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Watershed controls on the export of large wood from stream corridors

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ABSTRACT

Large wood maintains in-channel and floodplain habitats by influencing the biophysical character of the river corridor. Large wood dynamics in a river corridor are a product of watershed wide processes and also of local recruitment, transport, and storage. This complexity of scales added to the logistical constraints in taking measurements limits our understanding of large wood dynamics through the watershed. To begin to unravel this issue, we compiled a data set of the volume of large wood deposited annually into 131 reservoirs across Japan and compared large wood export to flow discharge and watershed characteristics (watershed size, latitude, channel slope, percent forest, and forest type). We found that large wood was predominately transported during peak flow events. Large wood export increased logarithmically with watershed area. The decreasing export rate of large wood per watershed area is interpreted as a combination of annual export variability in upper watersheds, a non-significant increase in large wood recruitment along the longitudinal gradient (potentially human influenced), the increase in long-term storage on adjacent large floodplains, and significant decay/fragmentation downstream. Watersheds $<$10–20 km^2 had a highly variable large wood export pattern, conforming generally to previously published work that suggest transport limitation in smaller watersheds. The data suggest the existence of an *export threshold* ($\sim$75 km^2) where large wood export is no longer related to watershed size. Export across all watershed sizes was controlled by watershed characteristics (slope, percent forested, etc.) and peak discharge events. The connection with upstream watersheds and laterally with the floodplain increases the net flux of large wood through downstream transport and retransport of buried logs. Identifying rates of large wood transport from watershed connectivity as a potential key input process will improve our basic understanding of geomorphic and ecological patterns within the watershed. These results highlight the importance of understanding the local- and watershed-scale dynamics of large wood in creating and maintaining more heterogeneous riparian and aquatic habitat along the river corridor.

1. Introduction

The presence of large wood in river systems has pronounced geomorphic and ecological significance (Montgomery et al., 1996; Gregory et al., 2003). Large wood alters in-channel and floodplain processes, such as flood inundation and sediment transport, and increases overall biocomplexity (Abbe and Montgomery, 1996; Gurnell et al., 2002). The presence of large wood increases available aquatic habitat for invertebrates and fish, and can facilitate seedling recruitment on floodplains by altering scouring flows (Gregory et al., 2003) as well as the rates of hyporheic water abduction (Stanford and Ward, 1993). Removal of large wood decreases habitat heterogeneity and further simplifies highly impaired temperate river corridors (Naiman et al., 2005). Gaps in our current knowledge of large wood dynamics include how large wood processing changes from headwaters to large river corridors (Nakamura et al., 2000), the comparative rates of local and watershed-scale production (Tockner et al., 2000), and how these patterns impact described biological patterns of longitudinal structure (e.g., Vannote et al., 1980). By linking watershed characteristics with observed export patterns of large wood, we isolated upstream contributions to downstream watersheds (connectivity) and attempted to identify the driving processes (recruitment, transport, and storage) within the watershed. Specifically, our objectives were to (i) quantify watershed export of large wood, (ii) correlate watershed and hydrological drivers of large wood export per watershed area, and (iii) estimate net flux and variability of recruitment, transport, and storage processes over a range of watershed sizes.

A watershed approach to large wood dynamics is valuable for understanding the multiscale drivers of large wood and connectivity among watersheds (Wohl and Jaeger, 2009). However, quantifying the large-scale patterns of large wood export is hampered by the highly variable and discontinuous recruitment and transport of large wood during high flow events (Moulin and Piégay, 2004; Comiti et al.,

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2006; Young et al., 2006). The range of processes that influence large wood is complex and involves patterns of riparian forest development and legacy effects, large wood physical characteristics (e.g., size, density, shape), channel morphology (braided versus meandering), disturbance processes (fire, wind throw), watershed hydrology (magnitude, frequency, etc.), and the associated human alterations (forest clearing, levees, dams) (Harmon et al., 1986; Gurnell et al., 2002).

Large wood dynamics are broken down into five general processes—recruitment, transport, storage, decay/fragmentation, and export (Benda et al., 2003; Seo and Nakamura, 2009). The relative contribution of large wood *recruitment* by different processes along the watershed size gradient remains unclear. Episodic disturbance (wind throw, landslides, fire) in headwater watersheds typically produces irregular high volume transport events that move large wood to downstream reaches (Reeves et al., 2003) where downstream lateral bank erosion continuously adds more large wood to the system (Benda et al., 2003). A potential transition from mortality driven processes (tree fall) to bank erosion occurs around 20 km^2 where mortality and landslide recruitment processes from the riparian and hillslope areas overwhelmingly dominate in only the smallest watersheds (<10 km^2) (Benda et al., 2004; Seo and Nakamura, 2009).

