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Geomorphic and riparian forest influences on characteristics of large wood and large-wood jams in old-growth and second-growth forests in Northern Michigan, USA

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Abstract

Large wood (LW; pieces with diameter greater than 10 cm and length greater than 1 m) and large-wood jams (LWJs; two or more pieces of LW in contact with each other) are important components of stream ecosystems that are often distributed along stream channels in response to geomorphic and riparian forest factors that interact hierarchically. As a result, information on these relationships is valuable for predicting patterns of wood accumulation and characteristics of individual pieces of wood. We studied relationships between geomorphic and riparian factors and LW and LWJ structure in different geomorphic settings associated with old-growth and second-growth settings in Upper Michigan. We used redundancy analysis (RDA) and regression tree analysis to evaluate changes in LW and LWJ structural characteristics among geomorphic and riparian forest settings. Geomorphic factors explained 38·5% of the variability in LW and LWJ characteristics, riparian forest factors uniquely explained 18·4% of the variance and the intersection of the two categories of environmental factors (i.e. the redundant portion) was 29·8%. At the landscape scale, our multivariate analyses suggest that the presence of rock-plane bedding was an important predictor of the number of LWJs and the percent of channel spanned by LWJs. Our analyses suggest differences in relationships between geomorphic factors and LW and LWJ structure. Channel width, distance from headwaters, gradient and sinuosity were identified by regression tree analyses as the most important variables for predicting LW characteristics, while channel width and confinement were the most important variables for predicting LWJ characteristics. Old-growth settings generally contained a higher proportion of conifer and LW (both in and out of LWJs) with greater diameter and volume than in second-growth settings. Our study supports the view that restoration of wood to streams will benefit from considering the associations of wood structure with landscape and reach-scale geomorphology.

Keywords: Lake States; hierarchy theory; large wood; redundancy analysis; regression trees

Introduction

The physical and spatial characteristics of large wood in streams reflect a variety of environmental factors interacting hierarchically (Abbe, 2000; Wing and Skaugset, 2002; Swanson, 2003). At large spatial scales (e.g. landscape and stream corridor-scale), geomorphology controls stream structure and processes, as well the composition and structure of riparian forests (Palik *et al.*, 1998; Ward *et al.*, 2002; Nakamura and Swanson, 2003; Goebel *et al.*, 2003, 2006). Hydrologic regimes, the geomorphology of stream channels and riparian forests directly influence streamflows, channel characteristics and the characteristics of pieces of wood (Piégay and Gurnell, 1997; Benda and Sias, 1998; Hyatt and Naiman, 2001; Swanson, 2003). At small spatial scales (e.g., reach and channel unit-scale), the retention and recruitment of wood in streams reflects interactions among individual pieces of wood, local stream dynamics and local channel geomorphology (Hedman *et al.*, 1996; Abbe *et al.*, 2003; Mutz, 2003; Swanson, 2003).

Many researchers have recognized the controlling influence of geomorphic context on large wood pieces in streams (LW; e.g. Piégay and Gurnell, 1997; Palik *et al.*, 1998; Rot *et al.*, 2000; Wing and Skaugset, 2002) and on large-wood jams (LWJs; e.g. Zimmerman *et al.*, 1967; Keller and Swanson, 1979; Abbe, 2000). Richmond and Fausch (1995), for instance, found that in the western United States LW abundance varied with stream size in response to a variety of factors including drainage geomorphology and channel size. Palik *et al.* (1998) reported similar results for streams in the Gulf Coastal Plain of the southeastern USA and suggested stream valley geomorphology strongly regulated the source–sink relationships of LW in streams. Much remains to be understood, however, about the relationships between LW, LWJs and geomorphic factors, especially in the Great Lakes region of the north-central USA, a region dominated by freshwater streams, rivers and lakes.

Understanding the relationships between LW and LWJ characteristics and stream valley geomorphology has particular interest for guiding restoration of wood to streams. Channel and stream valley geomorphology varies discontinuously to some degree at all spatial scales (Poole, 2002), potentially influencing patches of large-wood structure along stream corridors, and supporting the restoration of large-wood structure appropriate for the scale and nature of geomorphic settings. Current wood restoration practices include trends toward soft engineering techniques and landscape-oriented objectives (Bisson *et al.*, 2003). Managers and restoration professionals increasingly attempt to foster the development of wood structure favored by natural stream processes, in contrast to earlier restoration objectives that focused on adding fixed amounts of wood throughout a stream (Bisson *et al.*, 2003; Gregory, 2003). As restoration progresses in the eastern United States, where large old-growth or reference forest landscapes are rare, information is needed on the relationships between stream corridor geomorphology and large-wood characteristics from areas dominated by old-growth forests.

The objective of this study was to examine how the physical characteristics of LW and LWJs are influenced by stream valley geomorphology and riparian forests at different spatial scales along small old-growth and second-growth rivers in the Porcupine Mountains along the south shore of Lake Superior in Upper Michigan, USA. We predicted that variability in large-scale geomorphology would correspond strongly with changes in LW and LWJ characteristics because large-scale geomorphology interacts with processes that control the recruitment and retention of LW and LWJs, and that this should occur even when changes in stream valley geomorphology do not correspond to changes in stream order. This evaluation of wood in streams of the Great Lakes Region provides data for comparisons of wood in streams among ecoregions, while also providing new insight into the role of large-scale geomorphology as an influence on large-wood structure in streams.

Study Area: Porcupine Mountains of Upper Michigan

We studied wood in rivers in old-growth and second-growth forests in the Porcupine Mountains Wilderness State Park (PMWSP) in Upper Michigan. The Porcupine Mountains are a curved line of hills with maximum elevation of approximately 120 m above Lake Superior. The streams we studied formed in low-gradient, inland areas of the Porcupine Mountains, descended steeply as they flowed across lava inclusions that comprise the Porcupine Mountains and then flowed through moderate- to low-gradient, clay-lake plains until they entered Lake Superior (Figure 1).

The PMWSP contains 13 000 hectares of uncut forest: the largest, contiguous uncut, old-growth hardwood–hemlock forest in the Lake States (Frelich, 2002). We focused our old-growth sampling efforts within this large uncut forest in the Little Carp River. Eastern hemlock (*Tsuga canadensis* (L.) Carr.), northern white cedar (*Thuja occidentalis*, L.), yellow birch (*Betula alleghaniensis*, Britt.) and sugar maple (*Acer saccharum*, Hook) dominate riparian forests along the Little Carp River. Maximum tree height is approximately 40 m, with the mean height of the tallest trees in the study area roughly 25 m and mean dbh about 60 cm. Most of the river is forested to the edge of the bankfull channel. There is little evidence of major anthropogenic disturbance along the Little Carp River; most human activities consist of recreational hiking and camping. Beaver activity was apparent in the Little Carp River during our study, although all beaver dams were removed by spring flooding in 2003.

