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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 both watershed-wide processes but 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 dataset of the volume of large wood deposited annually into 131 reservoirs across Japan, and compared large wood export to both 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 that there is an *export threshold* (~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 re-transport of buried logs. Identifying rates of large wood transport due to 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 both the local and watershed scale dynamics of large wood in creating and maintaining more heterogeneous riparian and aquatic habitat along the river corridor.

Keywords: basin morphometry; ecogeomorphology; ecology; large wood; riparian; river corridor; watershed hydrology

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 (1) quantify watershed export of large wood, (2) correlate watershed and hydrological drivers of large wood export per watershed area, and (3) 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 multi-scale 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., 2006; Young et al., 2006). The range of processes that influence large wood are complex and involve patterns of riparian forest development and legacy effects, large wood physical characteristics (size, density, shape), channel morphology (braided versus meandering), disturbance processes (e.g. fire, wind throw), watershed hydrology (e.g. 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 produce 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 due to increased discharges and increased channel depths; however, it is unclear to what extent channel slope and channel type impact transport capacity. 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) suggest that this transition occurs in watersheds greater than 20 km^2.

Large wood *storage* on the floodplain and in the channel is higher in smaller streams because of greater channel, hillslope 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 due to the increased flow capacity coupled with intensified interactions with the channel bed in meandering or braided channels. With further 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) and nutrient levels are specific to each tree species (Bilby 2003). Ambient temperatures influence microbial action with higher temperatures increasing decomposition rate. In addition, the decay and subsequent fragmentation of wood is influence 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 can be extreme 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 correlates 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 datasets (Figure 1, 26º- 45º latitude).

2.1. Quantifying large wood export

MLITT annually removes fluvially transported woody debris from large reservoirs to protect dam infrastructure (Figure 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, length and height of the pile. Size and shape of individual pieces were not measured. The pore space were visually estimated per truck load and subtracted from the total amount. In some cases the pore spaces was estimated for each load (70%) (Harmon et al., 1986). In many years multiple truck loads have to be removed (e.g. Figure 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 there was only one annual large wood volume reading.

2.2. Flow discharge

Detailed hydrology data were collected from a subset of these dams between the years 1993 and 2003. The dataset 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 there could be multiple recorded discharge events. We calculated the sum of all recorded peaks, the average, and the maximum. Because the hydrology dataset was a subset of the entire data, they did not have the same watershed area extent. The hydrology dataset, 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 elevation model (DEM) from the Geographical Survey Institute of Japan at 50x50 meter resolution. The watersheds boundaries and channel networks were defined with stream initiation beginning at one-half hectare. This channel network was cross-checked against existing channel data from the Japanese government. Dam locations were also cross-checked (JDF, 2007).

Channel length was calculated for each watershed by summing the length of all segments. Channel slope was calculated by sampling a calculated slope grid under the generated channel network. We used the average channel slope of the channel network, not the watershed slope. Due to the large grid size we potentially sampled hillslope rather than just the channel slope, with a bias toward headwater streams. However, we feel this measurement still allows for a general slope characterization as hill slopes in steep watersheds contribute logs to streams.

Using a GIS layer of land cover for Japan, we calculated three metrics to represent forest character of the river corridor – non-forest, natural forest, and planted forest (JDF, 2007). Data spatial resolution was approximately 30 meters down to the dominant species level for forest communities. We then buffered each segment of the channel network based on Strahler's stream order classification to create a surface for the channel corridor (15 meters per stream order with the open water category excluded). We calculated the percent area forested versus non-forested within the channel corridor (ForestedArea). We also exaggerated the effect of natural and planted forests by multiplying the area by two and dividing the sum by the total area to make sure any effect was statistically observable. We calculated these metrics to test if the percent forested area could predict large wood export, and whether natural or planted forests produce more wood.

2.4. Watersheds and woodsheds

Within each watershed we identified control structures such as large dams and weirs that restrict large wood passage (39 structures). We retrieved data on the size of each structure from a national database and checked the locations and size of each control structure with managers before making this assumption (JDF, 2007). Based on these data, we assumed that small weirs and check dams did not affect the overall transport of wood, with large wood passing over a structure during peak events. For large structures and lakes we defined a variable called the ‘woodshed’ to indicate watersheds with impacted wood delivery processes. Woodsheds are defined as the remaining watershed area still connected downstream (no obstructions) and able to pass large wood and water (hereafter called 'impacted/impaired' watersheds). For example, the upstream area of Lake Biwa (Japan’s largest lake) was excluded because large wood is not passed out of the lake. In this case, the watershed is the entire collection area of water, where the woodshed is only the area downstream from the lake where wood is able to reach the stream and be passed downstream.

The woodshed was calculated for all dams with upstream infrastructure obstructions (19 total). We calculated of the ratio of $\text{Woodshed}_{\text{area}}/\text{Watershed}_{\text{area}}$ by watershed to represent the degree of impact these structures have on the large wood system. In the statistical analysis presented here, opposed to the Seo et al. (2008) manuscript, we analyzed differences in large wood export both with and without upstream flow structures; this study excluded all dams with more than 10% of their watershed impacted by upstream structures to eliminate a significant source of human-influenced variation in large wood export.

2.5. Analyses

To investigate patterns we applied multiple statistical techniques to analyze the relationship between large wood, watershed characteristics, and hydrology. We used a linear mixed-effect statistical technique to control for repeated measures at each dam for the large scale dataset (no hydrology). We included a 'Dam ID' in the hydrology dataset analyses as a random variable to test for correlated variation at each dam. This parameter was not significant in the hydrology analysis and therefore not reported in the results.

