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Instream large wood loads across bioclimatic regions

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ABSTRACT

Instream large wood in forested rivers creates diverse physical and ecological effects and is a vital component of river process and form. The majority of research on wood in rivers has been conducted within a limited geographic range, raising questions about the applicability of resulting insights. We analyze data from 438 river segments in old-growth or unmanaged forests and 250 river segments in lightly managed forests representing diverse environments. We evaluate whether drainage area, channel width, and channel slope influence instream wood load in unmanaged forests across bioclimatic regions. Here we show that, without accounting for variations across regions, these numeric variables do not correlate significantly with wood loads. When accounting for the influence of all available potential influences on wood load in unmanaged forest rivers, bioclimatic region, drainage area, and channel width are the dominant predictors of wood load, and the relationship between wood load and channel width differs between regions. Combining data across bioclimatic regions, unmanaged rivers have significantly greater wood loads than lightly managed forests. Splitting data by bioclimatic region, unmanaged rivers in the northern dry conifer and northern wet conifer regions have significantly greater wood loads than lightly managed forests, but wood loads in the northern wet deciduous region do not differ between unmanaged and lightly managed forests. Our findings suggest that (i) bioclimatic region is a critical factor in predicting and understanding wood dynamics in rivers, (ii) even historic or relatively light levels of timber harvest and wood removal can create persistent differences in wood loads, and (iii) substantial variation in wood load among river segments within a bioclimatic region suggests that riparian forest and river management should focus on processes that maintain wood loads capable of creating desired physical and ecological effects rather than specified volumes of wood.

1. Introduction

A fundamental question in field-based science is the extent to which place-based findings apply elsewhere. This is exemplified by studies of process and form in rivers. Although the underlying physics is consistent, each river segment reflects a place-specific combination of climate, geology, hydrology, biota, and natural and human disturbances. Consequently, a primary objective of river research is to distinguish the general from the particular. This applies to the physical and ecological effects of large wood in rivers, which have been quantified within a relatively small subset of the diversity of forested environments present around the world. Our objective in this paper is to evaluate whether consistent relations exist between wood load and potential control variables across diverse river segments.

Large wood, commonly defined as pieces ≥10 cm in diameter and ≥1 m in length (Wohl et al., 2010), enters rivers from channel boundaries, floodplains and adjacent uplands (Benda and Sias, 2003; Le Lay et al., 2013; Wohl, 2017). Large wood increases hydraulic resistance and obstructions to flow (Manga and Kirchner, 2000; Daniels and Rhoads, 2004; Wilcox et al., 2011), creating secondary effects including: local erosion of the channel bed and banks (Beschta, 1983; Montgomery et al., 2003a); increased retention of mineral sediment and particulate organic matter (Bilby and Likens, 1980; Nakamura and Swanson, 1993; Beckman and Wohl, 2014a; Ryan et al., 2014; Wohl and Scott, 2017); and habitat diversity (Wondzell and Bisson, 2003; Chen et al., 2008). Sufficient quantities of dispersed pieces or accumulations in logjams, particularly those that are at least temporarily stationary, can alter bed substrate (Keller and Swanson, 1979; Buffington and Montgomery, 1999; Faustini and Jones, 2003; Klaar et al., 2011), type and dimensions of bedforms (Keller and Tally, 1979;

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Gomi et al., 2003), channel geometry (Montgomery et al., 1996; Gendaszek et al., 2012), and channel mobility (Montgomery et al., 2003b; Collins et al., 2012). Large wood can also increase hyporheic exchange flows (Bolton et al., 1998; Sawyer et al., 2012) and channel-floodplain connectivity (Jeffries et al., 2003; Sear et al., 2010; Collins et al., 2012), thus influencing water quality and nutrient uptake. Numerous aquatic and riparian organisms rely on large wood (Benke and Wallace, 2003; Zalewski et al., 2003; Naiman et al., 2010) and biomass and biodiversity commonly increase in the presence of wood (Johnson et al., 2003; Steel et al., 2003; Whiteway et al., 2010).

Although mobile wood influences river process and form (e.g., Johnson et al., 2000), many of the documented geomorphic and ecological effects of large wood in rivers are associated with wood that is at least temporarily stored along the river. Wood storage is quantified as wood load, or volume of wood per area of channel ($m^3\ ha^{-1}$). Wood load reflects the balance between recruitment of wood to the river and decay, breakage, and transport of wood within the river (Benda and Sias, 2003; Benda et al., 2003; Le Lay et al., 2013; Wohl, 2017).

1.1. Influences on wood storage in rivers

Because of the primary influence of stationary large wood on river process and form, substantial effort has been devoted to inventorying wood loads in diverse environments. Much of this research seeks correlations between wood load and potential control variables that can provide insight into spatial patterns of wood within river networks and can be used to inform river management designed to restore wood to rivers. There is a conceptual basis for expecting at least within-region correlations between wood load and either drainage area or channel width because of the influence the latter factors exert on wood recruitment, mobility, and distribution within river networks (e.g., Gurnell et al., 2002; Fox, 2003; Fox et al., 2003; LeLay et al., 2013).

