Wood and Sediment Storage and Dynamics in River Corridors

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Abstract

Large wood along rivers influences entrainment, transport, and storage of mineral sediment and particulate organic matter. We review how wood alters sediment dynamics and explore patterns among volumes of instream wood, sediment storage, and residual pools for dispersed pieces of wood, logjams, and beaver dams. We hypothesized that:

- volume of sediment per unit area of channel stored in association with wood is inversely proportional to drainage area;
- the form of sediment storage changes downstream;
- sediment storage correlates with wood load; the residual volume of pools created in association with wood correlates inversely with drainage area; and volume of sediment stored behind beaver dams correlates with pond area. Lack of data from larger drainage areas limits tests of these hypotheses, but the analyses suggest that sediment volume correlates positively with drainage area and wood volume. The form of sediment storage in relation to wood appears to change downstream, with wedges of sediment upstream from jammed steps most prevalent in small, steep channels and more dispersed sediment storage in lower gradient channels. Pool volume correlates positively with wood volume and negatively with channel gradient. Sediment volume correlates well with beaver pond area.

More abundant instream wood and beaver populations present historically likely equated to greater sediment storage within river corridors and greater residual pool volume. One implication of these changes is that protecting and reintroducing wood and beavers can be used to restore rivers. This review of the existing literature on wood and sediment dynamics highlights the lack of studies on larger rivers.
Keywords: instream wood, large wood, LW, rivers, sediment, particulate organic matter, erosion, deposition, storage, channel, floodplain

1. Introduction

Large wood along river corridors creates numerous physical and ecological effects that influence sediment dynamics (e.g., Keller and Tally, 1979; Harmon et al., 1986; Keller et al., 1995; Wohl, 2013). Large wood (LW) refers to downed, dead wood pieces > 1 m long and 10 cm in diameter. The river corridor is composed of the active channel and adjacent floodplains. Sediment dynamics includes the entrainment (initiation of motion), transport, deposition, and storage of particulate matter, which here includes mineral sediment and particulate organic matter (POM).

Wood along river corridors creates hydraulic resistance that can decrease flow velocity and transport capacity in the vicinity of the wood (Shields and Smith, 1991; Davidson and Eaton, 2013) or, if sufficient wood is dispersed throughout the corridor, along an entire river reach (Webb and Erskine, 2003; Wallerstein and Thorne, 2004; Brooks et al., 2003, 2006; Umazano et al., 2014). By deflecting flow, LW can also locally enhance entrainment of bed material and scour of the channel bed and banks (Buffington et al., 2002). The magnitude of the effects of LW on sediment dynamics depends on factors such as wood load (volume of wood per unit area of channel), orientation and stability of LW, and sediment supply relative to transport capacity (Wallerstein and Thorne, 2004; Yarnell et al., 2006; Magilligan et al., 2008; Fisher et al., 2010; Cadol and Wohl, 2011). The cumulative effects on river corridors of persistent LW have been described as a mediated equilibrium condition in which water and sediment fluxes and river corridor geometry are substantially influenced by riparian vegetation and LW (Brooks and Brierley, 2002).
Numerous case studies now document the effects of LW on sediment dynamics, but the information presented in these case studies has not been effectively synthesized. The primary objectives of this paper are to review what is known of wood and sediment dynamics and to collect previously published information from diverse rivers to evaluate whether patterns of wood-sediment interactions can be discerned in relation to characteristics such as channel geometry, channel gradient, drainage area, or wood load. The presence of consistent patterns across diverse channels and spatial scales could be used to more quantitatively predict the effects of LW on sediment storage and to develop management goals for restoring LW in river corridors and facilitating sediment storage and channel stability. This review focuses on bedload mineral sediment because the majority of published work examines the effects of wood on bedload processes. However, because suspended mineral sediment and POM exert such important influences on river ecosystems (e.g., Bilby and Likens, 1980; Wallace et al., 1995), the review also includes these forms of sediment.

We hypothesize that the volume of sediment per unit area of channel stored in association with instream LW declines in a downstream direction as drainage area increases (Fig. 1A). Drainage area here is a proxy for several other variables that typically exhibit progressive downstream changes; specifically, increasing discharge and channel width and decreasing channel gradient and average bed grain size. As channels grow progressively larger and discharge increases downstream, transport capacity for instream LW should increase (Gurnell, 2003). Increasing transport capacity reflects smaller values of the ratios of LW piece length to channel width and piece diameter to flow depth, each of which positively correlates with mobility of instream LW (Braudrick et al., 1997; Welber et al., 2013). Larger channels with smaller bed material are also less likely to have protruding obstacles, such as
large boulders or ramped wood pieces extending across a substantial fraction of total channel width, which can trap wood in transport (Braudrick and Grant, 2001; Bocchiola et al., 2006; Beckman and Wohl, 2014b). If wood mobility increases downstream, then we expect to see decreasing sediment storage downstream because of less stable wood that can retain sediment (Wohl et al., 2009; Cadol and Wohl, 2011). Rivers can be categorized as large based on drainage area, channel dimensions, discharge, or other parameters. In the context of LW and sediment dynamics, we use the definition of Piégay (2003): a large river has a width several times greater than the height of the trees in its riparian area.

We also hypothesize that the manner in which sediment is stored in association with LW changes downstream (Fig. 1A). Steep, laterally confined, smaller channels are likely to have relatively closely spaced, channel-spanning steps (Chin and Wohl, 2005; Church and Zimmermann, 2007), at least some of which are created by in situ logjams (Abbe and Montgomery, 2003). Each of these steps creates a backwater that stores a wedge of sediment upstream. In steep channels, the downstream thickness of this wedge can be comparable to average channel width (Andreoli et al., 2007; Ryan et al., 2014), creating substantial sediment storage per unit area of channel. The size of log steps and the resultant thickness of the sediment wedge behind them also depend on the presence of coarse bed material and the diameter of the wood forming the step (Wohl et al., 1997; Scott et al., 2014). As the channel becomes less steep and laterally confined, as well as wider, fluvial transport capacity for instream wood increases. LW is likely to be dispersed along a reach or to form transport jams (Marcus et al., 2002; Abbe and Montgomery, 2003; Wohl and Jaeger, 2009). Dispersed wood can create sufficient hydraulic resistance to facilitate deposition and storage of dispersed sediment and transport jams can create local upstream and downstream deposition, but the volume of sediment stored per unit area of channel is likely
to be lower than in the steep segments of the river network because the sediment is finer grained and hence more likely to continue downstream or to move onto the floodplain.

Large, low-gradient, floodplain rivers in forested regions historically had extensive wood rafts (Triska, 1984; Wohl, 2014) that could block even large channels sufficiently to create enhanced overbank deposition and sediment storage on floodplains. These rafts, although still present in a few rivers (Webster et al., 2002; Martín-Vide et al., 2014; Boivin et al., 2015), are now very rare. Although there is stratigraphic evidence that wood rafts could cause substantial overbank deposition (Barrett, 1996; Patterson et al., 2003), this deposition was spread across broad floodplains. The deposition thus likely resulted in lower sediment storage per unit area than jammed steps in small, steep channels, but greater volume of deposition per unit length of channel.

An alternate hypothesis is that the presence of LW is the most important influence on the volume of sediment stored and therefore sediment storage correlates most strongly with wood load (Fig. 1B). This relationship could take the form of a linear increase if more wood per unit area of channel simply causes greater sediment storage. The relationship could also resemble an exponential increase if nonlinear interactions that occur with increasing wood load, such as the formation of logjams, also create nonlinear responses in sediment storage. The most likely nonlinear interaction would be the formation of a channel-spanning logjam or, in large rivers, a wood raft that facilitates overbank flow and deposition, as well as formation of a multithread channel planform (Triska, 1984; Brummer et al., 2006; Wohl, 2011; Collins et al., 2012).