The substrate of the Little Carp River generally consists of loose cobble and gravel with rock-plane bedding where the channel is steepest and in the clay-lake plain. Floodplain extent varies, with the least floodplain development in the central, high-gradient section that crosses the lava inclusions. Few records of streamflow exist for the Little Carp River. Goebel *et al.* (2003) reported discharge during annual floods ranging from 4·7 $m^3 s^{-1}$ in the upper, low-gradient sections of the river to 9·4 $m^3 s^{-1}$ in the lower, high-gradient portions of the river.

Portions of the PMWSP and adjacent forests have been logged within the last century, with logging currently ongoing in some areas. We examined segments of the Union River and the Little Iron River in these second-growth

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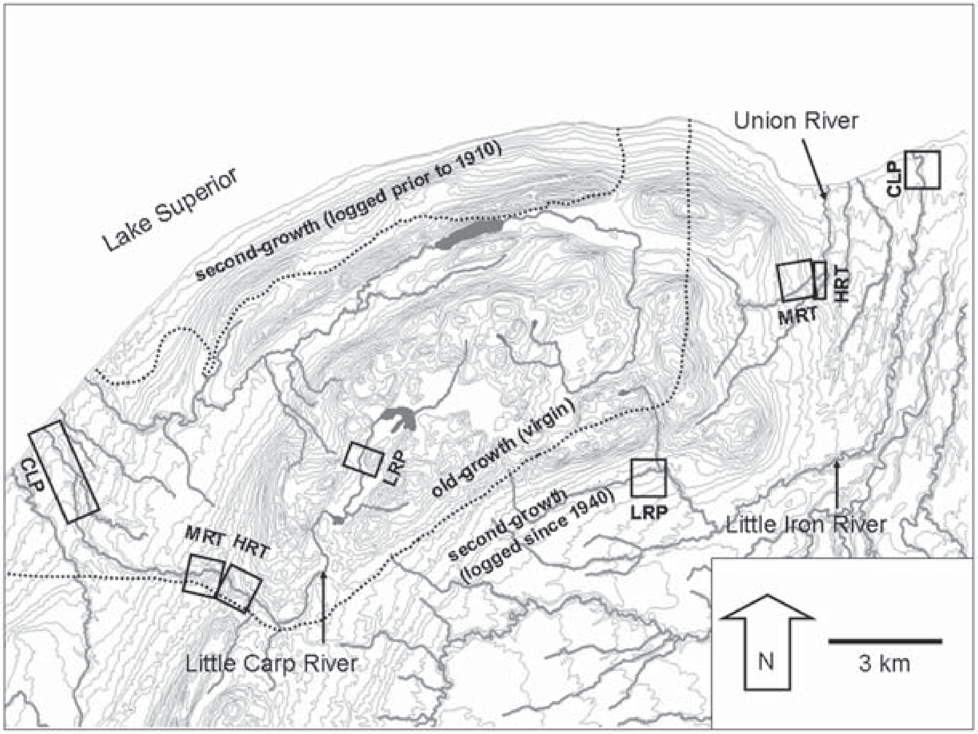

Figure 1. Map of the study area in the Porcupine Mountains. Locations of geomorphic sections are shown with boxes approximating their extent: CLP is the clay-lake plain; MRT is the mid-gradient, HRT is the high-gradient and LRP is the low-gradient geomorphic section. Dotted lines represent boundaries between old-growth and second-growth forest.

forests (Figure 1). Second-growth forest composition is similar to that of the old-growth forest in the PMWSP except with a higher proportion of hardwood species and smaller trees overall, especially maple (*Acer* spp.), birch (*Betula* spp.) and ash (*Fraxinus* spp.). Dense patches of small balsam fir (*Abies balsamea* (L.) Mill.) also occur more frequently in riparian areas of second-growth forest. Most of the Union River and Little Iron River forests extend to the edge of the river channels in segments we studied, and narrow strips (<10 m) of uncut trees remained along the channel in the clay-lake plain of the Little Iron River, where timber harvest has occurred within the last five years.

The substrate of the Union and Little Iron Rivers consists mainly of loose cobble and gravel except for rock-plane bedding where valley gradient is highest in the Union River and in the clay-lake plain of the Little Iron River. Along the upper portion of the Little Iron River, approximately 2–3 cm of sedimentation occurs along the stream bed. No records of stream flow exist for rivers in the second-growth forest, but the sizes of stream flows in the Union and Little Iron Rivers are believed to be similar to those of the Little Carp River. The segment of the Little Iron River in the clay-lake plain is the only third-order stream segment included in this study, but it was the best available second-growth counterpart to the clay-lake plain of the old-growth Little Carp River in width (13 m bankfull width in the Little Iron River, 15 m bankfull width in the Little Carp River) and relative location in the watershed. Although timber harvesting is the dominant human influence along the Union and Little Iron Rivers, localized camping areas exist, as well as trail and road crossings. Beaver activity is evident in the upstream portions of Little Iron River, although no active, channel-spanning dams occurred in the study area during our study.

The major sources of riparian tree mass mortality along study rivers in both old-growth and second-growth forests appear to be bank slope failure and windthrow (L. Frelich, personal communication), with aerial photographs revealing large bank slope failures along the streams in the old-growth clay lake plain (Figure 2). Windstorms frequently result in the felling of individual or small groups of trees. The last major windstorm responsible for mass mortality in the study area occurred in 1953, affecting 1800 ha near the center of the PMWSP. Seasonal precipitation can be heavy (800–900 mm precipitation, up to 7 m snowfall; McNab and Avers, 1994) but the topography is not conducive to avalanches, landslides or other forms of mass wasting, and fire is infrequent in these northern forests. The watershed of the Little Carp River is approximately 40 km^2, while the watersheds of the Union and Little Iron River are 30 and 50 km^2, respectively.

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Figure 2. Aerial view of slope failures and recruitment of large wood along the lower portions of the Little Carp River. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Study Methods

Study Design

We identified four different geomorphic segments of the Little Carp River corridor and then identified segments of streams flowing through nearby second-growth forests with similar geomorphic characteristics. These segments included: a clay-lake plain (CLP); a moderate-gradient stream channel (2% gradient) that is bedrock controlled and occurs transverse to lava inclusions (MRT); a relatively high-gradient stream channel (3–5% gradient), bedrock controlled, also occurring transverse to the lava inclusions (HRT), and a low-gradient (1% gradient), bedrock-controlled section occurring roughly parallel to lava inclusions (LRP) (Figure 3). Studied portions of the stream in these geomorphic settings are hereafter referred to as geomorphic sections.

