As these models continue to develop, they are likely to provide useful insights into wood regimes under changing conditions, including management of channel geometry and flow regime, changing climate, and progressive changes in forest cover associated with processes such as deforestation and afforestation. As the capability of models increases for simulating specific effects associated with the presence of wood, such as sediment deposition or pool formation (e.g., Eaton et al. 2012), the models can also be used to evaluate management scenarios on the basis of differing wood loads or fluxes. For the most part, models are only currently available for regions with decades of basic research into wood dynamics and these data form the basis for model development and verification. The difficulties inherent in trying to quantify or model the natural wood regime, however, need not preclude management directed toward restoring a less altered wood regime that balances desired versus hazardous aspects of wood.

The widespread disruption of natural wood regimes suggests that the most effective approach to wood management in many regions is to strive for a target wood regime. In a management context, a target wood regime is one that results in a channel that maintains sufficient recruitment,

Table 2. Examples of wood-focused management actions and associated effects that could be targeted as part of managing for a target wood regime.

Management action	Effects and example references
Emplacing stationary logjams or maintaining wood fluxes that create logjams in the channel, with associated bed scour and backwater effects, and pressure gradients that drive hyporheic exchange	Increased pool volume and salmonids (Richmond and Fausch 1995, Herdrich et al. 2018; see supplemental text 1 for additional references) hyporheic exchange flow (Sawyer et al. 2012) snag habitat (Simpson and Mapleston 2002) sediment storage (Wohl and Scott 2017) organic carbon storage (Beckman and Wohl 2014)
Emplacing stationary wood pieces or logjams or maintaining wood fluxes that create logjams in regularly inundated portions of the floodplain	Increased macroinvertebrate habitat (Benke and Wallace 1990) Increased organic carbon storage (Sutfin et al. 2016) Increased habitat for terrestrial invertebrates, amphibians, reptiles, small animals, and birds (Harmon et al. 1986; see the references in Wohl et al. 2016)
Maintaining wood fluxes that create logjams, and associated bars, islands, avulsion, and secondary channels	Increased channel planform diversity (Collins et al. 2012)
Maintaining wood fluxes that deposit wood on floodplain through time, creating stored wood in differing stages of decay	Increased soil floodplain moisture and fertility (Zalamea et al. 2007)

storage, and transport (or decay) to sustain desirable geomorphic, hydrologic, social, and ecological characteristics without causing socioeconomic losses beyond acceptable levels (Wohl et al. 2016; box 1 and table 2). These losses frequently stem from increased flood risk at narrow sections potentially obstructed by wood during floods but can also result from other modifications such as reduced hydropower production when reservoirs are removed to restore wood connectivity. In most scenarios, a target wood regime will reflect a human-altered condition in which altered water, sediment, and wood supplies vary within a range constrained by human activities such as changes in land cover and flow regime. In exceptional cases with minimal or no human alteration of the wood regime, management can be designed for a target wood regime that preserves the existing, natural wood regime (e.g., prohibiting timber harvest or channel engineering in an unaltered river corridor).

Process domains can be explicitly defined in a management context, such as in relation to hazards associated with infrastructure or human presence, with some high-risk portions of a river network managed for wood removal and other portions managed for wood retention (Piégay and Landon 1997, Wohl et al. 2016). Wood process domains can also be used as a tool to explore and map spatial transitions in wood regimes along a channel network and temporal changes in wood regimes through time in response to disturbance or changes in regional drivers such as geology, climate, or land use (Kramer and Wohl 2017).

All components of the wood regime play into developing a target wood regime, although constraints (e.g., infrastructure near rivers) may be imposed that limit certain aspects of the target wood regime. With regards to recruitment, a target wood regime should attempt to maximize sustainability of wood transport and storage by maintaining some mode of recruitment at a magnitude, frequency, duration, timing, and rate that is compatible with other aspects of the target wood regime. This should include riparian forest management that ensures a sufficient supply of wood, which can be characterized on the basis of parameters such as tree-stand density and tree height.