We hypothesize that the residual volume of pools created in association with LW declines in a downstream direction (Fig. 2). Pools are a readily measured manifestation of the effects of LW on sediment entrainment and removal. LW steps can create backwater...
pools upstream from the step crest and scoured plunge pools downstream from the step crest (Bilby and Ward, 1989). These pools can be substantial (Richmond, 1994; Zelt, 2002; Buffington et al., 2002), despite the high erosional resistance of coarse-grained streambeds. Dispersed wood can create local scour of the bed and transport jams can create backwater and local scour, but at lower channel gradients, LW is less likely to form tall jams with extensive backwaters or plunging flow. Our limited experience with relatively small wood rafts on channels in central Alaska suggests that deeper bed scour can be present beneath these features, but the resulting pool volume is likely to be smaller per unit area of channel than in steep, narrow channels.

We test these hypotheses and the underlying assumptions about interactions between LW, stream flow, and channel boundaries by evaluating trends in LW, sediment storage, and pool volume in relation to drainage area, channel gradient, and bankfull width from published datasets. We focus on datasets from channels with minimal human alteration of wood recruitment, instream and floodplain LW, and flow regime. Diverse human activities have substantially altered land cover and reduced recruitment of LW to river corridors, as well as directly removing LW from channels and floodplains (Montgomery et al., 2003; Wohl, 2014). The net result is that most river corridors in forested environments are wood-poor relative to conditions prior to intensive human resource use. Comparisons of LW in (i) old-growth, (ii) younger but natural, and (iii) managed forests indicate that old-growth forests have the largest wood loads within river corridors, but naturally disturbed forests are closer to old-growth conditions than are managed forests and river corridors that have experienced timber harvest and LW removal from rivers (Beckman and Wohl, 2014b). The datasets used in our analyses come from rivers within old-growth forests or forests with only natural disturbances.
We also consider the effects of beaver dams on sediment storage within river corridors. Beaver dams form a distinctive subset of instream wood because beavers actively create and maintain dams. Beavers recruit wood to the channel and floodplain by cutting down living trees and beaver dams commonly incorporate wood pieces of a size that would otherwise likely be mobile within the channel. Beavers can also create ponds that are perched along the valley sides more than a meter above the active channel and primary floodplain (Fig. 3). Because beavers actively shape dams that obstruct flow and create upstream backwaters, we hypothesize that the sediment volume behind beaver dams will correlate positively with pond area.

2. Existing Knowledge of Wood and Sediment Dynamics

Before testing the hypotheses presented above, it is useful to review what is known of how LW in channels and floodplains influences sediment dynamics. Very few studies quantify factors such as residence times of sediment stored in association with LW, but at least qualitative understanding of the effects of LW on sediment dynamics can be gleaned from existing literature. The following sections review what is known of how LW influences sediment entrainment and transport within channels, sediment storage within channels, floodplain sedimentation, POM dynamics, and effects of wood removal on sediment dynamics.

2.1. Influences of wood on in-channel entrainment thresholds and transport rates

By increasing hydraulic resistance within channels, LW typically decreases flow velocity (MacFarlane and Wohl, 2003; Andreoli et al., 2007; Yochum et al., 2012), sediment
entrainment, and suspended and bedload transport at spatial scales > $10^1$ m (Assani and Petit, 1995). However, by creating flow separation and locally accelerated and plunging flow, LW can enhance entrainment of bed and bank sediment at scales of $10^0$-$10^1$ m and create persistent scour features such as pools (Lisle, 1995; Abbe and Montgomery, 1996; Buffington et al., 2002; Klaar et al., 2011).

The effects of LW on sediment entrainment and transport may be stage dependent. Working in gravel-bed Mack Creek of western Oregon, USA, Faustini and Jones (2003) found that stream reaches with abundant LW exhibited less cross-sectional change than reaches lacking LW during moderate flows (return period < ~ 5 years), but responded similarly to larger peak flows with return periods of ~ 10 to 25 years.

When LW that is storing sediment breaks or becomes mobile, a substantial pulse of sediment transport can result. Bugosh and Custer (1989) documented how breakup of a logjam on gravel-bed Squaw Creek in Montana, USA (drainage area 106 km$^2$, channel width 8-20 m, gradient 0.02-0.03) resulted in bedload transport two times greater than that measured at similar discharges prior to the breakup. Similar observations of accelerated sediment transport and channel change following LW movement or jam breakup come from a stream in the Colorado Rocky Mountains (Adenlof and Wohl, 1994).

The effects of LW on sediment entrainment and transport also depend on channel substrate and the distribution of the wood. Flow deflection and acceleration associated with LW, especially LW accumulations that form channel-spanning steps in steep channels, can be particularly important in locally enhancing entrainment in gravel- to boulder-bed channels with relatively high values of critical shear stress. Dispersed wood in lower-gradient, sand-bed channels can reduce near-bed and average velocity and associated sediment transport capacity and result in increased storage (e.g., Brooks et al., 2003), which
presumably reflects substantially reduced entrainment and transport. Most studies that directly document the effects of LW on sediment transport, however, focus on coarser-grained streambeds, as reflected in the literature cited above.

The effects of beaver dams on in-channel entrainment thresholds and transport rates are similar to those described for other forms of LW. Beaver dams decrease sediment entrainment and transport within the backwater zone upstream from the dam (Butler and Malanson, 1995; John and Klein, 2004; De Visscher et al., 2014), enhance bed scour where flow plunges over a dam (Pollock et al., 2014), enhance spatial variation in average bed grain size (Curran and Cannatelli, 2014), and can create substantial pulses of sediment transport when a dam fails (Butler and Malanson, 2005; Russell et al., 2009).

### 2.2. Influences of wood on in-channel sediment storage

The majority of studies that examine how wood affects sediment storage focus on material transported as bedload. A few studies, however, have explicitly examined sediment transported in suspension. Skalak and Pizzuto (2010) document fine-grained deposits that accumulate downstream from LW along the margins of the gravel-bed South River in Virginia, USA. These deposits include a total mass equivalent to 17% to 43% of the annual suspended sediment load, with an average turnover time of 1.75 years for sediment. Along this river, marginal LW creates sufficient flow separation to facilitate deposition and storage of sand, silt, clay, and POM that would otherwise remain in transport.

Individual LW pieces or jams can create flow obstructions, resulting in backwater areas in which particulate matter is stored (Keller and Swanson, 1979; Megahan, 1982; Webb and Erskine, 2003; Andreoli et al., 2007; Scott et al., 2014) (Fig. 4). In addition to
promoting sediment storage, LW can facilitate deposition of finer sediment on the streambed than is present in segments of channel without wood (Faustini and Jones, 2003; Dumke et al., 2010). The orientation and stability of pieces and jams is particularly important: pieces oriented parallel to flow are less likely to facilitate storage of particulate matter (Magilligan et al., 2008). LW that is frequently mobilized may create only temporary sediment storage (Wohl et al., 2009; Cadol and Wohl, 2011), whereas deposition around stable wood can completely bury the wood and create a streambed with alternating strata of LW and sediment (Gippel et al., 1992).

LW commonly creates high spatial variability in average bed grain size in relatively steep, coarse-grained channels. This spatial variability takes the form of relatively homogeneous but spatially limited textural patches (Hogan, 1989; Buffington and Montgomery, 1999). Working in a relatively small stream (bankfull width 15 m) in British Columbia, Canada, however, Haschenburger and Rice (2004) found that individual large jams could influence bed material texture over lengths of up to 100 times the bankfull width.

