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Large wood export regulated by the pattern and intensity of precipitation along a latitudinal gradient in the Japanese archipelago

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[1] We examined the relationships between large wood (LW) export and precipitation patterns and intensity by analyzing the data on the annual volume of LW removed from 42 reservoirs and the daily precipitation at or near the reservoir sites. We also calculated the effective precipitation by considering the antecedent precipitation. Both daily and effective precipitation data were used as explanatory variables to explain LW export. The model selection revealed that the precipitation pattern and intensity controlling LW export varied with latitude in the Japanese archipelago. In small watersheds with narrow channel widths and low discharges, mass movements, such as landslides and debris flows, are major factors in the production and transport of LW. In this case, the effective precipitation required to initiate mass movements regulated the LW export and did not vary with the latitude. In intermediate and large watersheds with wide channel widths and high stream discharges, heavy rainfall and subsequent floods regulated buoyant depth, influencing the initiation of LW movement. In southern and central Japan, intense rainfall accompanied by typhoons or localized torrential downpours causes geomorphic disturbances, which introduce abundant pieces of LW into the channels. However, these pieces continue to be removed by repeated rainfall events. Therefore, LW export is supply-limited and potentially produces less LW accumulation. Conversely, in northern Japan, where typhoons and torrential downpours are rare, LW export is transport-limited because LW pieces recruited by bank erosion, tree mortality, and windthrow accumulate and persist on valley floors. These pieces may be easily exported by infrequent flooding.

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1. Introduction

[2] The initiation of various geomorphic processes that constitute a disturbance cascade in mountain landscapes is driven by precipitation. Rainfall, the most common form of precipitation, infiltrates the land surface and reaches the groundwater tables or runs off as surface water and enters channels [*Allan*, 1995]. Elevated groundwater tables can contribute to geomorphic processes, such as landslides and debris avalanches, and these disturbances deliver massive quantities of large wood (LW) and sediment from hillslopes to stream channels [*Swanson et al.*, 1982, 1998; *Nakamura et al.*, 2000]. In addition, as rainfall and snowmelt increase stream discharge, stream banks are eroded or undercut, and standing trees in the riparian zone are toppled and recruited to stream channels [*Nakamura and Kikuchi*, 1996; *Johnson et al.*, 2000]. The recruited LW pieces, which initially may be distributed at random, are entrained by subsequent floods and fluvially exported downstream in a repeating cycle of transport and redistribution that can affect aquatic ecosystems [*Keller and Swanson*, 1979; *Lienkaemper and Swanson*, 1987; *May and Gresswell*, 2003].

[3] Since the pioneering study of LW in channels by *Zimmerman et al.* [1967], several studies have explained temporal variations in LW distribution and dynamics at the watershed scale in the context of channel geomorphology, wood characteristics, and hydrological regimes. In a representative study, *Marcus et al.* [2002] explored temporal variations in the distribution of LW in a watershed where large-scale floods with approximately 100 year recurrence intervals occurred. They showed that the floods produced an increase in LW recruitment associated with the undercutting of trees in second-order streams and redistributed LW on bars in third- and fourth-order streams. *Moulin and Piégay*

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[2004] quantitatively addressed the temporal variance in the fluvial export of LW trapped in reservoirs in France and discussed the export processes associated with flood events. These studies clarified that the fluvial export of LW occurs episodically and is associated with infrequent and large flood events. However, the precipitation patterns and subsequent disturbance regimes that influence the temporal variation in LW export in a given watershed network are not yet fully understood.

[4] In Japan, the volume of LW removed from dammed reservoirs in watersheds is monitored annually by local reservoir management offices. In this data set, *Seo et al.* [2008] and *Fremier et al.* [2010] used the annual LW removal volume data that were not affected by the construction of upstream dams during the monitoring periods, and examined watershed characteristics controlling LW export. The geomorphic, hydrologic, and land use parameters of the watersheds that they examined were watershed area, channel length, number of channel confluences, mean channel slope, mean watershed slope, annual precipitation, mean annual discharge, peak flow discharge, latitude, ratio of forest area to all other land uses, and forest type, although some of these parameters were not available for all of the watersheds. Among these variables, *Seo et al.* [2008] found that watershed area was the strongest predictor in explaining LW export, followed by annual precipitation, and *Fremier et al.* [2010] reported on the effect of a latitudinal gradient on LW export. Other parameters were either very weakly significant or insignificant in their analyses. In the present study, we therefore focused on the short-term (daily) variation of the precipitation data and its difference patterns along a latitudinal gradient. The objectives of this paper were (1) to elucidate the effects of the variability in precipitation on LW export and (2) to examine the variation in LW export with precipitation patterns, which vary with the latitude in the Japanese archipelago. Using the same data set analyzed by *Seo et al.* [2008] and *Fremier et al.* [2010], we investigated the annual LW removal volume data of the reservoirs for which daily precipitation data were also available. The daily precipitation data were transformed into effective precipitation to consider trends in both current and antecedent precipitation. We then used both forms of precipitation data as explanatory variables to examine the variation in LW export.

2. Methods

2.1. Selection of the Study Watersheds

[5] The streams draining into the reservoirs whose LW volumes are reported in the database may or may not have upstream dams and reservoirs. We predicted that, within each watershed, large upstream dams and reservoirs could restrict LW passage even during peak events, whereas small weirs and check dams would not affect overall LW transport. We therefore selected only those reservoir watersheds with no upstream reservoirs as our study sites. This selection was made using *Japanese Dam Foundation* [2007] topographic maps and aerial photographs. In addition, we hypothesized that the extent of land use in riparian zones influences LW export; therefore, we calculated the ratios of forest area (F_a) to total riparian zone area (R_a). Here, we treated the riparian zone areas as polygons with a 200 m radius from channel network data (1:25000) derived from a digital elevation model (50 × 50 m resolution). The polygon data were used to calculate the F_a/R_a on the basis of the land use data (100 × 100 m resolution) from the Geographical Survey Institute of Japan. We selected only the reservoir watersheds with the F_a/R_a value that were greater than 0.85, corresponding to the quasi-natural conditions of the riparian zone and a limited degree of river management. Last, to ensure that we could examine temporal trends in LW export, we selected only those dam reservoirs that had monitoring periods of at least 5 years. Consequently, we selected 42 reservoirs throughout Japan and examined variation in the export of LW from the surrounding watersheds (Figure 1).