We used principal components analysis (PCA) to reduce the number of cross-correlated variables in the dataset (Mardia et al., 1979). The variables with the highest eigenvalues were selected from the dataset. The subset of variables were then analyzed using the Akaike's information corrected criterion (AICc), classification and regression trees (CART), and backwards stepwise multiple linear regression. AICc shows the likelihood of each variable being in the best or top models by calculating a log likelihood metric that penalizes all possible candidate models based on the number of included variables (Sakamoto and Kitagawa 1987). The purpose of our CART analyses, a tree-building algorithm, was to determine a set of split conditions to illustrate the potential hierarchical relationships within the large wood and hydrology datasets (Breiman et al., 1984). CART trees are an efficient non-parametric method of showing relationships between variables that change over a larger gradient, as was the case with the large wood dataset. The regression analyses were perform to statistically describe and test the relationships. In addition, we analyzed the relationship of large wood export per unit watershed/woodshed area and applied quantile regression (Koenker and Bassett, 1978). Quantile regression separates the data into quantiles (lower 10% and upper 90%) and fits a regression line to show how the pattern changes within the dataset (i.e. do the rates of large wood transport change with the amount of large wood in the system?).

All data were log-transformed to fit the homogeneity of variance assumption and normalize the errors. The hydrology data were evaluated using Cook's distance and three outlier data points were removed to heteroscedasticity. All statistical analyses were completed using the R-project statistics software (version 2.6.1). Multivariate model selection methods followed the advice found in Statistics: An Introduction using R (Crawley, 2005).

3. Results

3.1. Patterns of large wood export along watershed area

Woodshed area, watershed area, and channel length were highly correlated measures of watershed size (PCA analysis); therefore, watershed area was retained in the statistical analyses (with exceptions when direct comparisons are made) as it is a more standardized measurement of watershed size. Large wood export regressed onto watershed area showed a non-linear relationship as reported by Seo et al. (2008) after removing the reservoir data with upstream flow control structures (Figure 3A, Table 1). The watershed regression was slightly different with the elimination of the upstream influenced reservoirs (Figure 3B) – note the right shift in hollow circles. The confidence (p-value) in the non-linear shape was decreased compared to Seo et al. (2008), as many of the largest dams had upstream reservoirs that removed large wood (Figure 3 A-D, Table 1); however, the quadratic relationship was still significant at the $p<0.005$ level and included in the top model using the AICc (Table 1 and 2). Significance of the quadratic term illustrates a statistically significant non-linear relationship. Larger watersheds showed a leveling-off of large wood export for watersheds around 75-100 km^2 (CART analyses in Figure 4 and visual analysis of Figure 3A, B). The *export rate* of large wood decreased linearly with watershed size and watersheds that tended to produce more large wood had a more pronounced decline (upper compared to lower quantile lines on Figure 3C). No statistics are reported here due to the watershed being in both axes. After removing the effect of watershed size, the latitudinal variable showed a weak but significant explanatory relationship with large wood export increasing with southern latitudes (Figure 3D; $R^2 = 0.01$, $p < 0.005$, $N = 783$, 99 groups). Our overall large wood export values compare well with those modeled by Martin and Benda (2001) in watersheds <80km^2.

Watersheds with upstream flow control structures showed the expected reduction in large wood. Although reduction varied, the metric of watershed area explained the reduction in large wood export (Figure 3 A-C). We were unable to tease apart the effect of upstream woodshed impact on the downstream reduction in large wood; however, the data suggest some reduction in large wood even with relatively small areas of headwater impact. On average, dams with upstream control structures produced slightly less large wood, though the annual variability is too large to say anything with confidence and these ‘impacted dams’ have been removed from further analyses.

CART analysis revealed a strong break in the dataset around 75 km^2 in watershed area (Figure 4). This break corresponds roughly to the location of the break in slope of the fitted regression between export and watershed area (Figure 3B). Moving down the CART figure, two more watershed area breaks appear at 10 and 360 km^2. The larger break might indicate a further reduction in the rate of export (19.69 log-scale); however, considering the small number of dams on either side of these breaks (both large and small), we ascribe less confidence to these thresholds.

3.2. Other factors influencing large wood export

As shown in Figure 3D, there was a weak decreasing trend in export with northern latitudes with the effect of watershed size removed. The CART analysis identified 34.48°N as a break point in large export. This roughly corresponds to the southern east-west directing portion of the southern main island (Honshu), including the southern islands of Shikoku, Kyushu, Amami, and Okinawa. These areas have increased typhoon and large precipitation events, and do not have large, spring snowmelt events (Sakamoto et al., 1999). On the lower nodes of the CART figure (Figure 4), the statistical results show that the large wood export/watershed area relationship is further explained by latitude and slope/forested area in the larger watersheds. These relationships are only in mid-sized watersheds between 10 and 360 km^2. Slope and ForestedArea were somewhat correlated (0.72 correlation coefficient) and it is difficult to assign much confidence to the driving factor. However, note the negative relationship of ForestedArea and large wood export, meaning that in less forested and steeper watersheds there was more exported volume (Figure 4, 656 m^3/year). These findings are supported in the linear mixed-effect and AICc statistics presented in Tables 1 and 2, with the quadratic form of watershed area, latitude and slope being significant predictors of large wood export. The best model using AICc included all predictor variables.

To further the analysis, we assumed that the latitude gradient was caused by increased peak hydrologies in southern Japan and that peak hydrology increased linearly with watershed size. Using the truncated hydrology dataset, we found that peak hydrology is highly correlated with watershed size (Figure 5A) and that the residuals of this regression are highly correlated with latitude (Figure 5B). Further analysis showed that the residuals of the large wood export onto watershed area were weakly correlated both with peak hydrology (Figure 5C) and negatively with ForestedArea (Figure 5D). Scatter surrounding these regressions are large but they generally confirm that increased peak hydrologies increase wood export. Because of the distribution of watersheds in the ForestedArea regression and therefore bias in normality, there is weak support for this relationship. However, the linear mixed-effect and backwards stepwise regression analyses confirm a statistical relationship between all three parameters (peak hydrology, slope, and forested area) (Table 3). The latitudinal gradient was dropped from the model because it was strongly cross-correlated with peak hydrology, based on the backwards stepwise method (Table 3) and AICc (Table 4).

4. Discussion

The processes contributing to large wood export are complex and intertwined when considering the linked large wood processes of recruitment, transport, fragmentation/decay, and storage. Recruitment and transport processes are linked with peak hydrology (Piégay, 2003); peak hydrology drives both large wood transport and disturbance processes (bank erosion, landslides, etc), including potential increases in downstream storage with associated changes in geomorphology (slope, channel type). In addition, watershed patterns of large wood export do emerge outside the effect of increased hydrology with strong evidence of some general patterns in watershed connectivity, process controls and thresholds, and knowledge gaps.