Valley geomorphology in the study area remained generally constant for at least 1 km in each type of geomorphic setting (i.e., stream valley shape did not change dramatically within geomorphic settings relative to variability among settings). However, we only studied 980 m of LRP section in the Little Carp River to avoid sampling in an area of beaver meadows dominated by tag alder (*Alnus incana* (L.) Moench), grasses (*Leersia* spp.) and sedges (*Carex* spp.). Additionally, the HRT section of the Union River was intersected by two large culverts, through which the entire Union River flowed under a paved road crossing. As these culverts presented an artificial control on stream and LW dynamics, we focused our efforts on the 480 m of HRT upstream from the culverts.

Preliminary surveys in the Little Carp River indicated that 300 m reaches contained several (three or more) LWJs. Therefore, within each geomorphic section, we delineated three non-overlapping reaches 300 m in length. We chose 300 m reaches so that each reach was long enough to contain several LWJs and short enough for three reaches to occur in each study section. In sections at least 1200 m in length (containing at least four possible study reaches) we randomly designated three reaches to study. In the old-growth LRP (Little Carp River) and second-growth HRT (Union River), where study sections were less than 1 km, we designated long enough reaches for three to fit in each section (old-growth LRP reach length = 280 m; second-growth HRT reach length = 150 m).

Large-wood measurements

We determined the distance of each piece of LW (pieces greater than 10 cm diameter and 1 m in length) and the approximate centers of each LWJ from the end of the section in each study reach. Aggregations of at least two pieces of LW contacting each other and extending into the bankfull channel were termed LWJs. We chose to use two pieces of aggregated LW as the lower limit for LWJ designation because we observed that in the small streams of our study aggregations as small as two pieces of LW frequently altered hydrologic processes, trapped sediment and trapped smaller pieces of wood. For each piece of LW not in LWJ we identified species when possible, and noted approximate midpoint diameter and length of the piece. We also counted the number of pieces in each LWJ, classified pieces by size (width 10–20 cm, 21–50 cm, >50 cm; length 1–5 m, 6–10 m, >10 m) and estimated the percent of the wetted channel spanned by the LWJ in increments of 10% (see Table I for a list of the variables we used to describe LW and LWJs).

Figure 3. View of the different geomorphic settings in the Little Carp River (moving from the mouth to the headwaters), including the clay-lake plain geomorphic setting (A), mid-gradient, bedrock controlled, transverse bedding geomorphic setting (B), high-gradient, bedrock controlled, transverse bedding geomorphic setting (C) and low-gradient, bedrock controlled, parallel bedding geomorphic setting (D). This figure is available in colour online at www.interscience.wiley.com/journal/espl

Table I. Variables used to evaluate large-wood jams and large-wood characteristics in streams in or near the Porcupine Mountains Wilderness State Park, Northern Michigan, USA

Variable	Abbreviation	Units
Large-wood jam variables		
Jams/100 m	J100M	number/100 m
Number of pieces per jam	PCJJ	number/LWJ
Volume per jam	VJJ	m^3/LWJ
Mean diameter per piece of LW in jams	JD	cm
Mean volume per piece of LW in jams	VPCLWJ	m^3/piece/LWJ
Percent of wet channel spanned by the jam	PSPAN	%
Large-wood variables		
Number of pieces/100 m	LW100M	number/100 m
Mean diameter per piece of LW	LD	cm
Mean volume per piece of LW	VPCLW	m^3/piece
Percent of conifer among LW	PCONLW	%

Geomorphology measurements

We used a Pentax® 24 total station for topographic surveying of the stream thalweg of each study reach, and for surveying stream valley cross-sections. Surveyed points were projected onto orthophotoquads of the Porcupine

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Mountains using ARCGIS (v. 9·0, ESRI, Redlands, CA). We drew polylines for stream channels on GIS maps by manually connecting surveyed points while tracing channels as they appeared in aerial images in each geomorphic section. These polylines were used to compute an index of sinuosity, defined as the length of the studied channel divided by the straight line between endpoints of that channel segment (Allan, 1995). We computed stream gradient from surveyed points except for second-growth CLP, where we computed gradient using reach endpoint elevations determined from digital elevation models (Michigan, 2005). Gradient was computed differently for second-growth CLP than for other sections because only a few survey points were established on the long, straight section of second-growth CLP and we considered the gradient measurements from GIS data to be more accurate than measurements interpolated from surveyed points for the second-growth CLP geomorphic section. We also measured the distance to each reach from the headwaters using ARCGIS and a perennial stream layer obtained from the Michigan Spatial Data Library (Michigan, 2005). We considered headwaters to be the furthest upstream end of the perennial portion of the stream as determined from the stream maps.

Mean wet widths and bankfull channel widths were calculated from at least five measurements (endpoints and at least three randomly selected internal measurements) in each reach. We estimated channel confinement using by dividing the channel width at twice the bankfull depth by the bankfull channel width as suggested by Rosgen (1996). Any confinement metric less than 6·1 we classified as high confinement, greater than 12 was low confinement and in between ($6{\cdot}1 \leq x \leq 12$) was medium confinement. We also characterized valley constraint of the main channels based on the valley width (bottom of escarpment slope) divided by the bankfull channel width (Fetherston *et al.*, 1995), then we visually characterized constraint of second-growth sections relative to Little Carp River designations. Predominant channel bedding material was visually classified as rock-plane bedding or other material (e.g. sand, gravel, cobble). We noted bedrock geology, specifically the presence of lava inclusions, for each section, using a bedrock geology map from Reed (1987). We also noted quaternary geology (glacial till or lacustrine sand and sediment) for each section from a 1982 glacial geology map of Michigan (Ferrand, 1982).

Riparian Forest Measurements

We used point-quarter transects to describe riparian forest overstory composition and structure in each geomorphic setting (Fitzpatrick *et al.*, 1995). Two transects were established 10 m from the bankfull channel edge for 300–500 m, one on each side of the river near the upstream end of each geomorphic section. At points every 20 m along these transects we measured the distance from the transect to the nearest stem in four directions (quadrants divided by imaginary axes parallel and perpendicular to the stream channel). For each of the nearest stems we identified species, noted whether the stem was alive or dead and measured the diameter at breast height. We also measured the location, species and diameter and estimated the height of trees we considered likely to fall in to the river within a few years on both sides of the river in each reach. Those trees (regardless of whether dead or alive) within 10 m of the bank that leaned more than approximately 45°, or for which more than half of the stem was undercut by the stream, and dead trees (snags) within 10 m of the bank, were considered imminent recruits (i.e. those stems most likely to enter the pool of large wood within a few years). Because of limited access in the second-growth clay-lake plain section (private land being logged), we did not note imminent recruit characteristics in this section.

For evaluation of scale, we considered factors for which values were the same for all three reaches in a study section to represent information at the landscape level: bedrock geology, quaternary geology, forest management, rock-plane bedding, valley constraint and the proportion of conifer in the riparian forest. Factors that varied between reaches represented reach-scale information: the number of imminent recruits per 100 m, the proportion of conifers in imminent recruits, the diameter of riparian snags, channel gradient, sinuosity, confinement, wet width, bankfull channel (BFC) width and distance to the headwaters. (See Table II for a list of variables we used to describe geomorphic and riparian characteristics.)