[6] The spatial and temporal dynamics of LW vary considerably along a gradient of watershed sizes because the channel characteristics that influence wood movement, such as channel width, depth and slope, and bed composition, also vary throughout the stream network [*Gurnell et al.*, 2002; *Piégay*, 2003; *Chen et al.*, 2006; *Wohl and Jaeger*, 2009; *Seo et al.*, 2010]. To examine the difference in LW dynamics under the influence of scale-dependent controls, we classified all of the selected watersheds by area into three categories on the basis of the results provided by *Seo et al.* [2008] and *Seo and Nakamura* [2009] as follows: small- (<20 km^2; 10 sites), intermediate- (20–100 km^2; 14 sites), and large-size watershed groups (>100 km^2; 18 sites). The drainage areas of these watersheds range from 6.2 to 470 km^2, with means of 12.1, 54.1, and 227.2 km^2 for small, intermediate, and large watersheds, respectively. The characteristics of the 42 study sites used in this study are shown in Table 1. Other relevant data are reported by *Seo et al.* [2008].

[7] All of the spatial analyses were conducted using a geographic information system (GIS) [*Environmental Systems Research Institute*, 2007].

2.2. Estimation of LW Export

[8] The export of LW pieces was calculated as the total volume (m^3) of all LW pieces that were collected annually at each reservoir site. Although the monitoring periods of the study sites differed, the export of LW was routinely measured every year at each of the 42 reservoir sites. Thus, the data set included a total of 354 data points (the sum of the monitoring data from the 42 reservoirs). Initially, this data set included many observations in which the LW volume was zero; however, no transport of LW pieces at all in a year is unrealistic. We therefore considered that an observation of zero means very few pieces of LW (i.e., a total volume of LW under 1.0 m^3) and decided to substitute a value of 0.5 m^3 for all of the zero data. The methods of measuring LW volume and the assumptions used in calculating the LW biomass were given by *Seo et al.* [2008]. To remove the area-proportional effect of the watershed on LW export, all of the LW biomass data were transformed to express the LW export per unit watershed area (unit LW export) [*Seo et al.*, 2008; *Fremier et al.*, 2010].

2.3. Analyses of Precipitation Data

[9] To examine the influence of precipitation variability on LW export, we compiled data on daily precipitation (DP), which was monitored directly by the local reservoir

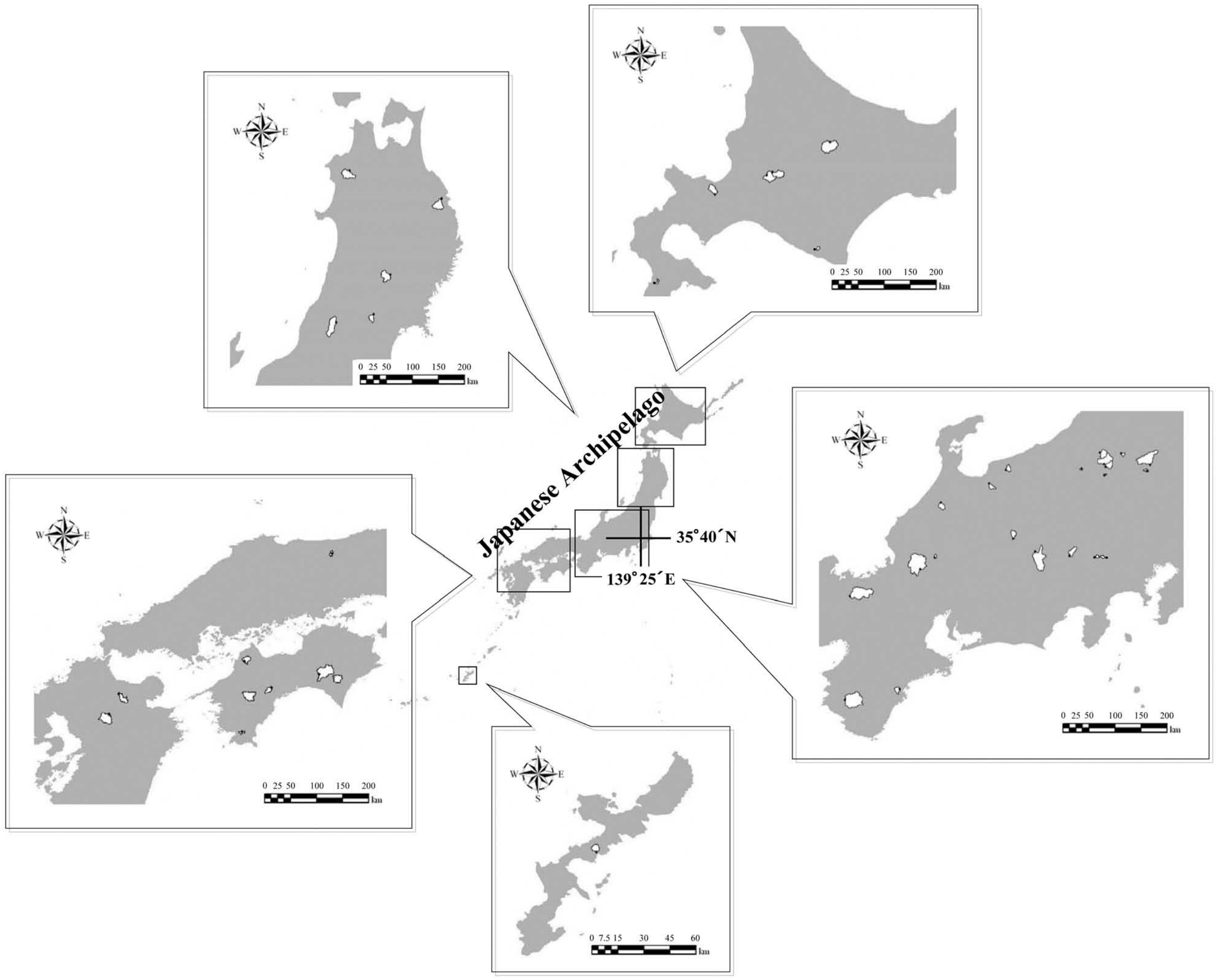

Figure 1. Location of the 42 study watersheds in Japan. The lines and dots denote the watershed boundaries and dam locations at the watershed outlets.

management offices or was collected from the Japan Meteorological Agency station closest to each study watershed. Initially, we tried to collect only the DP data monitored directly by local reservoir management offices. However, whereas such data were generally available in intermediate and large watersheds, most of the reservoir management offices in small watersheds had not been monitoring the DP directly. Consequently, we investigated the DP data that (1) were collected from the Japan Meteorological Agency station closest to each study watershed for small watersheds and (2) were monitored directly by the local reservoir management offices in intermediate and large watersheds.