Large wood *transport* capacity is presumed to increase with watershed size because of increased discharges and increased channel depths; however, to what extent channel slope and channel type impact transport capacity is unclear. One general pattern to emerge from field and flume studies is that large wood movement is affected by the ratio of piece size to channel width and is dependent on the specific channel morphology of a river reach (Lienkaemper and Swanson, 1987; Bilby and Ward, 1989; Nakamura and Swanson, 1994; Braudrick and Grant, 2000). These studies found that smaller wood pieces move more frequently through larger streams that have a higher capacity to move larger pieces of wood; however, it has been observed that some pieces are too large or anchored by the bank that transport does not occur even at high flows (Piégay et al., 1999). As you move downstream, a transition occurs from a system where the stream is transport-limited (piece size > channel width) to one that is supply-limited (piece size < channel width). Martin and Benda (2001) suggested that this transition occurs in watersheds > 20 km^2.

Large wood *storage* on the floodplain and in the channel is higher in smaller streams because of greater channel, hillslopes and floodplain interactions coupled with a lower capacity to move large wood (Nakamura and Swanson, 1993; Piégay et al., 1999). Large wood storage is potentially highly variable because of the increased flow capacity coupled with intensified interactions with the channel bed in meandering or braided channels. With farther downstream distance and increases in river size, the geomorphology and floodplain characteristics produce complex interactions with large wood and can lead to periodic long-term storage (Abbe and Montgomery, 2003; Brummer et al., 2006; Latterell and Naiman, 2007).

Multiple factors control the *decay/fragmentation* of large wood to smaller particulate (Harmon et al., 1986; Bilby, 2003). Piece size and nutrient availability are factors controlled by the physical break up of pieces through the physical hydraulic forces breaking and abrading wood (Murphy and Koski, 1989) while nutrient levels are specific to each tree species (Bilby, 2003). Ambient temperatures influence microbial action with higher temperatures increasing the decomposition rate. In addition, the decay and subsequent fragmentation of wood is influenced by biologically mediated decay during submergence (Bilby et al., 1999) or not (Spies et al., 1988), and the residence time of large wood in the system (Hyatt and Naiman, 2001). Martin and Benda (2001) summarized field studies of annual decay rates citing a midpoint rate of 3% for their wood budget modeling procedure. On the Queets River, dating pieces of wood showed that large pieces can be extremely old (~1500 years) but most of the pieces have been deposited within the last 50 years (Hyatt and Naiman, 2001), indicating high variability of residence time.

To empirically investigate large wood export at the watershed scale, we compiled annual large wood deposition data for 131 reservoirs across Japan and calculated patterns of export for a range of watershed sizes and flow discharges. Here, we explore the watershed correlations of large wood export patterns described in previous work (Seo et al., 2008); however, we further the analysis by comparing peak flow discharge, watershed characteristics, and large wood export to show how the fluvial export of large wood changes with watershed size. We hypothesized 1) that steeper slopes, more forested slopes would increase the volume of large wood; 2) we postulated that lower latitude watersheds would have significantly higher export rates due to large typhoon and rain events, and 3) that headwater streams would input proportionally more large wood than downstream segments of the river network. Our work here explores these watershed characteristics of large wood export rather than carbon budgets in relationship to particulate organic material (Seo et al., 2008). In addition, in this paper we took a more conservative statistical approach to the statistical analyses. The ultimate goal of this research was to understand patterns of large wood dynamics and watershed connectivity to inform management of river corridors.

2. Methods

In 2003 we contacted multiple dam managers in Japan to retrieve large wood and hydrology data from publicly managed dams of the Ministry of Land, Infrastructure, Transport and Tourism (MLITT) (Seo et al., 2008). Large wood data were collected from a total of 131 dams, and at a subset of dams (68 between 1993 and 2003) we acquired corresponding hydrology data sets (Fig. 1, 26°–45° latitude).

2.1. Quantifying large wood export

MLITT annually removes fluvially transported woody debris from large reservoirs to protect dam infrastructure (Fig. 2). Large wood pieces deposited in each reservoir were collected and placed in dump trucks for measurement and removal. The total volume was measured in each truck load by multiplying the width, lengths and height of the pile. Size and shape of individual pieces were not measured. The pore space was visually estimated per truck load and subtracted from the total amount. In some cases, the pore spaces were estimated for each load (70%) (Harmon et al., 1986). In many years, multiple truck loads have to be removed (e.g., Fig. 2). Measurement error was considered low compared to the total annual amount and gives a rough estimate of large wood volume. The large wood data used for this study is the annual amount of large wood volume extracted from each reservoir. Some dams had multiple peak hydrology readings, but only one annual large wood volume reading was used.

2.2. Flow discharge

Detailed hydrology data were collected from a subset of these dams between the years 1993 and 2003. The data set consisted of the recorded peak flow discharges for each major event (68 dams). At each dam, managers recorded peak flood events in the main channel as it entered the reservoir. Within each year multiple recorded discharge events were possible. We calculated the sum of all recorded peaks, the average, and the maximum. Because the hydrology data set was a subset of the entire data, they did not have the same watershed area extent. The hydrology data set, unfortunately, did not include the small watersheds (<22 km^2). We recognized this limitation in comparing large- and small-scale patterns.

2.3. Watershed characteristics

We delineated each watershed using the analysis tools in GIS (ESRI, 2007). To define the watershed for each dam, we used a digital