4.01. Climate driven patterns of export

Climatic patterns in Japan are spatially patterned with larger average and maximum discharges at lower latitudes and higher longitudes due to large summer rain storms from the southeast with frequent scattered typhoon events (Figures 3D - 5). The north of Japan does not typically receive typhoons and peak discharges are commonly produced by snow melt events (Sakamoto et al., 1999; this dataset). Lower latitude watersheds produced more large wood potentially due to higher peak discharges with increased typhoons that cause increased transport capacity, bank erosion and land sliding. This could also be related to higher tree growth rates and stem density in the south islands (Harmon et al., 1986).

4.02. Temporally episodic export

The temporal variation of large wood export is caused in part by punctuated recruitment of large wood caused by a range of disturbances, the episodic character of peak flow events, and lag effects from previous flow/disturbance events (Martin and Benda, 2001; Nakamura and Swanson, 2003; Moulin and Piégay, 2004). The recurrence of peak events will impact the amount of recruitable logs in a given watershed. For example, not all water flows export large amounts of wood due to the interaction with recruitment, transport, and storage processes (i.e. a second large event will not export as much large wood if the first storm cleared it from the river corridor, Moulin and Piégay, 2004). This lag effect complicates measuring export rate when considering large wood export due to past hydrological events. However, in general, we found a significant relationship between maximum discharge and the export of large wood with a large scatter. We presume some forms of recruitment can be continuous (e.g. mortality, bank erosion) and there tends to be a constant volume of standing stock on the floodplain that is moved periodically with large events. Yet, considering the high annual variability, the interaction between large events, and the lag time between storms, it should be assumed that the dynamics are not linear and are dependent on a longer time period lag effect caused by forest dynamics and climatic factors (e.g. fire, floods, disease, etc).

4.03. Export variability in small to medium sized watersheds

Watersheds <75 km^2 have high spatial and temporal variability. Variation among watersheds is caused by differences in watershed character, such as variable peak hydrology, channel slope, forest type, and land use history, among other variables (Martin and Benda, 2001). Channels with steeper slopes produce more large wood, caused most likely by higher transport capacity, less floodplain storage, and recruitment from adjacent hillslopes through episodic landslide and fire events (Reeves et al., 2003; Benda et al., 2004; Seo and Nakamura, 2009). In general, we should expect higher annual variation in upstream watersheds due to the fact that they have less area to capture precipitation events and runoff is relatively peaked. In addition, as is the case with smaller streams, their transport capacity is low due to the relative size of the stream and therefore even with relatively large flows, not all logs in the channel and floodplain are transported due to resistance caused by complex topography, constricted valleys, and small channel widths (Lienkaemper and Swanson, 1987).

4.04. Decreased export rate with watershed size

Large wood export increases log-linearly with watershed size (Figure 3A). Large wood export increases proportionally with size in small to mid-sized watersheds, and levels out around 100 km^2. At around 75-100 km^2 the rate of large wood per watershed area export decreases, despite the increase in discharge (15% drop of large wood export per channel length in watersheds > 20km^2) (Figure 3A). This is a compelling finding not fully discussed in the Seo et al. (2008) paper.

We believe there are five possible process-based explanations for the drop in large wood per channel length export rate: 1) since export variability in small watersheds is high, the average input downstream in any given year is only from a portion of the upstream channel network, 2) large wood storage on floodplains in larger streams increases significantly, 3) recruitment of large wood from hillslopes and floodplains decreases with no proportional increase in riparian channel interactions in larger streams, 4) significant fragmentation and decay of large wood pieces reduces upstream large wood into particulate material, and 5) considering the relative increase in human density with downstream distance, reduced export might be caused by increases in flood structure (e.g. levee building and revetment). We discuss them here independently, but assume the actual reduction in large wood export rate is a synergism of all four.

4.05. Explanation 1 – Network Production

The variance of the total annual large wood export is potentially highest in mid-sized watersheds (approx.75 km^2; Figure 3C). In any given year a subset of upstream watersheds will contribute large wood to downstream channels due to episodic hydrology and disturbance events. This temporal variation in network production is a possible explanation for the reduction in export rate in large watersheds where the average amount of downstream export is reduced. Meaning, downstream watersheds receive large wood from a subset of upstream watersheds in an individual year, although small watersheds in isolation appear to export more large wood per unit channel (Figure 3B).

Another possible explanation at the network scale is the impact of lag effects of past flows events caused by the inter-annual frequency of peak events. It is possible that the reduction of export rate in larger watersheds was caused by the variability of inter-annual peak floods in smaller watersheds, compared to the relative consistency of peak floods in large watersheds during the period of record. Where in small watersheds, single exporting events might have larger lag times between events, while large watersheds might have short lag times and potentially less recruitable wood from mortality or from bank erosion between events. This would be a property of the system and not an individual process and therefore difficult to quantify. Unfortunately, we could not evaluate the impact of flow frequency on export patterns since our data were event-based and not consecutive records, and remains an unanswered question, how do lag effects impact large wood export in small to large stream corridors?

4.06. Explanation 2 – Increased Storage

The long-term storage of large wood on the floodplain is a plausible cause for the reduction of wood export rate with increased watershed size (Comiti et al., 2006; Latterell and Naiman, 2007; Seo and Nakamura, 2009); however, the re-transport of previously buried material should be a significant source of large wood in a given event assuming that storage and re-transport are at equilibrium. For example, Lassettre et al. (2007) found that in a lowland meandering river the production and export of large wood are dynamic but tend to be equal as long as the river remains laterally dynamic. For the Japan dataset, equilibrium is probably not a safe assumption considering extensive floodplain and forest use over the last 50 years in Japan. This high level of wood extraction would cause a reduction in the total export over the period of the study, causing a significant delay t in the deposition and re-transport of large wood from upstream watersheds.

Export rates were also impacted by the amount of wood in the system (Figure 3C). Our data suggest that in watersheds with more wood the rate of export shows a steeper decline, suggesting a significant influence of log interactions, presumably logjams (slopes of quartile regressions in Figure 3C). Additionally, logjams might induce floodplain storage, particularly long term storage (Latterell and Naiman, 2007). Although this is only correlation-based evidence across watersheds and not an individual analysis of log transport, the data suggests that log density decreases export rates across the longitudinal gradient, and this has the potential to increase floodplain storage through log-jamming.