[10] From the DP data, we calculated effective precipitation (EP), which is widely used to predict the risk of large mass movements in Japan. The EP includes both the current and antecedent precipitation and reflects the assumption that large mass movements are influenced by current precipitation and also by antecedent precipitation that has infiltrated into the soil [*Tsukamoto and Kobashi*, 1991]. Thus, EP is strongly associated with streamflow in channels [*Kokkonen et al.*, 2004; *Onda et al.*, 2006], and we posit that the EP should lead to the various geomorphic disturbances (i.e., landslides, debris flows, and bank erosion) that regulate LW dynamics and export. The EP of day t (EP_t, mm) was defined as

$$\mathrm{EP}_t = \mathrm{DP}_t + \sum_{i=1}^{x} a_i \cdot \mathrm{DP}_i,$$

where DP_t is the DP of day t (mm); a_i is the reducing coefficient of i (1, 2, 3, ..., x) day(s) before day t; and DP_i is the DP of i day(s) before day t (mm). The coefficient a_i was also defined as

$$a_i = 0.5^{i/T_h},$$

where T_h is the assumed period of time for precipitation to decrease its contribution to landslide (or debris flow) initiation by one half (half period). In this study, we assumed $T_h = 3$ days on the basis of the result given by *Onda et al.* [2006].

Table 1. Characteristics of the Study Sites[a]

Watershed ID	Watershed Area (km^2)	Ratio of Forest Area to Total Riparian Area (%)	Annual Precipitation (mm yr^{-1})	Latitude (°N)	Annual LW Export per Unit Watershed Area (kg km^{-2} yr^{-1})	Investigation Period (Years)
			Small Watersheds			
S-01	6.2	90.5	1907.8 ± 70.4	36°46′29″	82.4 ± 34.3	14
S-02	6.4	100.0	1357.4 ± 56.4	34°42′59″	875.1 ± 277.1	10
S-03	6.7	91.8	2424.9 ± 125.3	36°51′30″	385.0 ± 329.9	7
S-04	7.7	91.5	2272.8 ± 224.7	26°28′55″	1465.1 ± 536.6	6
S-05	12.8	92.2	3027.1 ± 271.6	35°44′15″	1050.0 ± 231.0	7
S-06	13.3	100.0	1389.3 ± 52.1	34°43′07″	1049.3 ± 373.8	10
S-07	14.9	90.0	2003.8 ± 68.7	36°49′32″	1429.9 ± 236.7	10
S-08	17.1	97.4	1662.6 ± 41.0	37°02′52″	253.5 ± 90.2	10
S-09	17.6	100.0	980.8 ± 70.2	41°48′10″	334.7 ± 110.4	6
S-10	18.1	92.0	1586.1 ± 54.9	42°14′22″	249.1 ± 121.0	9
			Intermediate Watersheds			
I-01	21.5	92.6	2192.9 ± 136.2	35°19′34″	967.4 ± 171.4	7
I-02	21.8	96.3	2832.9 ± 342.6	32°55′38″	3002.7 ± 1195.3	5
I-03	39.3	95.1	3649.6 ± 130.9	36°50′32″	672.3 ± 168.1	5
I-04	39.6	94.9	2853.0 ± 111.0	36°40′11″	724.9 ± 213.1	5
I-05	43.7	96.0	4013.5 ± 357.5	34°05′31″	5167.2 ± 1837.7	7
I-06	49.9	89.7	3020.9 ± 181.3	33°31′24″	980.1 ± 200.7	15
I-07	55.4	96.4	1858.5 ± 140.8	35°58′36″	471.9 ± 186.8	6
I-08	56.1	95.0	3489.4 ± 105.1	36°25′53″	817.6 ± 25.2	8
I-09	57.9	96.2	1546.5 ± 95.5	38°34′10″	556.1 ± 67.0	10
I-10	60.3	88.3	1697.0 ± 79.3	37°52′46″	604.7 ± 100.7	13
I-11	71.9	94.6	1053.9 ± 76.3	35°45′30″	152.5 ± 25.6	10
I-12	73.6	88.0	1439.3 ± 165.4	33°52′34″	168.5 ± 61.5	10
I-13	75.7	89.7	2022.7 ± 188.5	37°02′57″	800.0 ± 241.0	9
I-14	90.2	88.6	1866.9 ± 97.6	33°26′40″	1311.5 ± 296.9	8
			Large Watersheds			
L-01	101.7	91.7	3462.1 ± 284.6	33°35′34″	1549.5 ± 320.5	13
L-02	103.3	94.4	1378.1 ± 37.2	42°58′57″	762.1 ± 51.0	9
L-03	122.7	98.7	1647.8 ± 109.0	43°16′54″	1303.3 ± 346.2	5
L-04	148.6	91.5	1950.7 ± 124.4	39°06′38″	463.1 ± 140.8	7
L-05	150.6	92.1	1481.5 ± 87.8	43°14′14″	276.8 ± 56.2	6
L-06	151.0	88.1	1071.6 ± 101.6	40°08′55″	906.8 ± 581.8	7
L-07	165.4	86.1	1719.8 ± 88.6	36°54′31″	659.4 ± 110.4	9
L-08	167.6	92.8	1720.3 ± 75.0	40°31′57″	589.8 ± 238.5	7
L-09	172.0	87.9	2773.0 ± 235.4	33°20′59″	155.4 ± 25.6	9
L-10	185.9	85.9	2887.3 ± 225.6	33°09′22″	1229.2 ± 388.5	8
L-11	231.0	88.1	2883.5 ± 97.6	38°27′19″	501.5 ± 252.8	6
L-12	274.2	90.7	1532.6 ± 112.9	36°53′59″	700.0 ± 200.6	10
L-13	288.0	86.7	717.4 ± 50.4	43°40′25″	255.8 ± 43.8	9
L-14	298.8	87.9	2640.6 ± 234.4	33°42′21″	597.3 ± 194.7	9
L-15	309.3	89.1	1276.2 ± 81.5	35°48′36″	87.6 ± 41.0	5
L-16	349.8	86.5	1538.6 ± 58.9	35°15′37″	209.7 ± 95.7	10
L-17	397.6	91.5	2371.5 ± 164.4	33°57′33″	516.1 ± 138.6	10
L-18	469.6	91.5	2816.1 ± 180.9	35°35′23″	472.3 ± 213.1	8

[a] The annual precipitation and annual unit LW export are expressed as the mean ± standard error. To calculate the ratio of forest area to total riparian area, the channel shape lines within watershed boundaries were buffered to appear as polygons with a 200 m radius.