Studies of the effects of LW on storage of sediment moving as bedload include several different foci. Many studies of smaller streams focus on correlations between volumes of LW and stored sediment per unit area of channel (Table 1). Studies in the Pacific Northwest region of the US have also examined how LW can alter regional patterns of channel substrate in relation to drainage area and reach-scale channel gradient. In the steep channel networks of the Oregon Coast Range, USA, the distribution of bedrock and alluvial stream reaches reflects the influences of drainage area, channel gradient, sediment trapping by LW jams, and boulders deposited by debris flows (Montgomery et al., 2003). Bedrock and free-formed alluvial reaches can be distinguished based on slope-area relations.
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predicting constriction scour associated with LW. The orientation of LW pieces influences scour, with pieces perpendicular to flow creating greatest scour (Cherry and Beschta, 1989). Published values of LW volumes and residual pool volume are summarized in Table 2.

Studies of larger rivers emphasize processes, rather than volumes, of sediment storage associated with the presence of LW. Wood deposition can initiate the formation of bars or islands that then become stabilized by riparian vegetation (O’Connor et al., 2003; Collins et al., 2012) (Fig. 5). Work by Mikus et al. (2013) on a gravel-bed river in the Polish Carpathians provides an example of how LW can enhance bed-material storage in larger rivers. Deposition of LW on gravel bars creates a sheltered spot in which woody riparian plants preferentially germinate and mature. As the plants grow larger, they create greater hydraulic resistance and increase the erosional resistance of the sediment in which they are growing, and this in turn enhances sediment deposition and storage (Gurnell et al., 2012; Bertoldi et al., 2013). The volumes of sediment historically stored in association with LW were likely to have been substantial on at least some larger, lower gradient rivers, although records are mostly unavailable. Gippel et al. (1992) cite historical descriptions of removing LW from the Latrobe River in Australia. Streambed scour after the first round of LW removal exposed underlying layers of wood. Up to three layers of logs had to be removed before the channel was cleared, resulting in as much as 2 m of bed incision.

A few studies have estimated residence time of bedload associated with LW. Fisher et al. (2010) used cosmogenic $^7$Be to estimate storage time of bedload associated with LW along the mixed sand-gravel-bed of the Ducktrap River in Maine, USA. Transport-limited river segments had longer bedload storage times (~ 100-200 days) than supply-limited segments (< 100 days). Relative to sediment stored around large boulders, LW created more storage sites with larger sediment volumes and longer storage times (Fisher et al., 2010).
The presence of abundant LW has the potential to create transport-limited conditions by substantially increasing hydraulic resistance, as shown on the Cann River in Australia, where removal of LW altered the channel from a sediment sink to a sediment source (Brooks et al., 2003).

Another approach to LW-sediment storage has been to develop empirical or stochastic models of the influence of LW on sediment retention. Working on five river segments in western Oregon, Nakamura and Swanson (1993) developed the following relationship for sediment trapped by LW:

\[ V_s = a(W)^b(S)^c \]  

in which \( V_s \) is sediment volume per unit channel length (\( m^3/100 \) m), \( W \) is average channel width (m), \( S \) is average channel gradient (per cent), and \( a, b, \) and \( c \) are constants that can vary over several orders of magnitude. Lancaster et al. (2003) modeled debris flow runout lengths for scenarios in which debris-flow velocity was reduced by wood entrainment or by wood-induced changes in flow direction. Modeling debris flows at the network scale indicates that, in scenarios with wood, debris-flow runout lengths are shorter and debris-flow deposits are widely distributed throughout the network, whereas the absence of wood increases runout lengths and basin sediment yield. Eaton et al. (2012) developed a stochastic model of wood and sediment dynamics in gravel-bed streams. They used an equation for sediment trapping based on laboratory experiments (Davidson, 2011; Davidson and Eaton, 2013):

\[ \Delta V_{sed} = Q_{bm} \bar{z}_{bm} \left( \frac{R_z}{\sum B} \right) e^{-t_x} \]
in which $\Delta V_{\text{sed}}$ is the change in volume of sediment stored by an individual LW piece over a year, $Q_{\text{bm}}$ is the annual bed-material transport rate entering a stream reach, $\zeta_{\text{bm}}$ is a reach-average bed material trapping efficiency, $B_i$ is the area of the $i$th LW piece that is projected across the channel, $\sum B$ is the sum of the projected areas for all pieces, and $t_x$ is the length of time that the LW piece has been in its current location.

As noted for sediment entrainment and transport and illustrated in Figure 1A, the effects of LW on sediment storage vary with substrate and LW characteristics. Studies quantifying the volume of sediment storage come primarily from relatively steep, coarse-grained rivers, although a few studies of this type have focused on larger, sand-bed channels in Australia. Many of the studies of larger gravel-bed rivers focus on the nature of LW-sediment interactions, however, rather than quantifying wood-associated sediment storage.

The effects of LW on sediment storage can also exhibit substantial variation through time as a result of three basic mechanisms: (1) Fluctuations in wood recruitment to a channel through time. As summarized by Benda and Sias (2003), wood recruitment to a river segment results from downstream LW fluxes and from lateral inputs in the form of individual tree mortality, mass mortality (e.g., wildfire, windstorm, insect infestation), hillslope instability (e.g., debris flows), bank erosion, and exhumation of buried logs from the floodplain. Each of these recruitment sources can vary over timescales of $10^1$-$10^2$ years. (2) Fluctuations in wood transport capacity within a river segment through time as a result of processes such as floods or debris flows. (3) Fluctuations in sediment supply to the channel as a result of downstream sediment fluxes and lateral inputs from the banks, floodplain, and adjacent uplands. Each of the studies cited in relation to LW and sediment storage essentially represents a ‘snapshot’ of LW-sediment interactions over a relatively short time interval. Although several models predict fluctuations in wood load through time.
in relation to factors such as lateral LW inputs (e.g., Bragg, 2000) or stochastic interactions among LW recruitment and discharge (e.g., Eaton et al., 2012), few field studies quantify changes in sediment storage through time (exceptions include Brooks et al., 2003 and May and Gresswell, 2003b).

Numerous studies document increased sedimentation associated with beaver dams via both ponding of water upstream from the dam and sediment deposition within the pond (Naiman et al., 1986; Butler and Malanson, 1995; John and Klein, 2004; Pollock et al., 2007; Green and Westbrook, 2009; Butler, 2012; Levine and Meyer, 2014) and enhanced overbank flows and floodplain sedimentation (Westbrook et al., 2011). Scheffer (1938), for example, estimated 7.8 m$^3$ of sediment stored per linear meter of stream along Mission Creek in Washington, USA. Individual beaver dams can retain up to 6500 m$^3$ of sediment along streams in boreal forest near Quebec, Canada (Naiman et al., 1986). Pollock et al. (2007) estimated 7200 m$^3$ of sediment in 13 beaver dams along an unspecified length of Bridge Creek in Oregon, USA. Very few studies, however, actually quantify the resulting sediment storage per unit area of the pond or valley bottom (Table 3). Only three of the five sets of published data for pond area and sediment volume use direct field measurements of sediment volume (Butler and Malanson, 1995; Meentemeyer and Butler, 1999; John and Klein, 2004). The other two studies use a regression equation between pond area and sediment volume developed by Butler and Malanson (1995). The lack of direct measurements of sediment volume in relation to pond area or unit area of valley bottom is a striking gap in the literature.