4.07. Explanation 3 – No Significant Increase of Recruitment

As watershed/stream size increases there is no net increase in the channel to riparian contact zone; meaning as the channel size increases the zone of contact between the channel and floodplain remains constant. If so, the mortality driven recruitment processes would also remain constant, however, this form of recruitment is less in total volume than recruitment by lateral erosion. Lateral erosion increases downstream from headwater to meandering and braided streams; yet, in the largest streams, lateral erosion might diminish and floodplains become more stable both in terms of lateral erosion and erosive overbank flows (Nanson and Croke 1992). Potentially the recruitment rate is significantly decreased but the floodplain trapping capacity is not reduced at the same rate downstream.

The coupled effect of transport capacity and recruitment through bank erosion might play the most significant role determining export rates. Significant recruitment from upstream hillslopes coupled with episodic floods that cause bank erosion and transport capacity downstream could synergistically increase upstream rate of export while decreasing the export rate with downstream changes to the floodplain dynamics (Marcus et al. 2002; Reeves et al. 2003; Seo and Nakamura, 2009; Wohl and Jaeger, 2009).

4.08. Explanation 4 – Significant Fragmentation/Decay

As large wood travels downstream, the biological and physical processes begin to fragment and decay of wood pieces (Bilby and Ward, 1989). The processes of fragmentation and decay reduce the total amount of the large wood in the longitudinal dimension; however, the actual rate per downstream distance is unclear, being complicated by a number of factors including physical hydraulic forces, biotic decay rates, and residence time. Residence time impacts this rate as wood travels downstream, but it is unclear how residence time and decay/fragmentation rate interact as the wood pieces move downstream. It is clear that large wood is removed from the system by decay/fragmentation, however it is unknown if the rate of removal significantly high enough to reduce the total amount of wood transported to downstream channels as shown with dataset.

4.09 Human density decreases stream-riparian interactions

The density of human settlements in downstream reach might increase the construction of levees and revetments for flood control. This would directionally limit the recruitment and storage processes in larger streams. If larger watersheds have higher human density, human modification of the floodplain could directly cause the reduction in export rate we observed. To check this we tested and found that percentage of urban areas and watershed size were not correlated as most of the dams in this survey lie above significant urban areas; dams were typically built for flood control, power generation, and municipal water supply above human settlements (JDF, 2007).

4.10. Export and transport thresholds

Our data indicate a threshold around 75 km^2, where large wood exports no longer increase significantly with watershed size. This *export threshold* indicates the watershed size where large wood production processes are equal to the storage/export/fragment/decay processes, with a relatively low annual variance between watersheds. This threshold is most likely between 75-100 km^2. Marcus et al (2002) suggest a conceptual model of large wood on the floodplain over the longitudinal gradient where headwaters streams are transport-limited but move to a dynamic equilibrium downstream and then become supply-limited in-streams with bankfull widths larger than ~200 m. Coupled with our results on the reduction of large wood flux in larger rivers, the pattern that larger streams generally have less large wood is supported (Benda et al., 2003; Seo et al. 2008).

In addition, a separate threshold was suggested in the literature at around 20 km^2 relating to transport capacity, or a *transport threshold* (Martin and Benda, 2001; Marcus et al., 2002; Brummer et al. 2006). This threshold relates the relative sizes of wood and channel widths. There is some suggestion that this threshold exists in our data, just at a smaller watershed size (10km^2).

This threshold might be smaller due to fact that Japan's trees are 2-3 times shorter than those typically in the previous studies mentioned (those of the Pacific Northwest and Greater Yellowstone regions of the U.S.). This threshold might reflect a break in channel slope and changes in geomorphic character which influences the transport capacity of large wood (Braudrick and Grant, 2000). We summarize the patterns in Figure 6 which shows the patterns we describe for large wood export with potential export and transport thresholds.

5. Conclusions

Understanding large wood variability, connectivity, and the processes that drive large wood through the watershed has increasingly become a priority for stream corridor managers. General watershed characteristics (slope, discharge) affect average large wood export with transport predominately occurring during peak events; however, the temporal and spatial variability and subsequent lag-effects produced by variable recruitment, storage and transport cloud any definitive result on why export rate decreases so significantly with watershed size. The interaction between processes remains a current knowledge gap at both the inter- and intra-annual time scales.

In headwater streams we should expect a high amount of spatial and temporal variability of large wood deliveries to downstream watersheds. Data suggest that export rates are relatively higher in small watersheds (this dataset) with more in-stream storage (Marcus et al. 2002; Seo et al. 2009). Downstream watersheds have less hillslope recruitment and more long-term floodplain storage of large wood (Latterell and Naiman, 2007). This implies that in-stream large wood has less of a significant ecological and geomorphic role than in upstream stream reaches, with floodplain storage becoming increasingly important downstream. Improving our understanding of watershed patterns of large wood processing, such as floodplain storage, in-stream short-term storage and recruitment, along the longitudinal gradient is particularly important from a eco-geomorphologic perspective to help improve our knowledge of the bio-physical interactions in riparian and stream systems.

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8. **Tables and Figures**

Table 1: Results of the linear mixed-effects analysis. The polynomial variable was added to illustrate the significant non-linear relationship.

	Estimate	p <
(Intercept)	11.26	0.588
Watershed	3.90	0.017
Watershed^2	-0.09	0.049
ForestedArea	-0.30	0.547
Slope	0.75	0.011
LatLong	-10.06	0.003

Groups: 104, Observations: 783
Low cross correlation between variables, except between Watershed and Watershed^2
All parameters (5) were log transformed and reservoir site used to account for repeated measures.

Table 2: Selected results using the AICc.

Model Parameters	AICc	ΔAICc
Watershed + Watershed^2 + Slope + ForestedArea + LatLong	2354	0
Watershed + Watershed^2 + Slope + LatLong	2357	3
Watershed + Slope + ForestedArea + LatLong	2360	6
All parameters (5) were log transformed and reservoir site used to account for repeated measures.		