2.4. Analyses of Latitudinal Difference

[11] The precipitation patterns in the Japanese archipelago generally vary along a gradient of latitude (LAT) with an annual rainfall of approximately 2000–4000 mm in southern and central Japan (below 36°N in latitude) and 1000–1500 mm in northern Japan (higher than 36°N in latitude). Typhoons, which are tropical cyclones that develop mainly in the western Pacific Ocean, generally move northeastward along the Japanese archipelago. They frequently pass over southern and central Japan, causing major damage along their paths. In contrast, in northern Japan where typhoons do not typically occur, intense rainfall is relatively sparse. Instead, these areas experience heavy snowfall, and peak stream discharges gradually increase with snowmelt in the spring. To include variation in the precipitation parameters (pattern and intensity) as well as different forms (e.g., rain and snow), the LATs of all of the selected reservoir sites were evaluated using the channel network data (1:25000) previously derived from a digital elevation model (50 × 50 m resolution).

2.5. Selection of Variables to Explain LW Export

[12] To reveal the explanatory parameters that had the greatest influence on LW export in this study, we used a generalized linear mixed model (GLMM) with a Gaussian error distribution and identity link function. The response variable was unit LW export. The explanatory variables chosen to explain the unit LW export were the following: (1) the precipitation parameter, expressed as the cumulative DP or EP greater than or equal to a mm ($\mathrm{DPc}\geq a$ or $\mathrm{EPc}\geq a$),

(2) the LAT category, classified into the lower- and higher-LAT zones with a threshold of 36°N, and (3) the interaction between variables 1 and 2. Here the *a* value in the DP parameter varied from 0 to 150 mm at 10 mm intervals (i.e., 0, 10, 20, … , 130, 140, and 150 mm), and the *a* value in the EP parameter varied from 0 to 300 mm at 10 mm intervals (i.e., 0, 10, 20, … , 280, 290, and 300 mm). Therefore, we built a total of 47 full models. Of these models, 16 models had a structure consisting of the $DPc \geq a$ parameter, the LAT category and their interaction, and 31 models had a structure consisting of the $EPc \geq a$ parameter, the LAT category and their interaction (as illustrated by the models in Table 2). In addition, to avoid pseudoreplication resulting from the multiple annual measurements at each reservoir site, we considered "reservoir site" to be a random effect and the other parameters to be fixed effects [*Lee et al.*, 2006].

[13] Model selection was performed by the best subset procedure based on Akaike's information criterion (AIC). The regression model(s) with the lowest AIC value was considered as the best fit model for the measured variation in the data, and models with $\Delta AIC < 2$ were also considered to be equally influential [*Burnham and Anderson*, 2002; *Crawley*, 2005]. Here ΔAIC refers to the difference between the AIC value for the best fit model and each of the other models in the set. In addition, if any interaction parameter without its corresponding parameter (i.e., $DPc \geq a$ (or $EPc \geq a$) or LAT) was selected as a predictor in the best fit model, we did not attempt to interpret it in the final model because the purpose of this step was only to evaluate and describe the interaction between the explanatory variables. As an index of goodness of fit, we used the percentage of deviance explained (D_{exp}, percent) for each best model, which is calculated as

$$D_{exp} = 100 \times \frac{\text{null deviance} - \text{residual deviance}}{\text{null deviance}}.$$

D_{exp} is logically analogous to the coefficient of determination (R^2), which is interpreted as the proportion of the total variation explained by the model [see *Dobson*, 2002].

[14] Prior to the analysis, the response variable (i.e., unit LW export) was $\log_{10}(x)$ transformed to stabilize the

Table 2. The Construction of the 10 Best Models Selected in the GLMM for the Precipitation Pattern and Intensity Regulating LW Export in Small, Intermediate, and Large Watersheds[a]

Construction of Parameters in the Model	AIC	ΔAIC[b]
Small Watersheds		
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 120)$	125.6	–
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 110)$	126.4	0.8
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 120)$ + LAT	128.4	2.8
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 110)$ + LAT	129.1	3.5
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 70)$	129.4	3.8
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 120)$ + LAT + $\log_{10}(EPc \geq 120)$:LAT	131.0	5.4
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 130)$	131.5	5.9
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 110)$ + LAT + $\log_{10}(EPc \geq 110)$:LAT	132.0	6.4
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 70)$ + LAT	132.6	7.0
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 70)$ + LAT + $\log_{10}(DPc \geq 70)$:LAT	133.5	7.9
Intermediate Watersheds		
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 40)$ + LAT + $\log_{10}(DPc \geq 40)$:LAT	152.4	–
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 60)$ + LAT + $\log_{10}(EPc \geq 60)$:LAT	160.8	8.4
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 50)$ + LAT + $\log_{10}(EPc \geq 50)$:LAT	161.3	8.9
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 40)$ + LAT + $\log_{10}(EPc \geq 40)$:LAT	162.5	10.1
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 30)$ + LAT + $\log_{10}(EPc \geq 30)$:LAT	162.7	10.3
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 30)$ + LAT + $\log_{10}(DPc \geq 30)$:LAT	163.6	11.2
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 20)$ + LAT + $\log_{10}(EPc \geq 20)$:LAT	165.6	13.2
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 80)$ + LAT + $\log_{10}(DPc \geq 80)$:LAT	165.8	13.4
$\log_{10}$(unit LW export) ~ $\log_{10}(EPc \geq 90)$ + LAT + $\log_{10}(EPc \geq 90)$:LAT	165.8	13.4
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 50)$ + LAT + $\log_{10}(DPc \geq 50)$:LAT	165.9	13.5
Large Watersheds		
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 60)$ + LAT + $\log_{10}(DPc \geq 60)$:LAT	226.8	–
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 50)$ + LAT + $\log_{10}(DPc \geq 50)$:LAT	230.1	3.3
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 60)$ + LAT	230.9	4.1
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 120)$ + LAT	235.2	8.4
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 120)$ + LAT + $\log_{10}(DPc \geq 120)$:LAT	236.1	9.3
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 80)$ + LAT + $\log_{10}(DPc \geq 80)$:LAT	236.7	9.9
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 70)$ + LAT + $\log_{10}(DPc \geq 70)$:LAT	237.3	10.5
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 80)$ + LAT	238.0	11.2
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 130)$ + LAT	238.1	11.3
$\log_{10}$(unit LW export) ~ $\log_{10}(DPc \geq 90)$ + LAT + $\log_{10}(DPc \geq 90)$:LAT	238.4	11.6

[a] GLMM, generalized linear mixed model; AIC, Akaike's information criterion; unit LW export, LW export per unit watershed area; $DPc \geq a$, cumulative daily precipitation greater than or equal to *a*, in mm. $EPc \geq a$, cumulative effective precipitation greater than or equal to *a*, in mm. LAT, latitude; $\log_{10}(DPc \geq a)$:LAT or $\log_{10}(EPc \geq a)$:LAT, interaction between $\log_{10}(DPc \geq a)$ or $\log_{10}(EPc \geq a)$ and LAT.