Pollock et al. (2003) proposed a relation between maximum potential sediment storage behind beaver dams, channel gradient, and dam geometry:

$$V_m = 0.5H^2W/S$$ (3)
In which $V_m$ is maximum sediment storage volume, $H$ is dam height, $W$ is dam width, and $S$ is channel gradient. Because of the lack of appropriate parameters for several of the datasets in Table 3, we did not test this relation for these data.

As with other forms of LW, the volume of sediment stored behind a beaver dam varies with time as the valley segment upstream from the dam gradually aggrades. The rate of filling depends on factors such as sediment load in the river and the geometry and location of the beaver pond (some ponds are perched along a valley wall well above the main channel, for example). Once a dam is no longer maintained by beaver, breaching of the dam can result in at least partial erosion of the pond sediment, although establishment of rooted aquatic macrophytes and, eventually, other wetland vegetation commonly limits evacuation of pond sediment. Where a beaver meadow (Morgan, 1868; Polvi and Wohl, 2013) – a more extensive floodplain wetland composed of numerous active and inactive beaver dams and ponds in various stages of infilling – is present, the cumulative sediment storage can greatly exceed average annual downstream sediment flux and temporal variations in sediment storage can be dampened over time periods of $10^1$-$10^3$ years (Kramer et al., 2012; Pollock et al., 2013).

2.3. Influences of wood on floodplain sedimentation

Concentrations of wood in jams or rafts can substantially reduce channel conveyance and increase overbank flow during higher discharges. This can result in either deposition of particulate matter on the floodplain (Jeffries et al., 2003; Sear et al., 2010) and local aggradation of the channel above the floodplain (Kochel et al., 1987; Montgomery and Abbe, 2006), or accelerated bank erosion and channel avulsion (Hickin, 1984; Brummer et
al., 2006; Phillips, 2012; Boivin et al., 2015), formation of secondary channels (O’Connor et al., 2003; Wohl, 2011; Collins et al., 2012) (Fig. 6), and localized scour or stripping of the floodplain during higher discharges (Piégay, 2003). The manner in which overbank flow affects floodplains depends on factors such as the ratio of shear stress generated by the flow versus floodplain erosional resistance and the concentration of suspended material in the overbank flow (Wohl, 2013).

Studies of the effects of in-channel LW on floodplain sediment dynamics emphasize how the obstructions created by LW enhance either overbank flows and vertical accretion or bank erosion, channel avulsion, and formation of secondary channels. Working on the Highland Water (gradient 0.0085, bankfull width 5 m) in the UK, Jeffries et al. (2003) documented increased frequency and extent of overbank flows because of in-channel logjams. They monitored 9 floods during the winter of 2000-2001 with mean overbank deposition rates of 1.6 to 8 kg/m$^2$, although rates were as high as 28 kg/m$^2$ in the vicinity of in-channel logjams. Overbank deposition reflected flood magnitude and suspended sediment load, but the high deposition rates around logjams were significantly above values recorded for other lowland rivers in Europe with less LW (Jeffries et al., 2003). Sear et al. (2010) demonstrated that enhanced floodplain deposition along this channel can occur at sites distant from the main channel when logjams divert sediment-laden water into floodplain channels. LW-induced overbank sedimentation can be a primary mechanism for vertical accretion on some floodplains (Nanson et al., 1995; Oswald and Wohl, 2008). LW can also influence lateral accretion by altering the rates and mechanisms of channel avulsion and migration. Accumulations of wood can accelerate migration or avulsion, but wood can also dampen channel migration, as in the scenario when a logjam blocks a chute cutoff along a sinuous channel (Hickin, 1984).
As with other aspects of LW-sediment interactions, the mechanisms and relative importance of wood-induced changes in floodplain sedimentation or erosion can scale with river size. Channel-spanning in situ jams (Abbe and Montgomery, 2003) are more likely to enhance channel-floodplain connectivity and associated changes in floodplain sedimentation in smaller rivers (Wohl, 2011), but wood rafts can have similar effects in very large rivers (Triska, 1984). Marginally deposited LW that limits or directs overbank flow (Piégay, 2003) can strongly influence floodplain sedimentation in large rivers. The primary scale effect may be that progressively larger rivers typically have progressively wider and more longitudinally continuous floodplains, although this is not always the case.

Few studies of sedimentation associated with beaver dams consider overbank deposition outside of a defined pond. Exceptions include Scheffer (1938), who described beaver-induced deposition of 4470 m$^3$ of sediment behind 22 dams along a 620-m-length of Mission Creek, Washington, Kramer et al. (2012), who used near-surface geophysical methods to quantify beaver-induced sediment storage over a 2 km$^2$ area in Rocky Mountain National Park, Colorado, and Westbrook et al. (2011), who documented 750 m$^3$ of sediment deposition over a 1.1 ha area along the upper Colorado River floodplain in Rocky Mountain National Park. Each of these studies examined the cumulative sediment storage associated with a beaver meadow.

2.4. **Influences of wood on particulate organic matter (POM) dynamics**

Most studies of POM dynamics have been conducted by stream ecologists (e.g., Webster et al., 1999). They divide POM into fine POM (0.45 μm to 1 mm) and coarse POM (> 1 mm). The amount of POM in streams reflects input rates, abiotic and biotic processing.
rates, stream transport capacity, and retention structures such as LW (Naiman and Sedell, 1979; Raikow et al., 1995). LW is thus only one of several controls on POM storage, but several studies demonstrate that greater wood loads correspond to greater POM storage (Bilby, 1981; Bilby and Ward, 1989; Raikow et al., 1995; Thompson, 1995; Beckman and Wohl, 2014a). This appears to be the case even in low-gradient channels in which LW is highly mobile (Daniels, 2006). In low-gradient, sand-bed, headwater streams, LW jams can facilitate trapping and burial of POM during higher discharges when much of the streambed is mobile (Jones and Smock, 1991).

Experimental releases of POM demonstrate that much of the material retained within the channel is associated with LW (e.g., Millington and Sear, 2007). When all LW jams were experimentally removed from a 175-m-long segment of Hubbard Brook Watershed 5 (channel width 2.8 m, gradient 0.213 m/m) in New Hampshire, USA, for example, POM export increased from 1450 kg/year to 9150 kg/year (Bilby, 1981). In addition to trapping and storing POM produced from other sources, LW can be a source of finer POM. Ward and Aumen (1986) found that POM resulting from wood processing via microbial activity and physical abrasion created several times the POM contributed by leaf and needle litter in western Oregon’s gravel-bed Mack Creek. By enhancing hyporheic exchange (Sawyer et al., 2012), in-channel LW may also influence movement of POM between the surface and subsurface.

Working in the Cascade Mountains of Oregon, USA, Naiman and Sedell (1979) showed that benthic POM was inversely proportional to stream order. Annual values of stored POM, including LW, ranged from 26 kg/m² in the smallest channel to 0.8 kg/m² in the largest channel (the 7th order McKenzie River). In all channels, LW accounted for > 90% of this material. Studies elsewhere also document decreasing volumes of POM storage as
channel size increases (e.g., Bilby and Ward, 1989) and a smaller proportion of POM storage being associated with LW as channel size increases (e.g., Bilby and Likens, 1980). Existing studies of instream POM have focused almost exclusively on smaller rivers draining areas smaller than about 100 km² (Tank et al., 2010), although a separate line of research in riparian ecology quantifies organic matter and carbon content of riparian and floodplain soils on large rivers (e.g., Hoffmann et al., 2009; Cierjacks et al., 2010).