Table 3: Results of the linear mixed-effects and backwards stepwise regression analysis with the peak hydrology datasets against residuals of LW on watershed area.

Linear Mixed-Effects			Backwards Stepwise Regression		
Y = LWD	Estimate	p <	Y = LWD	Estimate	p <
(Intercept)	-6.25	0.72	(Intercept)	-097	0.57
Watershed	0.62	0.000	Watershed	0.69	0.0001
Watershed^2	removed		Watershed^2	removed	
PeakMaxResid	0.53	0.000	PeakMaxResid	0.41	0.0001
Slope	0.64	0.09	Slope	0.79	0.0003
ForestedArea	-1.67	0.008	ForestedArea	-1.98	0.0001
LatLong	1.14	0.76	LatLong	removed	
Groups: 68, Observations: 256 Cross correlation between Slope and ForestedArea (-0.72)			RMSE: 0.81 on 255 df, p-value: < 0.0001 R^2: 0.48, Adj. R^2: 0.47 F-statistic: 57 on 4 and 255 df		

Table 4: Selected results using the AICc to select model (*Step* function in R-package, *k* = 2).

Model Parameters	AICc	ΔAICc
LWD = Watershed + Watershed^2 + PeakMaxResid + Slope + ForestedArea	627	0
LWD = Watershed + Watershed^2 + PeakMaxResid + Slope + ForestedArea + LatLong	629	2
All parameters (6) were log transformed.		

Figure 1

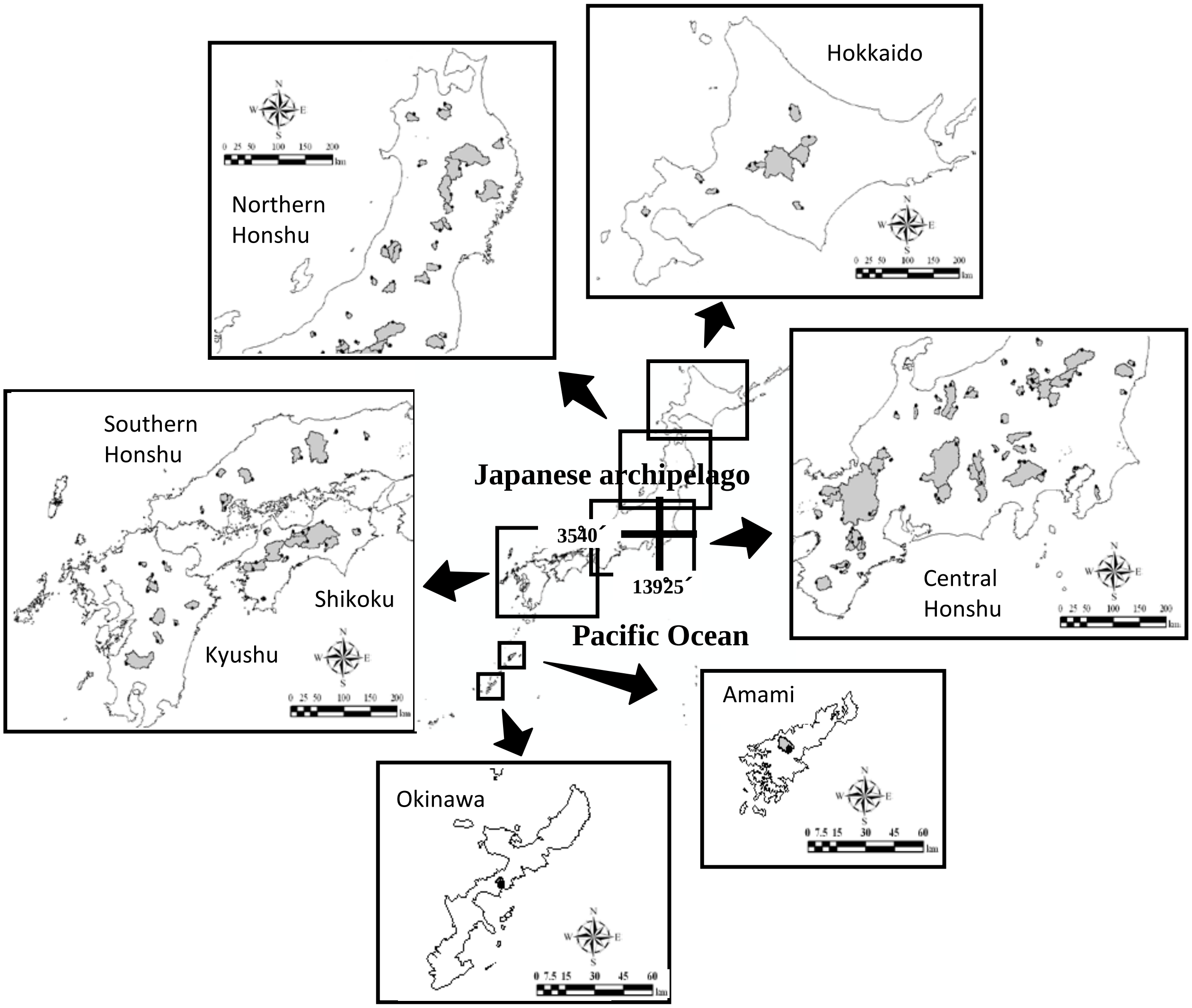
Hokkaido
Northern Honshu
Southern Honshu
Central Honshu
Shikoku
Kyushu
Amami
Okinawa
Japanese archipelago
Pacific Ocean
35°40´
139°25´
N
E
S
W
0 25 50 100 150 200
km
0 7.5 15 30 45 60
km