[b] ΔAIC refers to the difference between the AIC values for the best fit model and each of the other models in the set. The regression model(s) with $\Delta AIC < 2$ was considered to be as equally influential as the best fit model.

variances and improve the normality, and the precipitation parameters (i.e., DPc$\geq a$ or EPc$\geq a$) that represented one of the explanatory variables were $\log_{10}(x + a)$ transformed to promote linearity and avoid discontinuity in the model. The a value here is same with it described in previous paragraph.

[15] All of the statistical analyses here were performed using the *R* statistical language, version 2.11.1 (http://www.r-project.org).

2.6. Estimation of the Flood Depth Caused by the Selected Precipitation Pattern and Intensity in Relation to LW Diameter

[16] To evaluate flood depth, we used a hydrologic data set provided by the Japanese Ministry of Land, Infrastructure and Transport (http://www1.river.go.jp/). From this data set, we collected the water level data and channel cross-sectional profiles (surveyed every year by local gauging station management offices) at 23 gauging stations (i.e., small-sized (<20 km^2, 7 sites), intermediate-sized (20–100 km^2, 10 sites), and large-sized (>100 km^2, 6 sites) watershed groups). These gauging stations are located within the study watersheds but are unaffected by the reservoir in each watershed. Here, we initially tried to collect only the water level data on exactly the same dates when the precipitation with the selected DP or EP intensity occurred within the monitoring periods of the LW or DP (or EP) data compiled in the previous analyses. However, because the water level data during the periods were limited, we could not collect enough data points to evaluate the flood depths caused by the selected DP or EP intensity. Therefore, we collected all of the water level data on the dates when the precipitation of almost same intensity (± 0.5 mm d^{-1}) with the selected DP or EP intensity occurred during a whole monitoring periods of the data set. The water level data collected from the gauging stations were not coincided with the actual flood depths. Thus, we evaluated the mean channel bed height from the cross-sectional profiles and then calculated the flood depths.

[17] These flood depth data were compared to the diameters of LW stems and root wads using source data from several published studies of Japanese rivers with broadleaved riparian forests. These measurements allowed us to examine the possibility of LW movement at the flood depths produced by the selected DP or EP intensity.

3. Results

3.1. Model Selection to Explain the Variation in Unit LW Export

[18] The model selection using AIC in the GLMM revealed that the best fit models (or predictors) explaining unit LW export in the small, intermediate, and large watersheds were slightly different (Table 2). In the small watersheds, the model consisting of only EPc$\geq$120 was the best predictor explaining unit LW export ($D_{exp} = 48.5\%$). Additionally, the model consisting of only EPc$\geq$110 was equally influential (ΔAIC $= 0.8$; $D_{exp} = 48.0\%$). In the intermediate watersheds, DPc$\geq$40, LAT, and their interaction were the best predictors explaining unit LW export ($D_{exp} = 32.6\%$). In the large watersheds, DPc$\geq$60, LAT, and their interaction were the best predictors explaining unit LW export ($D_{exp} = 37.8\%$).

3.2. Flood Depth Caused by the Selected Precipitation Pattern and Intensity

[19] The supplementary data on water levels and channel cross-sectional profiles (collected from 23 gauging stations located within the study watersheds) showed that the flood depth ranged from 0.1 m to 1.1 m at an EP of 110–120 mm in the small watersheds, from 0.2 m to 1.4 m at a DP of 40 mm in the intermediate watersheds, and from 0.4 m to 2.2 m at a DP of 60 mm in the large watersheds (Figure 2). According to the source data from *Nakamura et al.* [1997], *Nagasaka and Nakamura* [1999], *Shin and Nakamura* [2005], *Seo and Nakamura* [2009], and *Takahashi and*

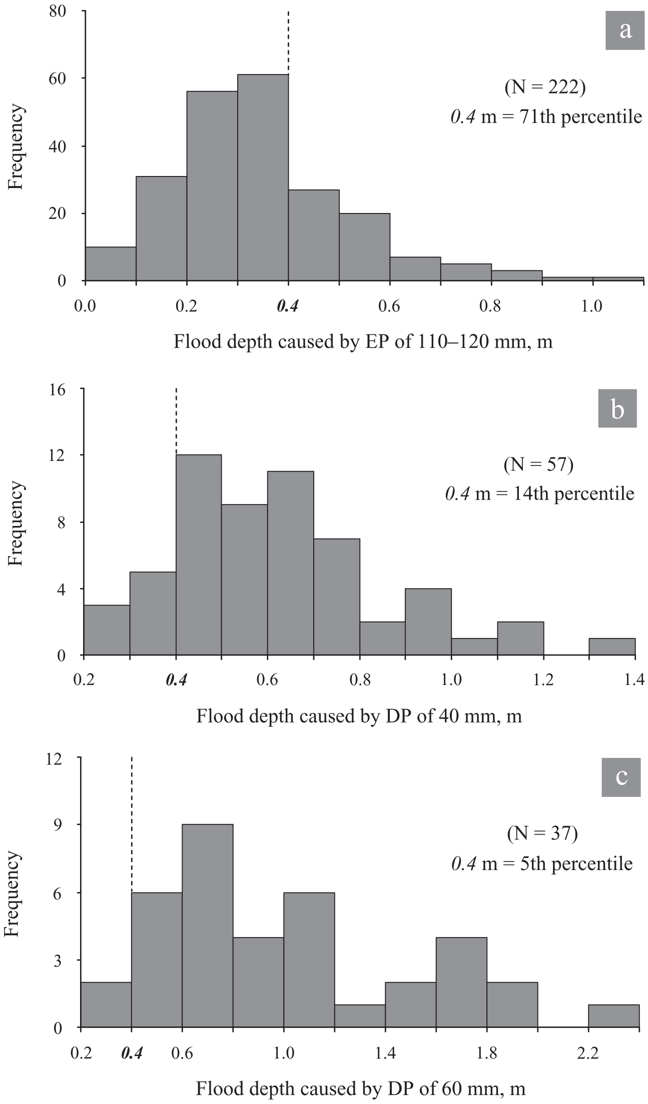

Figure 2. Histograms of the flood depths caused by the selected precipitation patterns and intensities in the small, intermediate, and large watersheds, identifying the percentile for the buoyant depth (i.e., 0.4 m) required to float LW pieces with the maximum diameter in Japanese rivers. (a) Small watersheds. (b) Intermediate watersheds. (c) Large watersheds.