Data Analysis

We estimated LW volume as the product of length and midpoint diameter. For LW in LWJs, we estimated volume using middle values of the length and diameter classes. Volume of LWJ represented the sum of estimated LW volumes in the LWJ. To compute mean stem density per section, we calculated density at each point, then averaged all point densities along a transect (both sides of the river included), after Jost (1993):

$$D = \frac{1}{N}\sum_{j=1}^{N}\frac{12}{\pi\sum_{i=1}^{4}(r_{ij}^2)} \tag{1}$$

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Table II. Variables used to evaluate stream valley and riparian forest characteristics for study areas in or near the Porcupine Mountains Wilderness State Park, Northern Michigan, USA

Environmental variable	Abbreviation	Units
Landscape-scale variables[1]		
Rock-plane bedding	RPBED	yes, no
Valley constraint	CONSTR	low, medium, high
Forest management	FOREST	old growth, second growth
Bedrock geology: lava inclusion	LAVAINC	yes, no
Quaternary geology	QUAGEO	lacustrine sand and silt (LSS), glacial till (TILL)
Percent conifer in riparian forest	PCONRI	%
Reach-scale variables[2]		
Channel wet width	WETW	m
Bankfull channel width	BFCW	m
Distance from headwaters	DISTHW	m
Channel gradient	GRAD	m/100 m
Channel sinuosity	SINU	m/m
Channel confinement	CONFIN	low, medium, high
Number IRs[3]/100 m	SF100M	number/100 m
Mean diameter of IRs[3]	SD	cm
Percent conifer among IRs[3]	PCONSF	%
Percent snags in riparian forest	RIPS	%
Mean diameter breast height of stems in riparian forest	RIPD	cm

[1] Landscape-scale variables include variables with values that are the same for all three reaches in each geomorphic study section.
[2] Reach-scale variables include variables with different values among reaches even in the same geomorphic study section.
[3] IRs = imminent recruits, i.e. individual trees identified as likely to enter the stream within the next few years.

where D is mean stem density (number/m^2), N is the number of points along the transect and r is the distance (m) from transect point to stem.

Simple comparisons among LW and LWJ characteristics and riparian forest variables were evaluated graphically using plots of means and standard deviations. In order to examine the relationships of LW and LWJs with environmental factors, we used redundancy analysis (RDA), a constrained form of the linear ordination method principal components analysis (Lepš and Šmilauer, 2003). Prior to the analysis, response variables (LW and LWJ characteristics) were centered and standardized because they were measured in different units; the ordination was performed using correlation matrices. Also prior to the analysis, correlations among environmental factors were determined (Minitab v. 14). Correlations with Pearson correlation coefficients (r-values) more extreme than ±0·70 were considered notably strong. We included correlated geomorphic variables in the RDA because we were interested in identifying the geomorphic factor(s) that corresponded most strongly to variability in LW and LWJ characteristics from the measures of environmental variability. However, because of our sample size ($n = 24$ reaches in total), we limited the number of riparian forest variables included in RDA to those associated with imminent recruits, percent conifer and forest management type (old growth or second growth). Additionally, we did not include BFC width or the categorical variables quaternary geology and bedrock geology in the RDA. Finally, the statistical significance of RDA gradients along the first axis and for the sum of all axes was determined using a permutation test of the association between environmental data sets and response variable data sets. RDA and permutation tests were performed with CANOCO software (v. 4·02 for Windows, Centre for Biometry Wageningen, Wageningen, The Netherlands).

After examining the RDA, we used a variance partitioning technique that allowed us to determine the variability associated with subsets of the environmental factors in a similar fashion to Miller *et al.* (2004). In these analyses, we first subtracted the variability associated with the large-wood characteristics explained by the covariables of interest (e.g. geomorphic or riparian forest) and then performed a constrained ordination on residual variability. Specifically, we partitioned variance due to geomorphic factors (sinuosity, gradient, width etc.), riparian forest factors (imminent recruit measures, percent conifer in the riparian forest and forest management) and the intersection of these two categories. Within geomorphic or riparian forest categories, we also partitioned the variance uniquely associated with each individual factor and the intersection of these factors (i.e. the redundant portion).

To evaluate the contribution of geomorphic variables and the interactions of these variables on individual LW and LWJ characteristics, we used regression tree analysis, with CART software (v. 5·0, Salford Systems, San Diego, CA).

Only geomorphic variables were included in regression tree analysis except for forest management type (old growth or second growth). In addition, the factors BFC width, quaternary geology and bedrock geology, which were not included in the RDA, were included in regression tree analysis. As in RDA, we included correlated environmental variables in the analysis to identify the strongest correspondence between measures of environmental variability and variability in LW and LWJ characteristics.

Regression tree analysis with CART methods uses hierarchical arrangements of single environmental variables to split collections of a particular response variable (e.g. number of logjams per 100 m) into groups on a decision-tree. Optimal decision-trees represent the number and arrangement of groups with the lowest possible variance (measured by least squares) within the groups relative to any other possible grouping. A CART analysis, therefore, identifies strong interactions between explanatory variables and provides a relatively direct measure of the hierarchical level at which environmental variables correspond to response variables. For regression tree analyses, we used untransformed values of the variables. We found the optimum tree regardless of size, with a minimum of two cases in the parent node and one in any terminal node. The maximum number of nodes was 24, therefore learn and test sample sizes were also set to 24 (reflecting number of reaches). No penalties or weightings were used for any variable.

In the CART analyses, the importance of a particular explanatory variable was calculated from its effect both as a primary splitter and as a surrogate or substitute for the reported primary splitter(s). All surrogates counted equally when calculating variable importance. We consider variable importance to be the best CART indicator of the qualitative association between environmental variables and LW and LWJ characteristics because variable importance rankings allow evaluation of the relative strength of association between several environmental factors and variability in the response factors. By comparison, the presence of an environmental variable in the best model indicates quantitative relationships, but it only presents one variable at each split even when several are equally or nearly equally related to the response variables. In CART analysis, highly correlated explanatory factors are likely to form good surrogates for each other.

Regression tree analysis is not probabilistic, so the likelihood that an arrangement of variables arose from random chance cannot be represented by a traditional *P*-value. The performance of a regression tree model is, however, represented by the relative decrease in the variability (sum of squares) within groups after being divided by the model (this is termed the relative error). The accuracy of the model is determined by considering its relative error as data sets not used to create the model are processed. Because we had a limited data set, we used 10-fold cross-validation (Lewis, 2000). In 10-fold cross-validation, the data are split into 10 parts, and models are created 10 times, each time with a different nine parts and using the remaining one part to test the model. The average size of the models (i.e. the number of nodes on the trees) with the lowest relative error is used as the size of the optimal tree. A tree with relative error of 1·0 indicates that variability within the divided groups is no different from variability of the original group, and therefore the tree does not provide any increased predictive ability. Conversely, the closer the relative error is to zero, the better the model allows predictability or separation of groups (i.e., variance within groups is minimal compared with variance between groups).