As with mineral sediment, temporal fluctuations in LW-induced POM storage occur as a result of fluctuations in discharge and associated trapping capacity within a river or floodplain, POM inputs, and wood load. POM is continually produced within the riparian zone and adjacent uplands, decays relatively quickly, and is typically readily mobilized. Consequently, fluctuations in POM supply and discharge can produce substantial variations in POM storage over timescales of less than a year (e.g., Heartsill Scalley et al., 2012), whereas changes in wood load are likely to create variations in storage over longer timescales. Analogous to wood-induced variations in storage of mineral sediment, few studies have quantified variations in wood-induced POM storage over time periods greater than a few years.

Beaver dams are also very effective at trapping POM in the pond associated with each dam. Examining boreal forest drainage networks in Quebec, Canada, for example, Naiman et al. (1986) documented a benthic standing stock of coarse POM of 125 g/m² in riffles and 4075 g/m² in beaver ponds. Although the ecologists who have primarily investigated this topic tend to focus on fluxes rather than storage (e.g., Naiman and Melillo, 1984; Correll et al., 2000), their work clearly indicates that POM fluxes are lower through beaver ponds than through adjacent riffles or through the same stream segment without a beaver dam. As Naiman et al. (1994) demonstrated for boreal forest drainage networks in
Minnesota, USA, beaver activities shift nutrient and ion storage from forest vegetation to sediments.

2.5. Effects of wood removal on sediment dynamics

Wood removal can occur directly when wood is physically taken out of a channel or floodplain for purposes of flood control (Gendaszek et al., 2012), navigation (Harmon et al., 1986), or limiting potential damage by mobile wood during floods (Mazzorana et al., 2011; Mao et al., 2013; Ruiz-Villanueva et al., 2014). Wood removal can also occur indirectly when recruitment of new wood to a channel or floodplain is reduced or eliminated by timber harvest or other changes in land cover (Montgomery et al., 2003; Wohl, 2014). Once wood is removed, the ability of a channel to retain subsequently recruited wood can decrease. Wood within a channel or floodplain, particularly less mobile pieces, creates obstructions to wood in transport and can therefore help to trap otherwise mobile wood (Braudrick et al., 1997; Braudrick and Grant, 2001; Bocchiola et al., 2008; Wohl and Beckman, 2014b). Direct or indirect wood removal can therefore continue to influence wood loads along river corridors even after the wood removal ceases.

Direct and indirect wood removal has been occurring for many centuries in Eurasia (Schama, 1995; Montgomery et al., 2003; Comiti, 2012) and for more than a century in the Americas (Wohl, 2014), Australia (Brierley et al., 1999), and New Zealand (Mackay, 1991). Wood removal has affected entire river networks, from the smallest headwater channels to the major rivers on these continents, with the result that the great majority of rivers in high-income countries now have wood loads that are orders of magnitude lower than wood loads prior to the Industrial Revolution. The net effect on sediment dynamics of removing
LW is to reverse all of the influences discussed in the earlier parts of this paper. The magnitude of these effects has not been quantitatively estimated at the largest spatial and temporal scales, but smaller scale studies provide some insight into the effects of wood removal.

When LW is removed from a channel, bedload transport rates can increase significantly. Experimental removal of LW from gravel-bed Bambi Creek (drainage area 155 ha, gradient 0.010, channel width 3.9 m) in southeastern Alaska, USA caused a four-fold increase in bedload transport during bankfull discharge for a year after LW removal (Smith et al., 1993). Wood removal can result in decreased volumes of stored sediment, as well as centralizing the locations of sediment storage (Klein et al., 1987). Pool volume can also decrease substantially (Bisson and Sedell, 1984), as observed during the first high flow following LW removal along gravel-bed Salmon Creek (drainage area 900 ha, gradient 1.5%, bankfull width 11.5 m) in western Washington, USA (Bilby, 1984). Wood removal along the sand-bed Little Sioux River (drainage area 69 km², channel gradient 0.5%, channel width 4.7 m before LW removal) in Wisconsin, USA resulted in 25% narrowing of mean channel width, 32% increase in mean velocity (but not thalweg velocity), incision of the bed, 58% reduction in sand bedload, and 400% increase in coarse channel substrate at the 300-m reach evaluated in the study (Dumke et al., 2010).

Removal of LW throughout a river corridor also strongly influences floodplain dynamics. As demonstrated most thoroughly for rivers in the Pacific Northwest region of the United States, LW removal has caused anastomosing rivers to become single-thread, in association with a loss of channel-floodplain connectivity and floodplain physical and biotic diversity (Collins et al., 2002; Gendaszek et al., 2012). Removal of historically occurring wood
rafts on large lowland rivers in the southeastern United States has resulted in decreased floodplain sedimentation rates (Barrett, 1996; Patterson et al., 2003).

Removal of beavers and their dams has also been practiced for centuries in association with fur trapping (Naiman et al., 1988) and, more recently, as a means of controlling flooding and the mobility of small instream wood along river corridors. As with instream LW removal, the net effects of removing beavers and beaver dams are to increase velocity, reduce instream sediment storage, reduce hyporheic exchange, reduce overbank flows and vertical floodplain accretion, and change multi-thread channels to single-thread planforms (Naiman et al., 1988; Marston, 1994; Green and Westbrook, 2009; Polvi and Wohl, 2013).

The spatial scale and magnitude of the effects on sediment dynamics of LW and beaver removal likely varied among different types of channels, just as the effects caused by the presence of LW and beaver vary among channels. Removal of beaver likely had the greatest influence on the smaller rivers (approximately ≤ 30 m bankfull channel width) that beaver are more likely to dam, although removing many beaver dams from headwater areas within a river network could have a substantial cumulative effect on sediment yield to downstream portions of the network. Removal of LW jams may have substantially reduced storage of bedload, and particularly the finer portion of bedload, in steep channels. Removal of dispersed LW is likely to have reduced instream sediment storage in moderately sized, pebble to sand-bed channels, as illustrated by work in Australia (Gippel et al., 1992; Brooks et al., 2003), and removal of LW rafts likely reduced floodplain sedimentation in large rivers (Barrett, 1996; Patterson et al., 2003).

3. Patterns of Wood and Sediment in Rivers
Numerous factors can potentially influence wood loads and associated sediment dynamics in river corridors. Proximal controls include the recruitment of LW and delivery of sediment to rivers and the flow regime that influences distribution of LW and sediment. Distal controls include geologic history, lithology, climate, and land use as these influence the downslope movement of water, sediment, and LW. Despite the importance of these variables in controlling observed quantities of LW and sediment storage along river corridors, the lack of consistently reported and relevant quantitative measures of these variables in many LW studies limits our ability to statistically analyze their effect. Consequently, we focus on potential patterns between LW and sediment in relation to commonly reported river variables.

3.1. **Volume of stored sediment**

We used the data in Table 1 to evaluate trends in stored sediment in relation to drainage area, channel gradient, bankfull channel width, and wood load (Fig. 7). Sediment storage associated with wood was estimated over different spatial scales (channel width versus reach-scale) and using slightly different field methods in all of the studies reviewed for this analysis. We chose only those studies from which we could derive volume of sediment per unit area of channel surface, either by using the data reported in the paper or, in some cases, by contacting the authors of a paper and requesting supplemental data. Despite our efforts to standardize data presentation, it is important to note that these data reflect different field methods and should be regarded as a reasonable approximation of patterns of wood and sediment storage across rivers, rather than precise and fully comparable quantities.