Nakamura [2011], the largest diameters of LW stems or root wads distributed in Japanese rivers were approximately 0.8 m. This size is very reasonable in view of the relatively small diameters of the trees in the Japanese broadleaved riparian forests, compared with the large conifers of the western United States [*Harmon et al.*, 1986]. When an LW density factor of 0.5 Mg m^{-3} is applied to convert LW volume to mass [*Polit and Brown*, 1996; *Braudrick et al.*, 1997; *Wyżga and Zawiejska*, 2005], the minimum buoyant depths required to float the LW pieces with the maximum diameter is approximately 0.4 m. This buoyant depth was equal to the 71st, 14th, and 5th percentiles of the flood depth distributions in the small, intermediate, and large watersheds; that is, whereas only 29% of the flood depth data collected in the small watersheds were greater than 0.4 m, 86% and 95% of all of the flood depth data collected in the intermediate and large watersheds, respectively, were greater than 0.4 m (Figure 2).

3.3. Changes in Unit LW Export According to Precipitation and Latitude in Small, Intermediate, and Large Watersheds

[20] The effects of the selected precipitation patterns and intensities on unit LW export differed according to LAT category (i.e., lower-LAT zone (<36°N) and higher-LAT zone (>36°N)) in the small, intermediate, and large watersheds (Figure 3). In the small watersheds, unit LW export increased with EPc≥110 or EPc≥120, regardless of the LAT zones. In the intermediate watersheds, although unit LW export increased with DPc≥40 in both LAT zones, the corresponding slopes of the regression models differed between the lower- and higher-LAT zones. Whereas unit LW export in the intermediate watersheds was sharply augmented with an increasing DPc≥40 in the lower-LAT zone, the rate of increase in the higher-LAT zone was substantially lower. In the range of comparable precipitation intensity shaded in the intermediate watersheds in Figure 3, unit LW export was relatively greater in the higher-LAT zone and was smaller in the lower-LAT zone. As in the intermediate watersheds, unit LW export in the large watersheds increased with DPc≥60 in both LAT zones, and the slope of the regression model in the higher-LAT zone was gentler than that in the lower-LAT zone. In addition, in the range of comparable precipitation intensity shaded in the large watersheds in Figure 3, unit LW export was relatively greater in the higher-LAT zone than in the lower-LAT

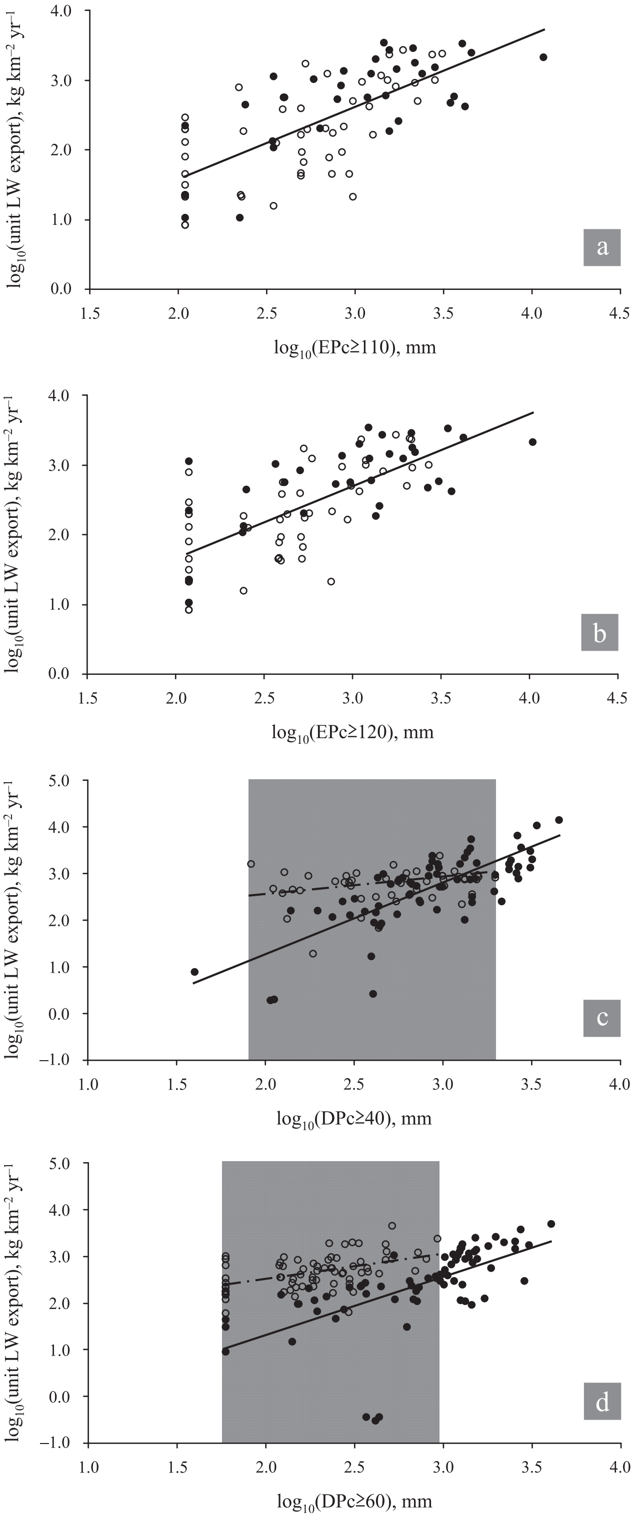

Figure 3. Changes in LW export per unit watershed area according to precipitation and latitude in the small, intermediate, and large watersheds. (a) Small watersheds (Case I: EPc≥110). (b) Small watersheds (Case II: EPc≥120). (c) Intermediate watersheds. (d) Large watersheds. The unit LW export and DPc≥*a* (or EPc≥*a*) represent the LW export per unit watershed area and cumulative daily (or effective) precipitation greater than or equal to *a*, in mm, respectively. The numbers on the *x* axis in all of the watersheds represent the values of the precipitation amounts, including the *a* values used in the $\log_{10}(x + a)$ transformation. The lower-LAT zone (solid circles) represents the areas where the latitudes are below 36°N, and the higher-LAT zone (open circles) represents the areas greater than 36°N. Whereas the regression lines in the Figures 3a and 3b were subjected to all of the data points of both lower- and higher-LAT zones, the regression lines in Figures 3c and 3d were subjected to the data points of each LAT zone (i.e., lower-LAT zone, solid line; higher-LAT zone, dash-dotted line).

zone. This trend was similar to that found in the intermediate watersheds.