Results

LW and LWJ characteristics

We measured a total of 3825 pieces of wood: 1544 pieces of LW that were not in LWJs, and 2281 pieces of LW that were in LWJs (Table III). The number of LWJs ranged from 0/100 m in one reach of second-growth CLP to about 5/100 m in four reaches in old-growth and second-growth settings (Figure 4(A)). Observed characteristics of LWJs (the number of pieces of LW in LWJs and the volume of LW in LWJs) differed more with geomorphic settings than did the number of pieces and volume of LW that was not in LWJs (Figures 4(B), (C) and 5(A), (B)). The maximum number and volume of LW occurred in old-growth MRT, where LW was trapped in LWJs. Diameters of LW pieces in LWJs (Figure 5(C)) and of LW pieces not in LWJs (Figure 4(D)) was similar among geomorphic sections. LWJs spanned more of the channel in LRP sections than in other geomorphic sections (Figure 4(E)).

The second-growth CLP section was notably extreme because it had a large (12 m wet width, 13 m BFC width), straight (mean sinuosity = 1·07), rock-plane bedded channel and because adjacent forests had been logged during the last 5 years. These conditions resulted in remarkably little LW stored in the channel. Initial exploratory analyses showed that the data from the second-growth CLP section formed a group of extreme outliers with disproportionate influence on ordination results, most likely originating from the logging activities in this portion of the Little Iron River. Consequently, they were excluded from RDA so that relationships among other study sections and reaches could be determined. Second-growth CLP data were included, however, in regression tree analysis.

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Table III. Reach LW and LWJ characteristics

Geom. section	Reach	FOREST	Reach length (m)	No. LWJs	No. LW in LWJs	No. LW not in LWJs	Total volume LWJs (m^3)	Total volume LW not in LWJs (m^3)	JD (cm)	LD (cm)	PSPAN (%)
CLP	1	old growth	300	8	86	43	37	19	27	24	32
CLP	2	old growth	300	7	33	88	16	31	30	23	10
CLP	3	old growth	300	5	126	73	76	30	34	23	23
MRT	1	old growth	300	13	251	59	88	37	27	27	39
MRT	2	old growth	300	16	522	46	175	12	28	25	33
MRT	3	old growth	300	16	169	38	54	19	27	26	29
HRT	1	old growth	300	9	60	53	25	40	28	30	21
HRT	2	old growth	300	11	219	78	69	29	25	23	23
HRT	3	old growth	300	3	16	53	6	15	32	22	44
LRP	1	old growth	280	4	64	55	19	19	25	23	56
LRP	2	old growth	280	12	71	48	13	7	21	18	64
LRP	3	old growth	280	14	95	56	23	13	25	28	42
CLP	1	second growth	300	1	5	6	1	4	35	40	1
CLP	2	second growth	300	2	4	7	5	3	33	26	1
CLP	3	second growth	300	0	0	2	0	3		43	
MRT	1	second growth	300	13	100	37	19	7	22	25	12
MRT	2	second growth	300	9	118	45	18	6	20	20	9
MRT	3	second growth	300	3	18	59	2	7	19	20	37
HRT	1	second growth	150	3	14	29	2	2	19	16	6
HRT	2	second growth	150	2	10	46	1	4	18	16	4
HRT	3	second growth	150	1	6	13	0	1	15	17	2
LRP	1	second growth	300	13	129	31	33	5	27	21	46
LRP	2	second growth	300	12	62	55	14	9	23	21	39
LRP	3	second growth	300	16	103	46	21	3	23	17	31

Variable abbreviations explained in Tables I and II.

Riparian forest characteristics

Riparian forest densities (stems/m^2) were similar among geomorphic settings, but also quite variable among the transects (Figure 6(A)). The number of imminent recruits/100 m decreased with increasing channel width ($r = -0{\cdot}70$, $P < 0{\cdot}01$). The number of imminent recruits/100 m, volume of imminent recruits/100 m and diameter of imminent recruits did not vary substantially, however, among geomorphic settings and between old-growth and second-growth forests, except for the second-growth CLP, where we did not observe any imminent recruits due to the recent logging activities (Figure 7(A)–(C)). The proportion of conifer in imminent recruits and the proportion of conifer in riparian trees correlated significantly with each other ($r = 0{\cdot}85$, $P < 0{\cdot}01$), and with old-growth designation ($r = 0{\cdot}78$, $P < 0{\cdot}01$, and $r = 0{\cdot}90$, $P < 0{\cdot}01$, respectively). Riparian forest characteristics were generally most similar between old-growth and second-growth forests in the LRP sections (Figure 6(B)–(D). The diameter of riparian trees was greater and the proportion of conifer was higher in old-growth than second-growth settings (correlation of old-growth with diameter of riparian trees $r = 0{\cdot}89$ and with proportion of riparian conifer $r = 0{\cdot}9$, $P < 0{\cdot}01$ for both), although neither the density of riparian trees nor the number of riparian snags differed consistently between old-growth and second-growth forests (Figure 6(A) and (B); correlation of old growth with density of riparian trees $r = -0{\cdot}11$, $P = 0{\cdot}61$; correlation of old growth with number of riparian snags $r = 0{\cdot}03$, $P = 0{\cdot}88$).

Relationships between LW, LWJs, geomorphic factors and riparian forests

Correlation analyses revealed that channel wet and bankfull widths were strongly correlated ($r = 0{\cdot}81$), and channel width increased with distance from the headwaters (wet width $r = 0{\cdot}93$, bankfull channel width $r = 0{\cdot}85$). Valley constraint increased with increasing channel gradient (high constraint $r = 0{\cdot}79$), and rock-plane bedding correlated positively with high channel confinement ($r = 0{\cdot}71$; $P < 0{\cdot}01$ for all reported correlations among geomorphic variables). Bedrock geology (categorized as lava inclusion or not) was significantly correlated with stream gradient ($r = 0{\cdot}73$, $P < 0{\cdot}01$), and was inversely related to low valley constraint ($r = -1{\cdot}00$; i.e., valley constraint was always