We hypothesized that sediment volume stored in association with LW would exponentially decrease downstream in relation to drainage area (Fig. 1A). Fig. 7A weakly
supports this hypothesized trend, with the exception of an outlier from Australia. A bivariate plot of channel gradient versus sediment volume indicates no relationship. The bivariate plot of channel width versus sediment volume (Fig. 7B) suggests a peak in stored sediment at intermediate values of channel width, although this peak is based on only five data points. We also hypothesized that sediment volume would increase with wood volume (Fig. 1B). Fig. 7C weakly suggests such trends, although it remains unclear whether this relationship is better described as a linear or an exponential increase. The data in Fig. 7 do not extend to sufficiently large drainage areas to include the wood rafts included in Fig. 1, but the hypothesized downstream change from jammed steps to dispersed wood appears to be present in Fig. 7A and 7B. We also evaluated wood volume per unit area against bankfull channel width (sensu Fox and Bolton, 2007). Although a slight trend was present, with wood load increasing as channel width increased, analogous to the pattern in Fox and Bolton (2007), the relationship was not significant at $\alpha = 0.10$.

The outlier (Fig. 7A) from the Australian site with larger drainage area is important. Historical records from North America and elsewhere suggest that substantial volumes of LW were present in large channels (Wohl, 2014). This LW likely created significant sediment storage within channels and across floodplains, but sediment storage was not measured prior to intensive and sustained LW removal during the second half of the 19th century and first half of the 20th century. If the Australian outlier in the upper right of Fig. 7A is representative of other rivers with larger drainage areas, our hypothesized relationship in Fig. 1A could be backwards, with the largest volumes of sediment storage per unit area actually occurring in larger, or at least mid-sized, rivers. At present, we do not have the data to evaluate this hypothesis.
We utilized multivariate analysis to model sediment volume using drainage area, channel gradient, bankfull channel width, and wood load. We performed all subsets multiple linear regression in the R statistical package (R Core Team, 2014) and used the corrected Akaike Information Criterion (AICc) weights to evaluate 16 potential models (Wagenmakers and Farrell, 2004). To accommodate the non-normality of the dataset, we used a square root transform on all variables before performing multiple linear regression. We used Akaike weights (Burnham and Anderson, 2002) to rank the relative importance of each variable in the model to better understand which predictors exerted a dominant influence on residual pool volume. We found a significant (p < 0.001) correlation ($R^2_a = 0.39$) (Fig. 8A) between drainage area, wood volume, and stored sediment volume, such that stored sediment increases linearly with drainage area and wood volume. Drainage area was the most important predictor (weight = 1.0), followed by wood volume (weight = 0.79). We also tested the sediment volume prediction relation proposed by Nakamura and Swanson (1993) (note that our model uses sediment volume per unit area, not per unit river length) using the dataset compiled here. We were able to moderately predict sediment volume using width and gradient ($R^2_a = 0.26$) (Fig. 8B). Applying the Nakamura and Swanson (1993) relation to only jammed steps resulted in a similar predictive ability ($R^2_a = 0.25$) (Fig. 8C). Our dataset weakly supports the idea of a power function relating sediment volume to width and slope: as gradient and width increase, the volume of sediment behind a jam increases. It is important to note, however, that both the Nakamura and Swanson (1993) relationship and our multiple linear regression perform poorly for larger sediment volumes (Fig. 8). Both of these models show an increase in sediment volume downstream (positive correlation with either width or drainage area), contradicting our hypothesis that sediment volume decreases downstream in a river network. This could indicate that (i) wood mobility
is not tied to sediment storage, (ii) dispersed LW is capable of creating greater sediment storage per unit area than the logjams that are common in the smaller streams in our dataset, or (iii) sediment storage has a peaked function, with increased sediment storage in mid-sized rivers and lower sediment storage in small and large rivers. As noted above, we cannot test the third possibility because of an absence of data from large rivers.

In testing our hypothesis regarding the effect of wood volume on sediment volume, we added a wood volume term to the Nakamura and Swanson (1993) relation, but we found that the wood volume term was most likely not significant in the model. Thus, our hypothesis that increasing wood volume should increase sediment volume is supported by our multiple linear regression, but not by the relationship of Nakamura and Swanson (1993). Wood volume likely plays some role in controlling sediment volume, although there may be a threshold sediment volume above which wood fails to control sediment volume, as indicated by the poor performance of the tested models at high sediment volumes. Our analysis fails to test for the possibility of a threshold sediment storage response that may occur due to the presence of extremely large wood jams.

One of the challenges in assembling the data for these analyses was the lack of consistent methods for quantifying sediment storage. Standardized measurements that allow sediment storage associated with LW to be quantified on the basis of per unit area of channel would be very useful.

### 3.2. **Residual pool volume**

We used the data in Table 2 to evaluate trends in residual pool volume in relation to drainage area, channel gradient, bankfull channel width, and wood load (Fig. 9). We hypothesized that residual pool volume would decrease as drainage area increased (Fig. 2). A bivariate plot of drainage area versus pool volume (Fig. 9A) contains so much scatter that
there is little support for this hypothesis. Similarly, Fig. 9B does not suggest any correlation between channel width and pool volume. Figs. 9A and 9B also do not indicate any trend with respect to the occurrence of plunge pools in relation to drainage area or channel width.

Pool volume is slightly more likely to increase with LW volume (Fig. 9C), but there is substantial scatter in the data. Analogous to Fig. 7, the data in Fig. 9 do not extend to sufficiently large rivers to include wood rafts (Fig. 2), so we cannot evaluate the potential for declining pool volume per unit area in much larger rivers.

We modeled residual pool volume using multiple linear regression in a similar method to our linear modeling of sediment volume. The best model explained the majority of the variance in the data ($R^2 = 0.63, p < 0.0001$) by utilizing channel gradient and wood volume as predictors (Fig. 10). Wood load (weight = 1.00) is the most important predictor, followed by channel gradient (weight = 0.98). Pool volume correlates negatively with slope and positively with wood volume, such that lower slopes and higher wood volumes produce greater pool volumes. This contradicts our hypothesis that pool volume decreases downstream, assuming that slope also decreases downstream. This could reflect (i) the greater ability of flow deflected by LW to scour a bed that is likely to be composed of finer grained substrate at lower gradients or (ii) the more extensive backwaters associated with logjams at lower stream gradients.

The results from the multiple linear regression also seemingly contradict the interpretations from the bivariate plots (Fig. 9). Multiple linear regression accounts for changes in the modeled variable with respect to the association of many predictor variables, as opposed to the individual effects of each variable. The sum of the effects of all variables might be able to predict the modeled variable when each individual variable by itself cannot. Consequently, we consider the results from the multiple linear regression analyses
to be more indicative of actual relationships between pool volume and potential control variables than the results from bivariate analyses.

We did not perform similar analyses for relations between LW volumes and POM storage because of a lack of published studies that report volumes or weights of instream LW and POM storage. We found only two studies (Naiman and Sedell, 1979; Beckman and Wohl, 2014a) that report these types of data. LW clearly exerts an important influence on POM storage, as reviewed above, and the lack of studies quantifying this effect represents a significant gap in our understanding of how forest, channel, and LW characteristics interact to influence storage of particulate material within rivers.

### 3.3. Volume of sediment stored in beaver ponds

Data from the three studies with direct measurements of beaver pond area and sediment volume indicate that sediment volume increases with pond area (Fig. 11A). We identified and removed two outlying data points that represent extreme sediment volumes in order to obtain a better model for the majority of the dataset (low sediment volumes and small ponds). The model should not include an intercept term, considering that a pond of zero area should hold no sediment. A linear regression through the data had highly non-normal error variance, leading to our choice of a logarithmic transformation of the data, which satisfied linear regression assumptions (Fig. 11B). The strength of this relation is uncertain, however, because of the small dataset. Insufficient data exist to understand the relationship between beaver ponds and stored sediment for extremely large beaver ponds.