Figure 2

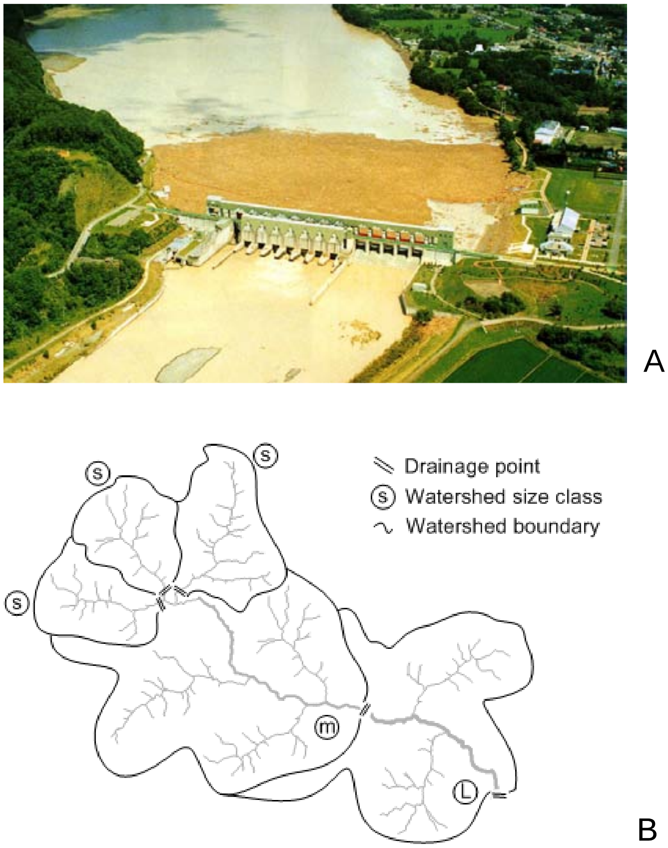
A
s
s
Drainage point
s Watershed size class
Watershed boundary
s
m
L
B

Figure 3

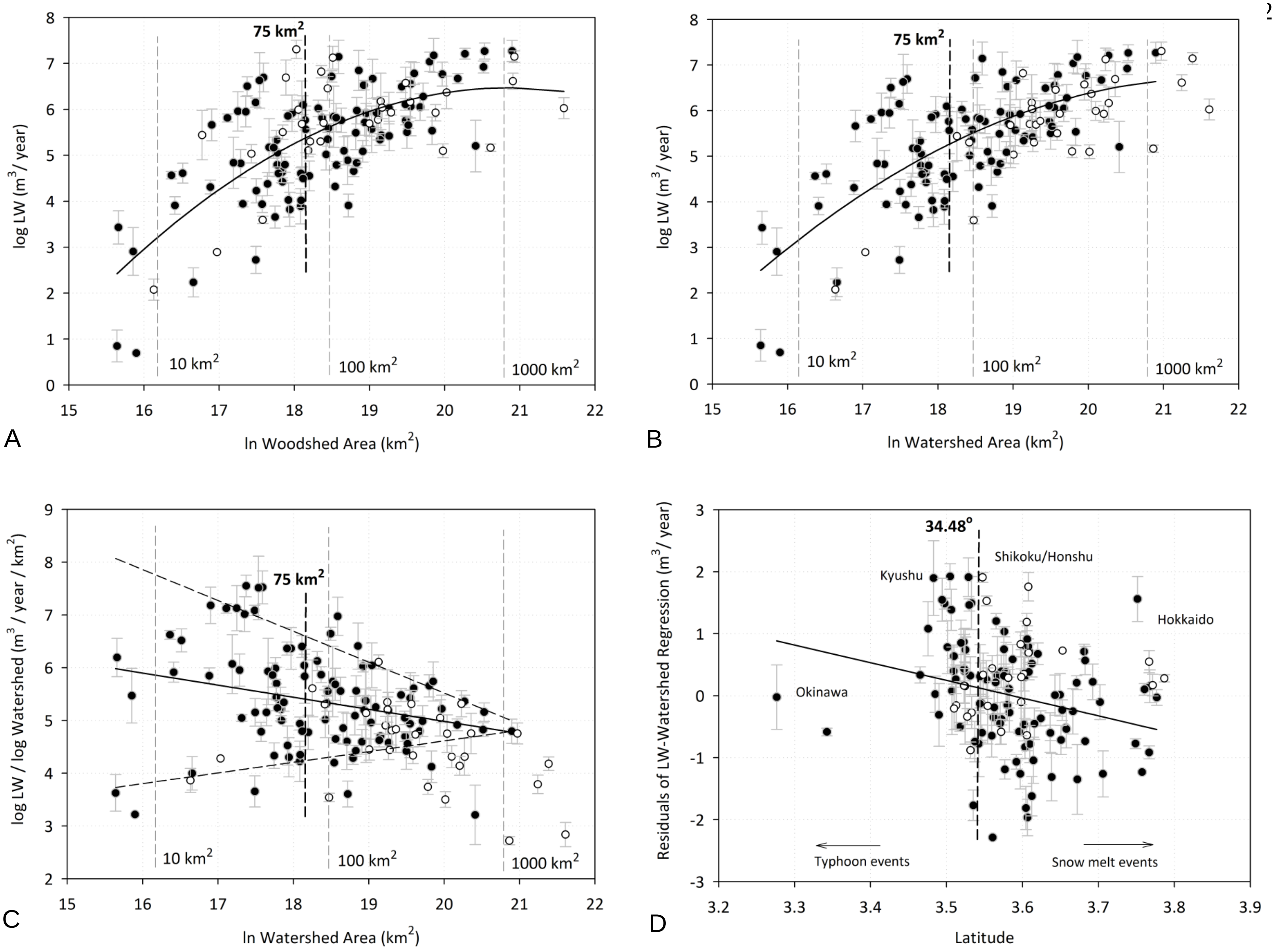
A
log LW (m³/ year)
ln Woodshed Area (km²)
75 km²
10 km²
100 km²
1000 km²
B
log LW (m³/ year)
ln Watershed Area (km²)
75 km²
10 km²
100 km²
1000 km²
C
log LW / log Watershed (m³ / year / km²)
ln Watershed Area (km²)
75 km²
10 km²
100 km²
1000 km²
D
Residuals of LW-Watershed Regression (m³/ year)
Latitude
34.48°
Kyushu
Shikoku/Honshu
Hokkaido
Okinawa
Typhoon events
Snow melt events