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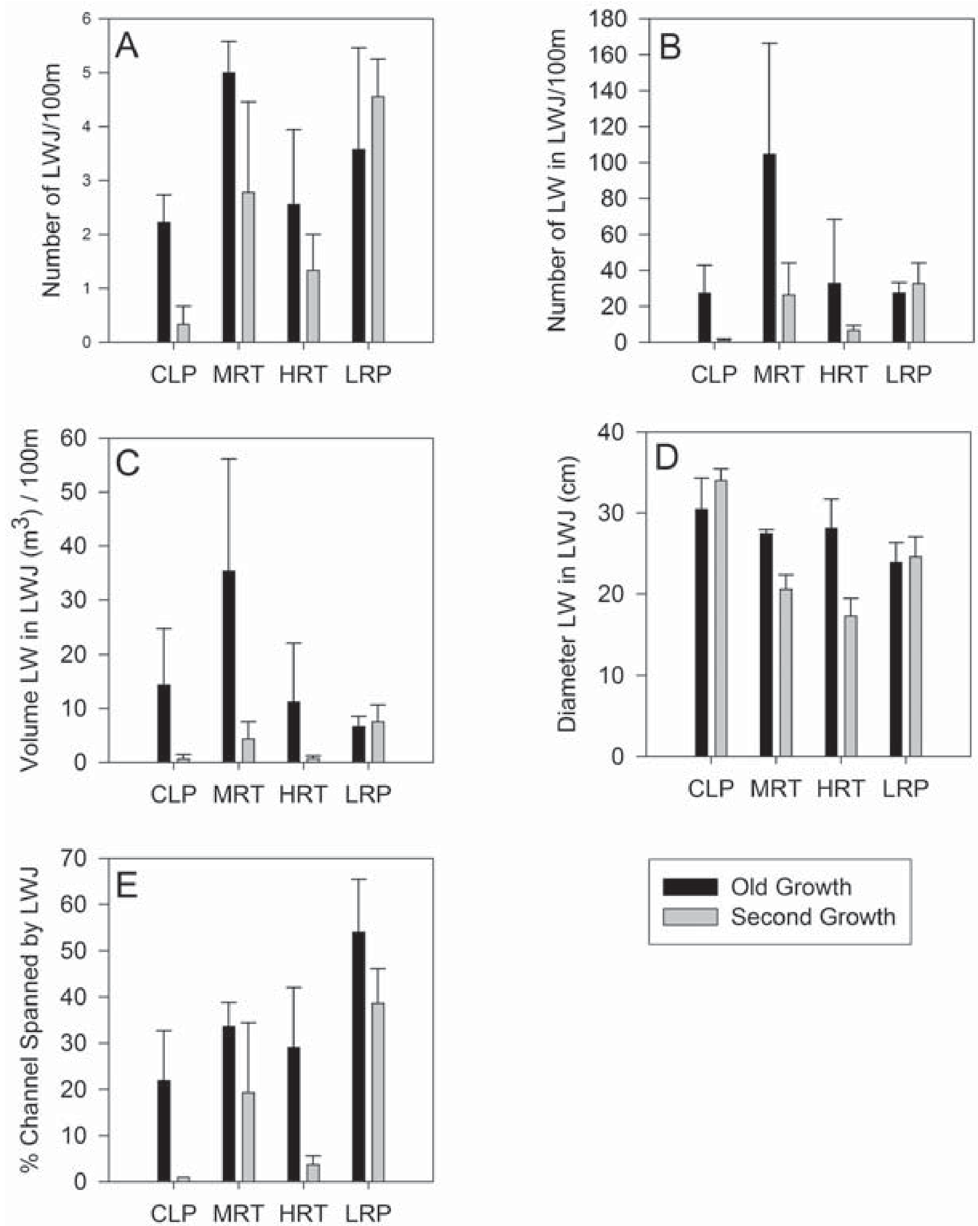

Figure 4. Mean (±1 SD) number of LWJs/100 m (A), number of LW in LWJs/100 m (B), volume of LW in LWJs/100 m (C), diameter of LW in LWJs (D) and percent of channel spanned by LWJs (E) in the old-growth and second-growth riparian forests. ($n = 3$, except $n = 2$ for LWJ diameter in second growth.)

low in the absence of lava inclusions). These correlations represent channels enlarging downstream, confined bedrock channels and higher gradient channels in steeper sections and narrower valleys where the streams cut across underlying bedrock structure. By comparison, sinuosity correlated most highly with high channel confinement ($r = -0{\cdot}46$, $P = 0{\cdot}02$), and represents one of the highest correlations among geomorphic variables other than those reported above (Table IV).

The environmental factors we evaluated in the RDA explained 86·7% of the variability in LW and LWJ characteristics (Table V). Reaches were generally grouped together by geomorphic section in the RDA, indicating less variability in the set of LW and LWJ characteristics within geomorphic sections than between geomorphic sections. Reaches from the old-growth LRP section grouped closely together with reaches from the second-growth LRP section, while reaches from other old-growth geomorphic sections did not group closely with their counterparts from second-growth forest (Figure 8).

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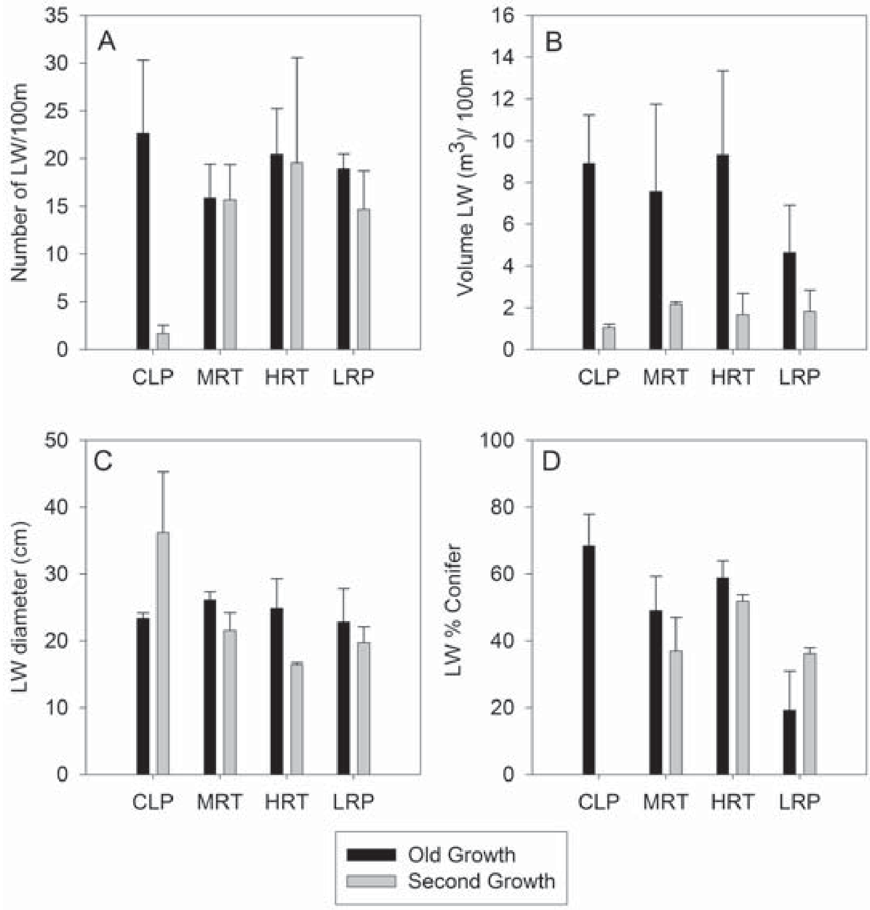

Figure 5. Mean (±1 SD) number of pieces of LW/100 m (A), volume of LW/100 m (B), diameter of LW (C) and percent conifer of LW (D) in the old-growth and second-growth riparian forests. These data represent LW that is not in LWJs.