The storage component of a target wood regime relates to desirable quantities of stored wood. This is highly dependent on context as governed by ecoregion and wood process domain (e.g., Dufour and Piégay 2009) and on time span and sequence in time (e.g., years after the last disturbance that influenced wood recruitment or transport). Because storage naturally varies over time, a natural or target wood load cannot be represented by a single value.

The most common example of managing for quantity of stored wood involves introducing wood pieces or logjams that are fixed in place (e.g., Reich et al. 2003, Roni et al. 2015). This is typically used where continuing recruitment of new wood that is at least temporarily stable is unlikely to replace mobilized wood and where mobile wood may create hazards for people and infrastructure. The most recent trend in restoring wood is sometimes called stage 0 restoration and involves wood that can move through time and is designed to create and maintain a multithread channel planform.

The reintroduction of wood to a river corridor is an example of active restoration. Passive restoration emphasizes creating and sustaining the conditions that result in wood recruitment, transport, and storage. Although more likely to be self-sustaining, passive restoration is not feasible in some river reaches because of existing constraints or lack of responsiveness of the river corridor to floods. Active and passive restoration of wood regime can be complementary, with different approaches used in different portions of a drainage network.

The common management approach of fixing all wood in place contradicts the idea of maintaining a dynamic wood regime by allowing for mobility in the form of recruitment and transport. Maintaining wood mobility is likely to be important for sustaining habitat and biodiversity within river corridors capable of reacting to the presence of wood through modification of river process and form (e.g., Sear et al. 2010). Mobile wood can be an integral component of floodplain or riparian disturbance regime by mechanically damaging or removing living plants and creating new germination sites (Johnson et al. 2000, Gurnell et al. 2001, Collins et al. 2012, Osei et al. 2015). Mobility can facilitate

Box 1. Example management strategies for attaining a target wood regime.

Passive restoration

- Cessation or limits on
  - deforestation (wood recruitment)
  - removal of downed wood in the river corridor (transport, storage)
  - river engineering (recruitment, transport, storage)
  - flow regulation (recruitment, transport, storage)
- Riparian forest management (e.g., planting, selective thinning or felling) to alter recruitment rate and piece characteristics
- Removal of bank erosion mitigation measures to promote wood recruitment
- Channel and floodplain design to control roughness and potential wood-trapping features such as bars and side channels
- Modified design for infrastructure such as bridges or dams that influence wood regime
- Altered regulatory framework that recognizes importance of presence of wood in river corridor

Active restoration

- Reintroduction of either potentially mobile or fixed wood within river corridor
- Beaver habitat enhancement or reintroduction.

the presence of wood in varying stages of decay, which influences habitat and biodiversity within river corridors by providing substrate diversity for microbial and macroinvertebrate communities (Harmon et al. 1986). Fluxes of wood from rivers to marine ecosystems supply nutrients and create habitat from nearshore to deep-sea environments (Maser and Sedell 1994, Simenstad et al. 2003, Schwabe et al. 2015). Wood recruited via river transport and shoreline erosion also provides important habitat within lakes (Marburg et al. 2006, Kramer and Wohl 2015). The characteristics of river morphology become particularly important in the context of wood mobility because wood is naturally more mobile in some portions of a river network.

These documented effects of wood mobility suggest the importance of managing for dynamic rather than static wood loads within river corridors. Managing for wood dynamics is challenging because it requires identifying and managing for processes of wood recruitment and transport, which commonly involve wider and longer portions of a river network than the limited channel segments that are typically the focus of management (e.g., Boyer et al. 2003). In addition, the presence of infrastructure that could be damaged by mobile wood may require installation of special structures to limit downstream wood transport (Comiti et al. 2016, Ruiz-Villanueva et al. 2016) or modifying structures such as bridges (DeCicco et al. 2018) to allow wood to pass. Such structures exist (figure 6), however, and can be used if the presence of potentially mobile wood is an important consideration. Supplemental text 4 discusses techniques that can be used to evaluate whether individual wood pieces or jams are likely to remain stable or become mobile.