Wood transport and storage, as directly observed in flume experiments and inferred from patterns of wood storage in rivers, are influenced by flow depth and average channel width (Martin and Benda, 2001; Gurnell et al., 2002; Welber et al., 2013). Mobility of individual wood pieces increases as the ratios of piece length to channel width and piece diameter to flow depth decline (Lienkaemper and Swanson, 1987). These trends are complicated by the specific characteristics of wood pieces (e.g., presence of a rootwad, piece density, piece angle relative to flow direction; Braudrick and Grant, 2001) and the effects of channel-margin irregularities (Braudrick and Grant, 2001) and wood load within the channel that influences piece-to-piece interactions (Braudrick et al., 1997; Bocchiola et al., 2006; Beckman and Wohl, 2014b; Bertoldi et al., 2014). However, greater wood mobility with increasing channel size has been either demonstrated or inferred in studies from diverse regions (e.g., Fox and Bolton, 2007; LeLay et al., 2013; Kramer and Wohl, 2017). This suggests the potential for relationships within or across regions between wood load and drainage area, which is used as a proxy for discharge in ungaged channels, or between wood load and channel width.

Most studies confined to a single drainage basin or limited geographic area document decreasing wood load with increasing channel width (e.g., Naiman and Sedell, 1979; Bilby and Ward, 1991; Chen et al., 2006; Baillie et al., 2008), although Fox and Bolton (2007) document increasing wood loads in rivers of the northwestern United States as a result of wood accumulating in jams that become exponentially larger as channel width increases. At least two factors limit the ability to definitively evaluate changes in wood load with increasing channel width. The first is the relative dearth of studies on very large rivers. Increasing availability of high-resolution remote imagery is rapidly enhancing the ability to quantitatively estimate wood loads on larger rivers (e.g., Atha, 2014), but only a few estimates of wood load have been published for rivers with channel widths exceeding approximately 500 m (Kramer and Wohl, 2017). The second factor limiting analyses of wood load with increasing channel width is the pervasive anthropogenic modification of riparian and upland forests, flow regime, and channel geometry in moderate to large rivers of the temperate zone. Wood recruitment has been reduced and instream wood has been actively removed from temperate-zone rivers for centuries in Eurasia and North America (e.g., Harmon et al., 1986; Montgomery et al., 2003a; Comiti, 2012; Wohl, 2014). Large rivers with unmanaged forests and wood loads unaltered by human activities now exist only in the tropical and boreal latitudes and wood loads in these environments have received very little study. The lack of unmanaged large rivers in the temperate latitudes and the lack of quantitative studies of wood loads in large rivers of lower and higher latitudes constrain the upper limit of channel size included in the dataset that we analyze here.

With respect to small to moderately sized rivers, relationships between wood load and drainage area or channel width across regions might be complicated by the existence of regional, climate-driven differences in the rate of increase in discharge and channel width as a function of increasing drainage area (Flores et al., 2006). Regional differences in the processes and rates of wood recruitment, wood piece size, and wood mobility also exist in relation to climate and forest type (Harmon et al., 1986; Benda et al., 2003; Gurnell et al., 2003; Fox and Bolton, 2007; LeLay et al., 2013; Comiti et al., 2016; Ruiz-Villanueva et al., 2016). Consequently, it is not obvious whether universal patterns can be expected to exist between wood load and drainage area or channel width. Existing syntheses of wood loads in diverse rivers commonly include data from moderate to large rivers in Europe and North America (e.g., Piégay, 2003; LeLay et al., 2013; Ruiz-Villanueva et al., 2016), which typically have a long history of management that might be expected to result in wood loads below the natural range of variability. The presence of contemporary (Boivin et al., 2015) or historical (Triska, 1984) wood rafts on large rivers suggests that contemporary assumptions of an inverse relationship between wood load and channel size may be heavily influenced by the long history of anthropogenic modification of forest and river characteristics in moderate to large rivers of the temperate zone.

1.2. Global-scale analyses

Previous syntheses have used published data from diverse field sites to evaluate differences in wood load with respect to forest type and stand age, channel width and gradient, and geographic region. Using a dataset of 152 and 314 river segments, respectively, Gurnell (2003, 2013) found significant differences in relation to forest type and stand age, with significantly higher wood loads in rivers within old-growth forests. When all of these data are combined, only weak relationships exist between wood load and either channel width or channel gradient. Ruiz-Villanueva et al. (2016) expanded this dataset to 390 sites and qualitatively demonstrated an inverse relationship between wood load and drainage area categories.

Our analysis expands on previous work by developing a larger dataset focused on unmanaged forests; differentiating bioclimatic regions; and statistically evaluating wood load in relation to channel characteristics within bioclimatic regions. We combined information on forest type and precipitation regime into the variable of bioclimatic region, which we categorize based on relative amount of mean annual precipitation and predominant forest type. Relative amount of mean annual precipitation here refers simply to wet (humid temperate, seasonal and humid tropical and subtropical) and dry (semiarid, arid), because many studies do not report mean annual precipitation for the study area. Predominant forest type refers simply to coniferous, deciduous, or mixed forests. More than half of the data come from sites in the United States.

We use segment-scale wood load data compiled from diverse environments to assess which variables exert a dominant control on wood load. Numerous factors can influence wood load, including processes of wood recruitment; transport, decay, and breakage of wood within