Two gradients associated with LWJ and LW characteristics were evident from the RDA (Figure 8). The first gradient (axis 1) related primarily to the forest type (old growth or second growth), the amount of conifer in riparian forests and the distance from the headwaters, and it was this axis that corresponded to the size and volume of pieces of LW and of LWJs, and with the number of pieces of wood in LWJs. The second gradient (axis 2) associated LWJ and LW characteristics with the presence of rock-plane bedding, channel confinement and sinuosity, and it was this axis that corresponded to the number of LWJs and pieces of LW, and with the amount of channel spanned by LWJs. Axis 1 represented 41·5% of the variance in LWJs and LW characteristics. Axis 2 represented an additional 20·3% of the variance. All reaches from the old-growth forest except for reaches from the LRP section were associated with the right portion of the ordination diagram, indicating that in this study old-growth forests with relatively high proportions of riparian conifers and medium channel constraint and far from headwaters contained larger pieces of wood (LW in and out of LWJs), and had LWJs containing the greatest number of pieces of large wood. However, as indicated by axis 2, reaches without rock-plane bedding and with low channel confinement and relatively high sinuosity contained the most abundant LWJs that spanned the largest proportion of the channel.

When single-factor RDA was performed (only one explanatory variable and no covariates), the following variables each significantly explained about 30% of the variability in LW characteristics: channel confinement, distance to the headwaters, percent conifer in the riparian forest, percent conifer in imminent recruits and old-growth classification (Table VI). Wet width significantly explained 17% of the variance, and the presence of rock-plane bedding significantly explained 16% of the variance in LW characteristics. Correlation between variables resulted in redundancy, however, so that substantial variability in LW characteristics could be explained by more than one environmental factor. With regard to geomorphic environmental factors compared with riparian forest factors, geomorphic factors alone or in combination explained 38·5% of the variability in LW characteristics, riparian forest factors alone explained

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Table IV. Geomorphic characteristics of reaches studied in the Porcupine Mountains, MI

GEO SECT	REACH	FOREST	RPBED	CONSTR	LAVA INC	QUA GEO	WETW (m)	BFCW (m)	DISTHW (m)	GRAD (m/100 m)	SINU (m/m)	CONFIN
CLP	1	old growth	YES	LOW	NO	LSS	8·8	18·6	15 937	1·92	1·31	HIGH
CLP	2	old growth	YES	LOW	NO	LSS	6·8	13·9	16 841	2·11	1·08	HIGH
CLP	3	old growth	YES	LOW	NO	LSS	6·2	13·0	17 441	0·93	1·47	MED
MRT	1	old growth	NO	MED	YES	LSS	4·6	6·7	11 327	1·79	1·15	MED
MRT	2	old growth	NO	MED	YES	LSS	4·5	11·0	10 429	1·47	1·22	MED
MRT	3	old growth	NO	MED	YES	LSS	4·8	10·9	10 729	2·31	1·24	MED
HRT	1	old growth	YES	HIGH	YES	TILL	7·0	11·2	9 779	4·47	1·04	HIGH
HRT	2	old growth	YES	HIGH	YES	TILL	4·7	10·3	9 181	3·73	1·38	MED
HRT	3	old growth	YES	HIGH	YES	TILL	6·6	9·3	9 480	3·92	1·11	HIGH
LRP	1	old growth	NO	LOW	NO	TILL	2·9	3·6	1 100	1·38	1·18	LOW
LRP	2	old growth	NO	LOW	NO	TILL	1·6	2·4	1 341	1·03	1·56	LOW
LRP	3	old growth	NO	LOW	NO	TILL	2·6	3·9	1 383	1·11	1·14	LOW
CLP	1	second growth	YES	LOW	NO	LSS	10·7	11·3	24 653	0·12	1·04	LOW
CLP	2	second growth	YES	LOW	NO	LSS	12·0	15·0	24 354	0·02	1·15	LOW
CLP	3	second growth	YES	LOW	NO	LSS	12·0	13·4	24 057	0·35	1·02	HIGH
MRT	1	second growth	NO	MED	YES	LSS	2·1	4·8	3 194	2·34	1·45	LOW
MRT	2	second growth	NO	MED	YES	LSS	3·2	5·3	3 495	1·89	1·28	MED
MRT	3	second growth	NO	MED	YES	LSS	3·1	4·1	2 885	2·40	1·14	LOW
HRT	1	second growth	YES	HIGH	YES	LSS	4·1	5·1	4 176	2·57	1·10	HIGH
HRT	2	second growth	YES	HIGH	YES	LSS	3·8	5·1	4 029	2·53	1·17	HIGH
HRT	3	second growth	YES	HIGH	YES	LSS	4·3	6·2	3 881	5·35	1·08	HIGH
LRP	1	second growth	NO	LOW	NO	LSS	5·2	8·6	6 183	0·73	2·06	LOW
LRP	2	second growth	NO	LOW	NO	LSS	4·2	5·9	5 888	0·76	1·43	LOW
LRP	3	second growth	NO	LOW	NO	LSS	5·5	5·8	5 589	0·80	1·45	LOW

Variable abbreviations explained in Tables I and II.