Figure 4

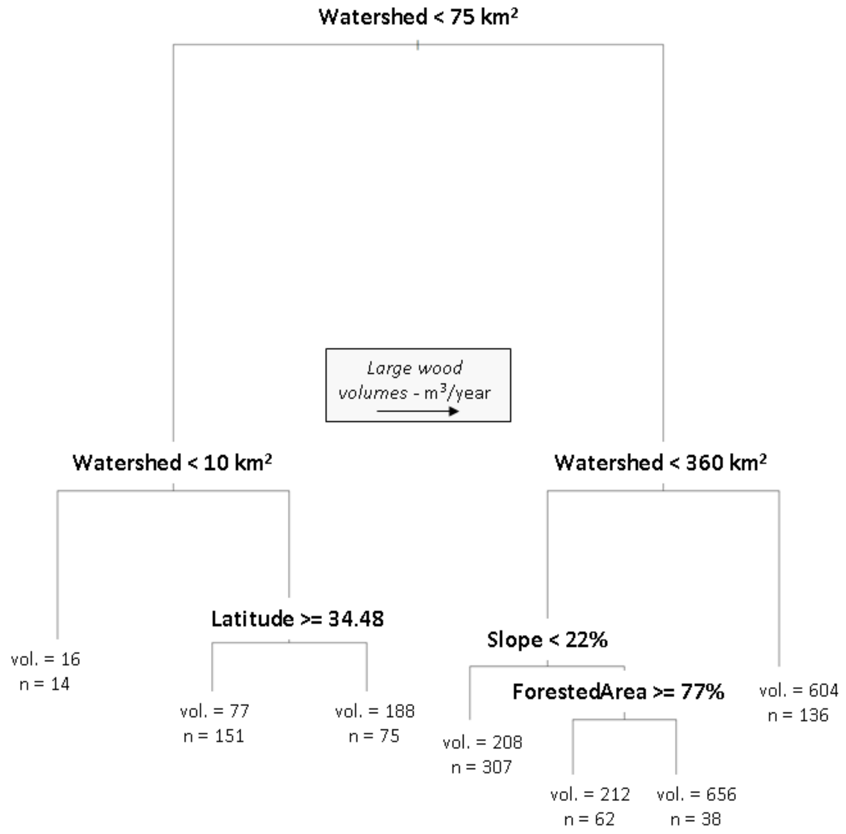
Watershed < 75 km²
Large wood volumes - m³/year
Watershed < 10 km²
Watershed < 360 km²
Latitude >= 34.48
vol. = 16
n = 14
vol. = 77
n = 151
vol. = 188
n = 75
Slope < 22%
vol. = 208
n = 307
ForestedArea >= 77%
vol. = 212
n = 62
vol. = 656
n = 38
vol. = 604
n = 136

Figure 5

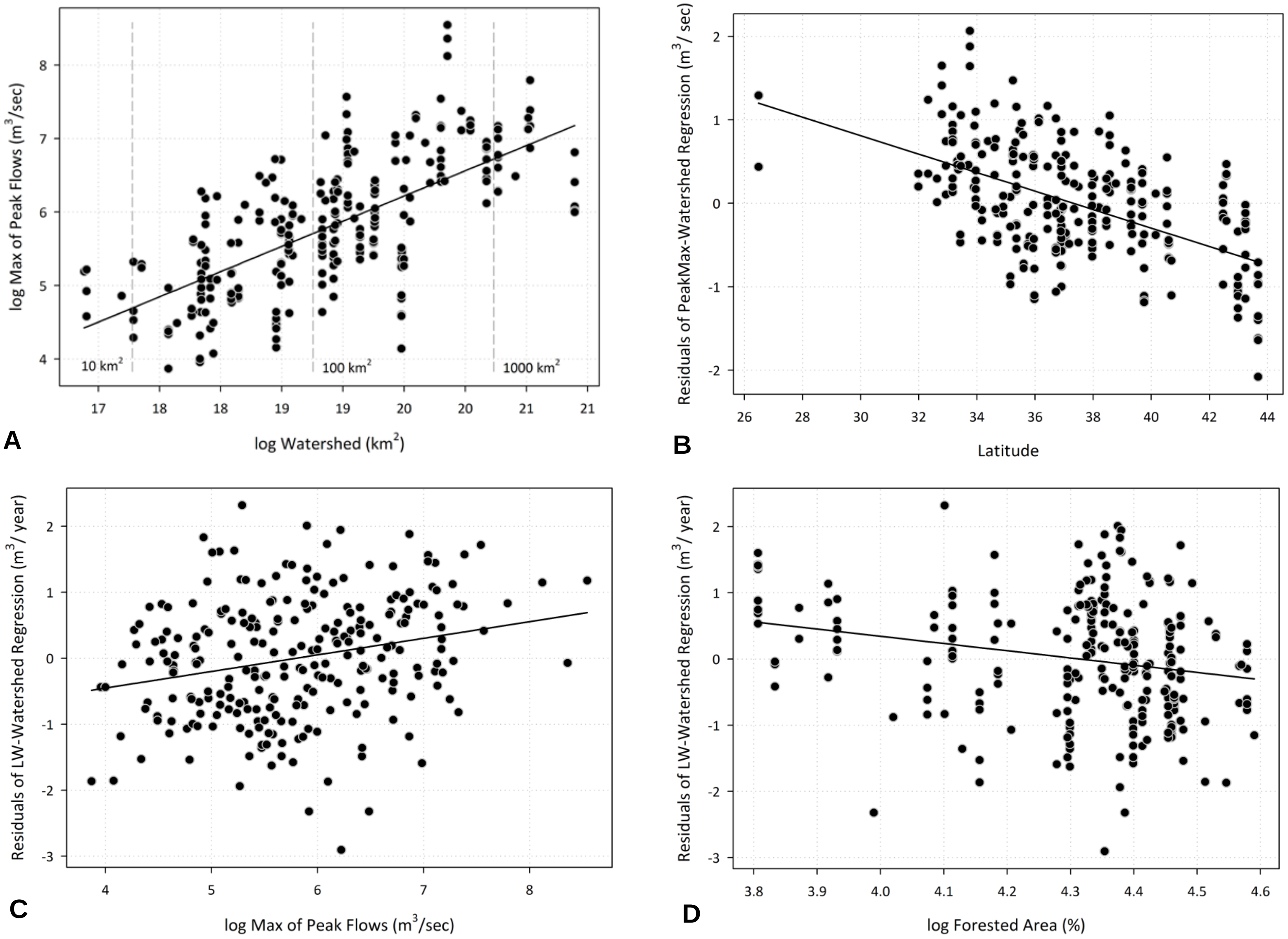
A
log Max of Peak Flows (m³/sec)
8
7
6
5
4
10 km²
100 km²
1000 km²
17
18
18
19
19
20
20
21
21
log Watershed (km²)
B
Residuals of PeakMax-Watershed Regression (m³/ sec)
2
1
0
-1
-2
26
28
30
32
34
36
38
40
42
44
Latitude
C
Residuals of LW-Watershed Regression (m³/ year)
2
1
0
-1
-2
-3
4
5
6
7
8
log Max of Peak Flows (m³/sec)
D
Residuals of LW-Watershed Regression (m³/ year)
2
1
0
-1
-2
-3
3.8
3.9
4.0
4.1
4.2
4.3
4.4
4.5
4.6
log Forested Area (%)