The stratigraphy and soil characteristics of diverse forested regions in the northern hemisphere suggest that much larger beaver dams and ponds existed in the past (Morgan, 1868; Mills, 1913). At least one very large beaver pond has been identified from remote sensing imagery in northern Canada (Discovery News, 2010), but this site has not yet been
measured. Systematic field measurements of the largest beaver ponds still in existence would help to clarify the relation between beaver pond area and sediment volume.

3.4. **Observed patterns relative to initial hypotheses**

As explained in the introductory sections, we hypothesized either that (i) the volume of sediment per unit area of channel stored in association with instream LW declines in a downstream direction as drainage area increases or (ii) the presence of LW is the most important influence on the volume of sediment stored and therefore sediment storage correlates most strongly with wood load. Multiple linear regression analyses indicate a significant relation in which sediment volume increases linearly with drainage area and wood volume. The lack of support for the hypothesized trend between sediment storage and drainage area could reflect either a poor understanding of how LW influences sediment storage in larger rivers or the limitations of the data analyzed here, which do not adequately represent medium to large rivers. We also hypothesized that (iii) the residual volume of pools created in association with LW declines in a downstream direction. Multiple linear regression analyses indicate that residual pool volume increases as LW volume increases, but is greater downstream. Finally, we hypothesized sediment volume behind beaver dams will correlate positively with pond area, a relationship that the results support.

An important consideration with respect to our ability to test hypotheses regarding downstream trends in sediment storage and pool volume is the limitations of this dataset. All of the channels for which LW and sediment data were obtained have a gradient $> 0.002$ and most of the channels for which LW and pool volume data were obtained have a gradient $> 0.01$. In other words, we are analyzing data primarily from small, steep, mountain streams, presumably because such streams are among the few remaining river segments
with old-growth or natural forest and minimal flow regulation and channel engineering. The
trends that we initially hypothesized might exist, but quantitative measurements of LW,
sediment storage, and pool volume focused on medium to large rivers are needed to fully
test these hypotheses.

Conclusions

Diverse investigations of the relatively small amounts of LW and beaver dams still
present in river corridors clearly indicate the importance of these LW and dams for
sediment dynamics. Obstructions from individual LW pieces to logjams, beaver dams, and
wood rafts can significantly alter entrainment, transport, and deposition of particulate
organic matter, suspended sediment, and bedload at spatial scales from the immediate
vicinity of the obstruction to river reaches $10^1$-$10^2$ m long. Over relatively small drainage
areas (0-200 km$^2$), the volume of sediment stored within channels in association with LW
tends to increase as drainage area and LW increase, and the residual pool volume tends to
increase with LW load and with declining gradient, but data that would allow us to examine
patterns at larger drainage areas do not exist. Similarly, the volume of sediment stored in
beaver ponds increases with pond area, although the details of this relationship are unclear
because of a lack of data from larger beaver ponds. One of the more important insights
arising from our review of the existing literature on wood and sediment dynamics in rivers is
the lack of studies on larger river systems. Most, or perhaps all, large rivers within the
temperate zone have been so altered by systematic removal of LW and beaver that
investigations of these systems will need to focus on characteristics of floodplain
stratigraphy or, where present, abandoned and preserved paleochannels (Howard et al.,
1999; Davies et al., 2014). Large rivers at higher or lower latitudes may provide useful
insights into wood and sediment dynamics, although tropical rivers, in particular, are likely to have such rapid rates of wood decay (Cadol et al., 2009) that wood may not influence sediment dynamics in the manner discussed in this paper.

In conclusion, it is worth emphasizing that wood was once much more abundant, from channel-spanning LW steps in steep, headwater channels to wood rafts and dispersed pieces within major lowland rivers. Similarly, millions of beavers once inhabited river corridors throughout the northern hemisphere. Although the trends presented here between LW volume and either stored sediment volume or residual pool volume only apply to the limited data and range of channel sizes used for this synthesis paper, all the available evidence suggests that more abundant wood equated to greater volumes of sediment stored and greater residual pool volume in diverse channels. The net effect of direct and indirect LW and beaver removal from river corridors has been to increase channel conveyance for water and sediment and to decrease the physical complexity of channels and floodplains. One of the management implications of these changes is that actively reintroducing LW and beavers and/or limiting active removal of naturally recruited wood from rivers can be used to restore river process and form.

Active design and placement of individual pieces of LW or of engineered log jams is increasingly being used as part of river restoration (Abbe et al., 2003; Abbe and Brooks, 2011; Gallisdorfer et al., 2014), as is reintroduction of beavers or building dams that mimic those built by beavers (Pollock et al., 2014). LW and beaver dams can be used to enhance fish habitat, trap sediment, stabilize channels, and enhance hyporheic exchange (Shields et al., 2004; Brooks et al., 2004, 2006). Understanding of how LW interacts with flow forces, sediment in flux, and channel boundaries can also be used in passive restoration that
facilitates LW recruitment and allows LW within the river corridor to influence channel and floodplain process and form (e.g., Piégay et al., 2000).

The very limited published quantifications of instream LW and associated volumes of stored sediment and residual pools, and the even more limited published quantification of beaver dams and sediment storage, highlight a data gap in the literature. Our analyses point to a correlation between stored sediment volume, drainage area, and wood volume, as well as a correlation between residual pool volume, slope, and wood volume. These analyses indicate that wood volume, in conjunction with drainage characteristics, plays a major role in controlling the geomorphically and ecologically important factors of volume of stored sediment and pool volume within a channel. Specific focus on quantifying relations among wood, sediment, pools, and beaver dams, including detailed field measurements of these variables, could help to expand the analyses presented here and provide clearer guidelines for restoring or protecting instream and floodplain LW and beaver populations in order to facilitate storage of sediment and creation of pools. The negation of our hypotheses regarding sediment and pool volume highlights our current lack of understanding of these relationships. An explicit focus on how sediment storage varies through time in relation to fluctuations in LW recruitment and storage, as well as in relation to fluctuating water and sediment discharges, is also missing from the literature.

In future studies, it would be particularly valuable to specify the area of channel which a set of wood and sediment measurements represent (e.g., channel-width versus reach-scale). Information that is integral to understanding wood and sediment relations in river corridors includes the most detailed description possible of land-use and natural disturbance history, stand age of the riparian forest, forms of LW recruitment (e.g., bank erosion versus hillslope failure), and contemporary conditions of the river corridor with
respect to LW recruitment. The last point can help to evaluate whether LW present in the river corridor represents a legacy of past human- (e.g., timber harvest) or naturally induced recruitment or whether the LW represents contemporary processes. Understanding the conditions under which LW is recruited can help to understand differences in wood load, piece size, spatial distribution (e.g., sunken logs versus unattached pieces), and decay rates, all of which can vary between old-growth forest and fast-growing pioneer tree species (Bunn and Montgomery, 2003; Chen et al., 2005; Keeton et al., 2007; Beckman and Wohl, 2014b). These differences in LW characteristics and distribution can significantly affect geomorphic function of the LW, and might explain some of the observed variability between sites, but we were unable to gather sufficient supporting data to evaluate these effects in the analyses reported here.