4. Discussion

4.1. Effects of Precipitation Pattern and Intensity on LW Export

[21] The export of LW pieces recruited and redistributed by various disturbance processes (e.g., landslides, debris and snow avalanches, wildfires, windstorms, tree mortalities, debris flows, and floods) should vary greatly with periods of infrequent but intensive precipitation. *Moulin and Piégay* [2004] observed that 7350 m^3 of LW pieces were trapped in a reservoir during a single flood of approximately 1490 m^3 s^{-1}, whereas only 990 m^3 were stored during a low peak flow of approximately 560 m^3 s^{-1}. *Fremier et al.* [2010] also found that LW export across all watershed sizes was controlled by watershed characteristics (e.g., slope and percentage forested) and peak discharge events. Although they explained the variation in LW export by flood discharge rather than by precipitation, their data suggest that the intensity and/or amount of precipitation influences the variation in the fluvial export of LW in channels.

[22] In the present study, the best fit precipitation pattern and intensity explaining unit LW export in the small watersheds corresponded to EP greater than or equal to 110 mm or 120 mm (Table 2). According to numerous studies documenting LW dynamics in rivers worldwide [e.g., *Lienkaemper and Swanson*, 1987; *Nakamura and Swanson*, 1993; *Braudrick and Grant*, 2000, 2001; *Iroume et al.*, 2010], the most important physical characteristics regulating LW export are the LW piece length relative to channel width and the buoyant depth relative to water depth. Thus, in small watersheds with narrow channel widths and low stream discharges, a substantial amount of LW should be retained on the valley floors. Although this study addressed only the buoyant depth relative to the channel flood depth, only 29% of the flood depths produced by an EP of 110–120 mm in the small watersheds exceeded the buoyant depths needed to float LW pieces with the maximum diameter (Figure 2). However, landslides that occurred on hillslopes or at the heads of steep tributaries during intensive precipitation can deliver considerable amounts of LW into the channel, and these pieces are exported to the confluences with main stem channels by subsequent debris flows, unrestricted by the physical characteristics of small streams [*Keller and Swanson*, 1979; *Benda and Cundy*, 1990; *Nakamura et al.*, 2000]. These LW pieces deposited at the confluence can be transported by peak flows of main stem channels to larger channels [*Piégay*, 2003; *Fremier et al.*, 2010]. In general, mass movements (e.g., landslides and debris flows) begin to occur when the EP ($T_h = 3$ days) exceeds approximately 100 mm, and the risk becomes very high when the EP exceeds approximately 200 mm [*National Research Institute of Earth Science and Disaster Prevention*, 2002]. *Nakai* [2009] examined a large database of mass movements in Japan and found that an EP ($T_h = 3$ days) ranging from 200 mm to 300 mm is critical for landslides and subsequent debris flows. The precipitation pattern and intensity selected in the small watersheds, an EP of 110–120 mm, can therefore be interpreted as a threshold for the initiation of landslides and/or debris flows. The EP greater than or equal to 110 mm or 120 mm occurred frequently (5–7 times per year on average), and the contribution of these events to the mass movements and subsequent export of LW pieces is expected to be great in small watersheds.

[23] This study also found that DPc≥40 in the intermediate watersheds and DPc≥60 in the large watersheds were the most important variables for explaining the variation in unit LW export (Table 2). In intermediate and large watersheds with wide channel widths and high stream discharges, LW pieces are less strongly influenced by mass movements (e.g., landslides and debris flows) than in small watersheds and are fluvially transported downstream by floods [*Lienkaemper and Swanson*, 1987; *Braudrick and Grant*, 2001; *Comiti et al.*, 2006; *Seo and Nakamura*, 2009]. *Braudrick and Grant* [2001] described that the probability that LW pieces will be transported or deposited is influenced by the ratios of buoyant depth to channel depth, piece length to channel width, and piece length to radius of curvature. They particularly noted that the buoyant depth at which a LW piece of a given diameter and density is able to float defines a threshold for the initiation of LW movement, and LW pieces are continuously transported as long as flow depth is larger than the buoyancy threshold even in rough and sinuous channels. The results of this study showed that the flood depths, which increased with a DP of 40 mm in the intermediate watersheds and a DP of 60 mm in the large watersheds, produced sufficient buoyant depths (i.e., 0.2–1.4 m in the intermediate watersheds and 0.4–2.2 m in the large watersheds) to float LW stems or root wads of the maximum diameter (approximately 0.8 m) (Figure 2). Thus, it is most likely that the LW pieces can float and move at the DP intensities predicted by the empirical model. Furthermore, on the basis of general knowledge suggesting that floodwaters occasionally export large amounts of LW pieces through headwater tributary streams to downstream rivers [*Braudrick et al.*, 1997; *Wondzell and Swanson*, 1999; *Gurnell et al.*, 2002; *Wipfli et al.*, 2007], the fluvial export of LW pieces should increase linearly with the repetition of intense rainfall events. However, a large proportion of the LW pieces floated and transported downstream is intercepted by areas of high geomorphic complexity (e.g., sinuous planforms with bars or lateral eddies and secondary channels), which is formed by certain combinations of channel types and floodplains [*Nakamura and Swanson*, 1993, 1994; *Gurnell et al.*, 2002]. Such interception can result in an accumulation of the LW pieces in the form of a wood jam in large watersheds [*Piégay*, 2003; *Seo et al.*, 2010]. Ultimately, more intense precipitation should be required for the fluvial export of LW pieces in large watersheds compared to intermediate watersheds, as shown by the difference (i.e., 20 mm d^{-1}) between the precipitation intensities selected in the intermediate and large watersheds in the present study.