Figure 6

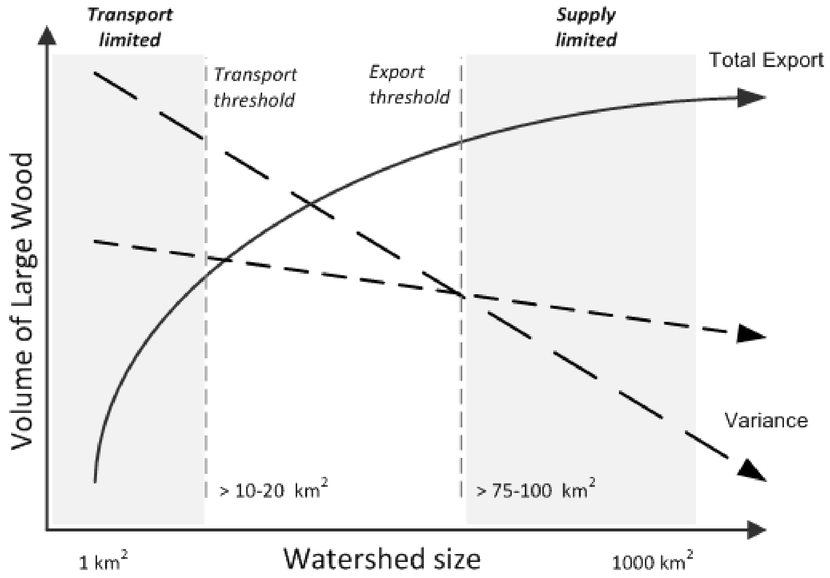
Transport limited
Supply limited
Transport threshold
Export threshold
Total Export
Variance
Volume of Large Wood
> 10-20 km²
> 75-100 km²
1 km²
Watershed size
1000 km²

Figure Captions

Fig. 1. Map showing the location of each watershed and dam on the five main islands of the Japanese archipelago.

Fig. 1. (A) Image of the Nibutani dam (Japan) with large wood coalesced at the structure to illustrate the magnitude of large wood export after storm events. (B) Diagram showing the general structure of the watersheds (small, medium, large). Of the 131 dams, 19 of them had nested upstream reservoirs that trapped and removed large wood. These datasets were analyzed separately.

Fig. 2. ● unimpaired woodsheds (sites without upstream control structures), ○ impaired watersheds (sites with upstream control structures). (A) Large wood export over the *woodshed* area gradient showing the strong log-linear relationship ($R^2 = 0.26$, $p<0.0001$, N = 1049, 131 groups, quadratic term $p<0.0001$). (B) Large wood export onto corrected (removal of impacted watersheds) *watershed* area ($R^2 = 0.27$, $p < 0.0001$, N = 783, 99 groups, quadratic term $p<0.005$). (C) Decreasing amount of large wood export per unit watershed area. The long-dashed lines are the 0.9 and 0.1 quantile regression curves illustrating the variable change in large wood with channel length watershed with different characteristics (D) The residual from the quadratic regression between large wood and watershed area plotted across the latitudinal gradient ($R^2 = 0.01$, $p < 0.005$, N = 783, 99 groups). Japanese island names are shown for reference along with the type of dominant precipitation type, and the threshold identified in the statistical analyses (CART).

Fig. 3. CART model showing correlative variables variable with large wood export volume (vol.). From left to right on the figure - the export of large wood generally increases. The taller the lines between nodes the more variance is explained. Weaker relationships are near the bottom. Export is generally higher in larger watersheds (>75kmk^2) with steeper slopes and more forested riparian areas (vol. = 656). Input data were the annual large wood export estimates with a random variable to control for repeated measures. The tree was pruned using a complexity parameter of 2% (if the R-squared value dropped more than 2% the tree was pruned).

Fig. 4. (A) Maximum peak event for each annual dataset plotted by watershed area ($R^2 = 0.46$, $p < 0.0001$, N = 256, 70 groups). (B) Residuals from the peak event and watershed regression plotted onto latitude to show the decline in peak event in the north direction ($R^2 = 0.064$, $p < 0.0001$, N = 256, 70 groups). (C) Residuals of the quadratic equation between large wood export and watershed areas plotted against the peak flows ($R^2 = 0.06$, $p < 0.0001$, N = 256, 70 groups) (D) and against ForestedArea ($R^2 = 0.05$, $p < 0.0005$, N = 256, 70 groups). Regressions are blocked by reservoir to account for repeated measures.

Fig. 6. Conceptual diagram showing the patterns of large wood export. Small watersheds (<10-20 km^2) produced more large wood per unit watershed area with high variability being caused by watershed characteristics such as slope and peak hydrology, and interaction between large wood recruitment and the timing of peak flows. Evidence of this *transport threshold* exist in this dataset and work by Marcus et al., 2002. The averaged rate of export decreases non-linearly with a break in slope occurring between 75-100 km^2. This *export threshold* is where export is no

longer related to watershed size and the other factors such as network production, floodplain storage, no increased recruitment and increased decomposition/decay are relatively equal to the export rate. The system here is thought to be supply limited where in-channel deposits are low but the transport capacity high.