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Fig. 1. Hypothesized relations between sediment storage and potential control variables. (A) Sediment stored per unit area of channel could correlate inversely with drainage area. In this figure, we assume that increasing drainage area correlates positively with floodplain extent and inversely with gradient and average size of channel substrate. Inset ovals represent different forms of instream wood and associated sediment storage. (B) Sediment stored per unit area of channel could correlate primarily with instream wood load, with either a linear or exponential relationship.
Fig. 2. Hypothesized relation between residual pool volume and drainage area. Inset ovals represent different forms of instream wood and associated bed scour to form pools.
Fig. 3. Downstream view of a beaver pond perched along the valley side wall ~ 3 m above the active channel of the Duke River (out of sight here in the right foreground), Yukon Territory, Canada.
Fig. 4. Channel-spanning logjams that create local sediment storage. (A) Upstream view of the base of a logjam on an unnamed tributary to the Upper Rio Chagres in Panama. The jam creates a wedge of sediment, approximately 6 m thick at the downstream end, which tapers upstream. Person holding 2-m-tall survey rod at upper left for scale, highlighted with white oval. (B) Downstream view of wedge of sand-sized and finer sediment and particulate organic matter stored upstream from a jam that is partially breached along North St. Vrain Creek, Colorado. Channel is approximately 15 m wide.
Fig. 5. Google Earth imagery of a portion of the Snake River, Wyoming, USA, showing a concentration of fluvially deposited wood at the upstream end of a bar. Flow direction is right to left and the bar is approximately 300 m long.
Fig. 6. Aerial view of a naturally formed wood raft on a side channel of the Slave River, Northwest Territories, Canada. White oval contains a person; channel width in the foreground is approximately 70 m. Photograph courtesy of Natalie Kramer.
Fig. 7. Sediment volume per unit area of channel in relation to (A) drainage area, (B) bankfull channel width, and (C) volume of wood per unit area of channel for the data in Table 1. Data point surrounded by a dashed oval represents an outlier from an Australian site. Each data point represents a reach-scale average, so points designated as jammed steps reflect a reach in which the majority of sediment storage was associated with jammed steps.
Fig. 8. Comparison of predicted versus measured sediment volume by applying: our multiple linear regression to the entire dataset (A), the Nakamura and Swanson (1993) relationship to the entire dataset (B), and the Nakamura and Swanson (1993) relationship applied to only jammed steps (C). A 1:1 line is shown in each plot to represent the behavior of an ideal model. The performance of the model can be evaluated by comparing the distance of each point from the 1:1 line. Notice that the model tends to perform better for data with low measured sediment volume.
Fig. 9. Residual pool volume per unit area of channel in relation to (A) drainage area, (B) bankfull channel width, and (C) volume of wood per unit area of channel for the data in Table 2. Solid black data points represent plunge pools. Each data point represents a reach-scale average, so points designated as plunge pools reflect a reach in which the majority of pools formed by this mechanism.
Fig. 10. Comparison of measured pool volume data to volume predicted by multiple linear regression using channel gradient and wood volume as predictors. A 1:1 line is shown to represent the behavior of an ideal model. The performance of the model can be evaluated by comparing the distance of each point from the 1:1 line.
Fig. 11. Beaver pond area versus volume of stored sediment within the pond, using data in Table 3 (A) and with outliers removed and model fit shown (B). The Spearman correlation coefficient for (A) is 0.89.
Table 1. Published values for volumes of in-channel wood and stored sediment

<table>
<thead>
<tr>
<th>Site</th>
<th>Drainage area (km²)</th>
<th>Gradient (m/m)</th>
<th>Bankful width (m)</th>
<th>Reach length (m)</th>
<th>Riparian stand age</th>
<th>Wood vol (m³/ha)</th>
<th>Sediment vol (m³/ha)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tres Arroyos, Chile</td>
<td>9.1</td>
<td>0.7</td>
<td>7.8</td>
<td>1500</td>
<td>old-growth</td>
<td>656 to 710</td>
<td>1600</td>
<td>Andreoli et al., 2007</td>
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<td>Tonghi Creek, Australia</td>
<td>187</td>
<td>0.002</td>
<td>14.5</td>
<td>715</td>
<td>No human disturbance; wildfires during 1960s-70s</td>
<td>576</td>
<td>5464</td>
<td>Webb &amp; Erskine, 2003</td>
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<tr>
<td>Bruces Creek, Australia</td>
<td>68</td>
<td>NA</td>
<td>10</td>
<td>310</td>
<td>not reported</td>
<td>751</td>
<td>&lt;10,645²</td>
<td>Webb &amp; Dragovic, 2004</td>
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<tr>
<td>Western Oregon</td>
<td>5.5</td>
<td>0.11</td>
<td>18.1</td>
<td>500</td>
<td>old-growth</td>
<td>570</td>
<td>408</td>
<td>Nakamura &amp; Swanson, 1993</td>
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<tr>
<td>Malaysia</td>
<td>0.33</td>
<td>0.027</td>
<td>2.9</td>
<td>500</td>
<td>no logging since 1960s</td>
<td>50 to 60</td>
<td>20 to 40 (varies over time)</td>
<td>Gomi et al., 2006</td>
</tr>
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<td>Colorado, USA</td>
<td>2.70</td>
<td>0.09</td>
<td>2</td>
<td>100</td>
<td>old-growth</td>
<td>225</td>
<td>117</td>
<td>Ryan et al. 2014</td>
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<tr>
<td>Colorado, USA</td>
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<td>0.09</td>
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<td>100</td>
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<td>289</td>
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<td>1.8</td>
<td>140</td>
<td></td>
<td>319</td>
<td>110</td>
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<td>0.022</td>
<td>8.9</td>
<td>2000</td>
<td>not reported</td>
<td>252</td>
<td>58</td>
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<tr>
<td></td>
<td>66.8</td>
<td>0.016</td>
<td>11.2</td>
<td></td>
<td>reported fire in 1988</td>
<td>166</td>
<td>53.6</td>
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<td>5700</td>
<td>not reported</td>
<td>22.6</td>
<td>1.86</td>
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<td>Queen Charlotte Islands, BC</td>
<td>6.9</td>
<td>0.0125</td>
<td>20.2</td>
<td>244</td>
<td>old-growth</td>
<td>570</td>
<td>287</td>
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<tr>
<td></td>
<td>6.8</td>
<td>0.0199</td>
<td>21.1</td>
<td>250</td>
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<td>37.8</td>
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NA indicates not available; sediment stored primarily as jammed steps and sediment wedges indicated with italicized font

1 This refers to age of riparian forest along the study reach, where reported. Sites for which riparian stand age was not reported were in some type of forest reserve with minimal human alteration during recent decades.

2 This is an upper bound; it is not clear what percentage of this sediment storage is caused by wood
Table 2. Published values for in-channel wood load and residual pool volume

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<th>Gradient (m/m)</th>
<th>Bankfull width (m)</th>
<th>Reach length (m)</th>
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<th>Wood vol (m³/ha)</th>
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| Western Oregon, USA | 6.5 | 0.022 | 7.8 | 1550 | logged 50 years | 232 | 228 Andrus et al., 1988 |
|                     | <6.5 | 0.049 | 6.1 | 1950 | earlier         | 251 | 126 |
|                     | <6.5 | 0.057 | 5.9 | 750  |                 | 393 | 54  |
|                     | <6.5 | 0.060 | 5.5 | 750  |                 | 596 | 53  |

Italicized font indicates predominantly plunge pools

1. Type of pool not indicated; assumed any gradient > 0.06 was predominantly plunge pools
Table 3. Published volumes of sediment storage in beaver ponds

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1. Estimated sediment volume using a regression for pond area and sediment volume developed by Butler and Malanson (1995)

NA indicates information not available

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