4.2. Effects of Latitudinal Gradient on LW Export

[24] The precipitation types of the Japanese archipelago include typhoons, localized torrential downpours from low-pressure frontal rainstorms, and snowfall. Typhoons generally accompany with severe windstorms and heavy rainfall, which can cause various disturbances (e.g., windthrow,

landslide, debris avalanche, debris flow, floods, and bank erosion), and these disturbances can produce and redistribute massive amounts of LW pieces into or through river channels [*Harmon et al.*, 1986; *Lienkaemper and Swanson*, 1987; *Nakamura and Swanson*, 1993]. However, the geomorphic disturbances vary with longitudinal location of the channel network; that is, landslides, debris avalanches, and debris flows occur in headwaters and high-gradient basins, whereas floods and bank erosion dominate large rivers [*Nakamura et al.*, 2000], except for windthrow that varies with topographic position, wind direction, soil moisture, and tree species, rather than with longitudinal location [*Nakamura and Swanson*, 2003; *Wipfli et al.*, 2007]. These tendencies should produce spatial and temporal variations in the dynamics of LW.

[25] The results of this study showed that the effect of LAT on the relationships between the selected precipitation patterns and LW export differed between the small watersheds and intermediate to large watersheds (Figure 3). In small watersheds, a significant proportion of LW is produced and transported by landslides and debris flows, which should be triggered by a particular amount of EP ($\geq$110 mm or $\geq$120 mm in this study). The increasing rate and amount of LW export at this threshold is likely to be similar regardless of LAT zone, as indicated by the minor differences between the two LAT zones in Table 2 and Figure 3.

[26] In contrast to the pattern in the small watersheds, the increasing rates and amounts of unit LW export in the intermediate and large watersheds varied with LAT (Figure 3). Typhoons, accompanied by heavy rainfall and localized torrential downpours, are a primary mechanism for the export of LW in southern and central Japan. *Moulin and Piégay* [2004] monitored two successive floods of equal magnitude and concluded that the second flood produced less amounts of LW export than the first; the first flood destroyed the pioneer vegetation in the riparian zones, scoured the channels, and made less LW available for transport by the second flood. In addition, *Wohl et al.* [2012] suggested that LW dynamics in tropical rivers with intense and frequent rainfall should differ significantly from those in temperate rivers with relatively lower rainfall. They demonstrated that the amount and residence time of LW stored in tropical rivers are relatively lower and shorter, respectively, because tropical rivers have a higher channel transport capacity than temperate rivers. LW pieces stored on the channel floor could be removed repeatedly by multiple typhoons and frequent torrential downpours in southern and central Japan. Thus, the fluvial export of LW is expected to be supply-limited, and its accumulation may be less than in northern Japan. This situation may be reflected in the lower unit LW export in the lower-LAT zone than in the higher-LAT zone for the same ranges of selected DP intensities (Figure 3). Conversely, northern Japan receives huge snowfall each and every year but rarely experiences typhoons or torrential downpours, and the amount of LW recruited by windstorms and rainfall may be smaller than that in southern and central Japan. Although snow avalanches, which destroy forest stands in the flow pathway, can add massive amounts of LW to the channel network [*Harmon et al.*, 1986; *May and Gresswell*, 2003; *Hassan et al.*, 2005], this process may be spatially limited and temporally infrequent. Its contribution to the recruitment of LW may thus be low. Accordingly, the dominant processes of LW recruitment in northern Japan may be bank erosion, tree mortality, and windthrows that are rarely caused by typhoons. In particular, a large peak of snowmelt during the spring may produce the LW associated with bank erosion. However, because precipitation that is intense enough to cause floating LW (i.e., DP$\geq$40 and DP$\geq$60 in the intermediate and large watersheds, respectively) is relatively infrequent in the higher-LAT zone (10 and 2 times per year in the intermediate and large watersheds, respectively) in comparison with the lower-LAT zone (14 and 9 times per year in the intermediate and large watersheds, respectively), the fluvial export of LW should be limited. Thus, in northern Japan, LW pieces recruited by bank erosion, tree mortality, and windthrow can accumulate and persist on valley floors, and the fluvial export of LW is expected to be transport-limited. These pieces may be easily transported by infrequent flood events. We believe that this is the reason why unit LW export in northern Japan was greater than that in southern and central Japan for the same ranges of the selected DP intensities (Figure 3).

5. Conclusions

[27] Several studies [e.g., *Marcus et al.*, 2002; *Seo et al.*, 2008] described that headwaters or small watersheds with low stream discharges and narrow channel widths contain a high standing stock of LW (i.e., transport-limitation), whereas downstream reaches or large watersheds with high stream discharge and wide channel widths show a low standing stock of LW (i.e., supply-limitation). The present study supports these patterns by considering the effects of antecedent precipitation and intensity. The model that included both current and antecedent precipitation could best explain LW export only for the small watersheds, and the models that included only current precipitation predicted LW export successfully for the intermediate and large watersheds. This result suggests that differences in the supply and transport processes of LW along the gradient of watershed size. However, it does not mean that the antecedent precipitation is not hydrologically relevant to LW export in the intermediate and large watersheds. The result simply expresses that the sum of the intensive precipitation exceeding a certain level was the strongest predictor for LW export and that it may be applicable to the watersheds having steep terrain, such as those in Japan. We used macroscopic analysis in this study, but the detailed investigations of the hydrogeomorphic processes (e.g., the relationship between precipitation and flood discharge, and the geomorphic effects on LW dynamics) in each watershed are required to determine the generality of this result.

[28] In addition to differences in watershed size, the present study indentified for the first time variation in LW export along a latitudinal gradient using a large database of LW export encompassing the Japanese archipelago. In southern and central Japan, where typhoons and heavy rainfall occur repeatedly, LW pieces are constantly removed from river channels. Therefore, LW export is supply-limited and potentially allows less LW accumulation than in northern Japan. Conversely, in northern Japan, where

opportunities to remove LW from the main channel are limited by lower levels of precipitation and infrequent flood events, LW pieces accumulate on valley floors for a long time, and LW export is transport-limited. However, these LW pieces can be transported easily if an infrequent flood occurs.

[29] Our novel findings, which describe the effects of antecedent precipitation on LW export in small watersheds and changes in LW export along a latitudinal gradient, are still in a hypothetical stage. Field surveys and further examination are required to validate these hypotheses. Moreover, the present study offers important thematic guidance for future research. Specifically, the variation in LW export along a latitudinal gradient suggests that climatic parameters are important drivers for predicting LW export. Thus, LW export in other climate zones, such as tropical, semiarid, and cold climate zones, may have different characteristics. In addition, the climate changes associated with global warming may alter the LW export regime on a global scale. This consideration is a very important in terms of ecology and disaster prevention.

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