For all aspects of a target wood regime, management actions will be effective when they are part of integrated basin management that considers the larger context and when specific actions are appropriate to the wood process domain. For example, reforesting upland hillslopes will not greatly change the wood regime unless hillslope mass movements are an important source of wood recruitment. Wood in a rapidly shifting braided river or a river with flashy discharge is likely to be more mobile under natural conditions than wood in a lowland river with limited hydrologic variability and cohesive, stable channel boundaries, so installation of stable wood structures in a braided or flashy river may not be appropriate. The widespread loss of old-growth forests and consequent absence of especially large, naturally stable wood pieces, on the other hand, may be compensated for by fixing some wood pieces in place. Another consideration is that wood is not equally effective in creating habitat, for example, in all river segments. Introducing wood pieces or logjams that are fixed in place (e.g., Reich et al. 2003, Roni et al. 2015) has the most utility in recruitment reaches in which wood transport occurs rarely or in reaches in which there is enough continuing recruitment of new wood to jam against the introduced wood and potentially replace wood that is mobilized. Anchored floodplain wood may also be more stable than wood within the active channel. Anchoring wood has utility such that mobile wood may create hazards for people and infrastructure, but in some systems and with sufficiently large flows, these anchored pieces could

Figure 6. Examples of structures used to limit downstream mobility of wood. (a and b) Rienz River, Italy; (c) Chiene River, Switzerland (the chair is outlined in yellow for scale); (d) Sihl River, Switzerland (people are outlined in yellow for scale). The structure on the Sihl River is unique in size and design. It is installed parallel to the flow in the outer bend of a meander to retain wood (which might otherwise reach the City of Zurich) but to allow sediment to be transported.

be mobilized along with any anchoring hardware, creating greater hazards.

Of critical importance is recognizing that a reach of river corridor targeted for management is connected to upstream and downstream portions of the river network and adjacent uplands and can therefore influence and be influenced by processes occurring outside of the reach. It is also critical to take into consideration that process and form in river corridors, including wood regimes, are dynamic, such that fluctuations will occur even if a consistent mean condition is present over the time span of interest. Using a wood regime framework, monitoring wood flux, and quantifying wood budgets can help river managers to identify reference, contemporary, and target wood regimes for a specific river reach. Finally, attention to the social context is critical for successful implementation of a target wood regime. This is likely to be most effective if considerations such as perceptions, social access to and use of a river, levels of acceptable risk, future trajectories of human influence, and interactions of human policies and regulations are included in analyses for the target wood regime.

Conclusions

River science now recognizes large wood as a primary driver of physical and biotic conditions in river corridors. This supports conceptualizing the natural wood regime, along with water and sediment, as the third leg of a tripod of physical processes that supports river science and management. The natural flow regime is enormously influential in river management and restoration because of growing recognition of the devastating effects of altered flow regimes on water quality and on aquatic and riparian biotic communities. Although it is impractical to completely restore natural flow regimes on many rivers, an understanding of the natural flow regime can be used to identify which aspects of flow regime may be critical to restoring lost or compromised ecosystem services, as well as to quantifying the extent of alteration of the present flow regime. Identification and restoration of the natural wood regime can also create substantial physical and ecological benefits. Forested river corridors that retain a natural wood regime illustrate how interactions among water, sediment, wood, and valley geometry create secondary effects such as peak flow attenuation, nutrient uptake, sediment and particulate organic matter storage, habitat abundance and diversity, and greater biomass of organisms per unit length of river corridor. The beneficial effects of wood in river corridors have largely been overlooked because of the widespread lack of abundant wood in forested river corridors. This reflects centuries of active wood removal from rivers, as well as diminished wood recruitment associated with changing land cover, reduced wood retention as river corridors have become more physically simple and homogeneous, and perceptions of wood in rivers as wasted or unsightly. Natural wood regimes are dynamic and challenging to characterize. However, river management that explicitly includes feasible targets for the wood regime, based on an understanding of the natural wood regime for a river catchment, can restore lost or diminished ecosystem services. Such management must be accompanied by efforts to change what are commonly negative public perceptions of wood in river corridors. Ultimately, river management that does not incorporate target wood regimes cannot sustain the physical and ecological attributes of rivers that people value.

Supplemental material

Supplemental data are available at *BIOSCI* online.

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