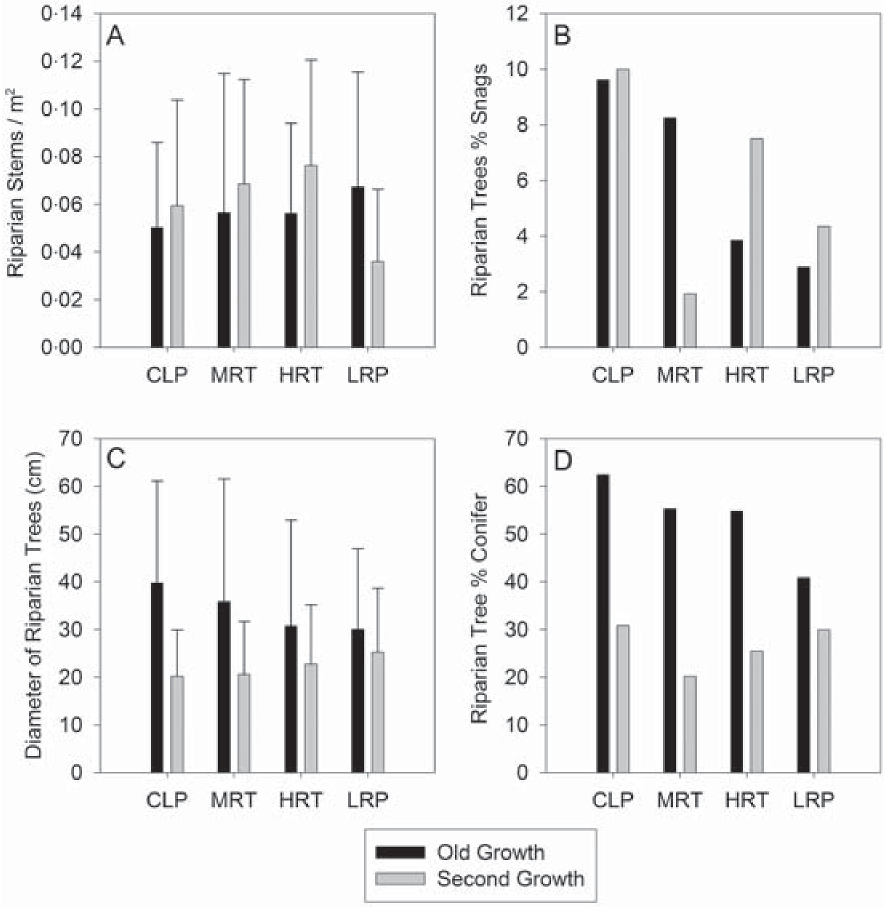

Figure 6. Mean (±1 SD) number of riparian trees/m^2 (A), total percent snags (standing dead trees) of riparian trees (B), mean (±1 SD) diameter of riparian trees (C) and total percent conifer of riparian trees (D) in the old-growth and second-growth riparian forests, based on point-quarter transects.

Table V. Summary of redundancy analysis (RDA) comparing large-wood characteristics, geomorphology, and riparian factors

Axis	1	2	3	4	Total
Eigenvalue	0·415	0·203	0·096	0·071	
Section–environmental factor correlation	0·969	0·991	0·939	0·865	
Cumulative % total variance	41·5	61·8	71·4	78·5	
Cumulative % variance explained by environmental factors	47·9	71·3	82·4	90·6	
Sum of all canonical eigenvalues (trace)					0·867
P-value	0·02				0·01

18·4% of the variance and the intersection of the two categories of environmental factors (i.e. the redundant portion) was 29·8% (Figure 9). No single variable uniquely explained a significant proportion of variance in LW or LWJ characteristics when all other variables were treated as covariates ($P > 0{\cdot}05$, permutation test for each model in variance partitioning).

Regression tree analysis

When optimal regression trees were compared, different geomorphic factors associated with LW and LWJ characteristics. Channel wet width figured as the most important geomorphic factor in splitting single LW and LWJ characteristics,

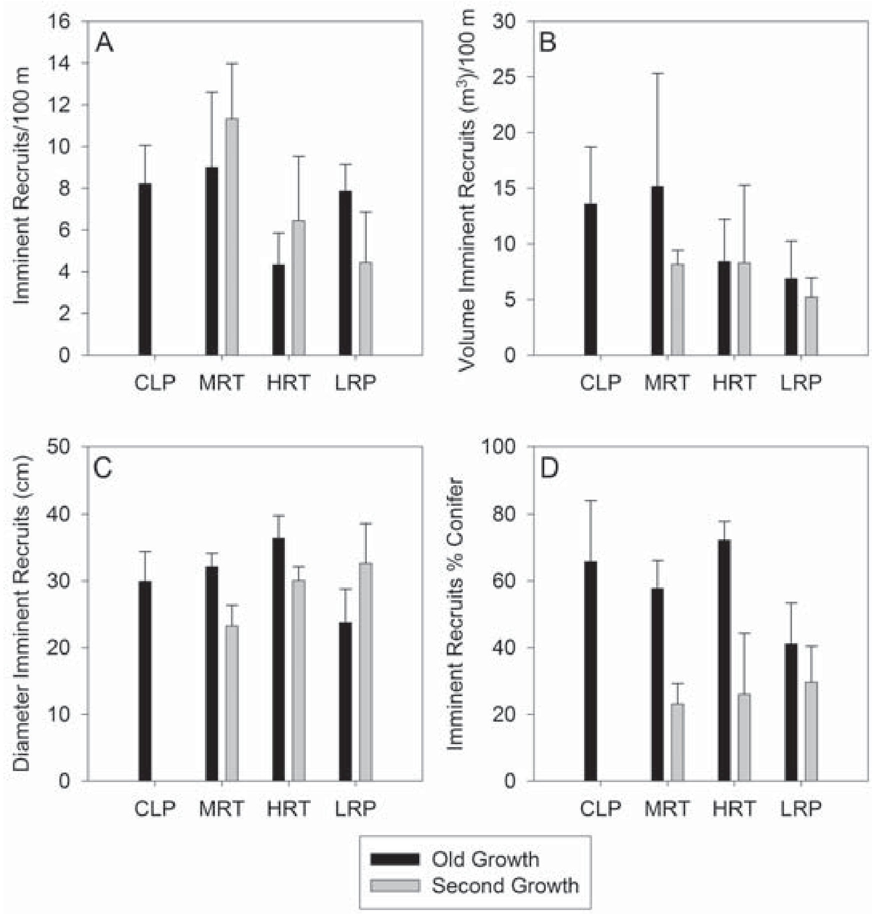

Figure 7. Mean (±1 SD) number of imminent recruits/100 m (A), volume of imminent recruits/100 m (B), diameter of imminent recruits (C) and percent conifer of imminent recruits (D) in the old-growth and second-growth riparian forests.

Table VI. Variance explained by individual variables when used alone in redundancy analysis (RDA) with no covariables

Environmental variables	Sum of all canonical eigenvalues (proportion of total variance explained)[1]	*P*-value[2]
Geomorphic variables	0·683	0·01
SINU	0·058	0·26
GRAD	0·087	0·12
WETW	0·174	0·01
CONFIN	0·308	0·01
DISTHW	0·301	0·01
CONSTR	0·127	0·23
RPBED	0·155	0·01
Riparian forest variables	0·482	0·01
SF100M	0·019	0·88
PCONSF	0·288	0·01
SD	0·072	0·17
PCONRI	0·337	0·01
OLD-GROWTH	0·279	0·01

[1] Each sum of canonical eigenvalues represents the proportion of variability corresponding only to the variable or group of the same row.
[2] The *P*-value indicates the probability that the association between an environmental variable or group and response variables (LW characteristics) was random (determined by comparison of actual patterns with 199 random permutations).

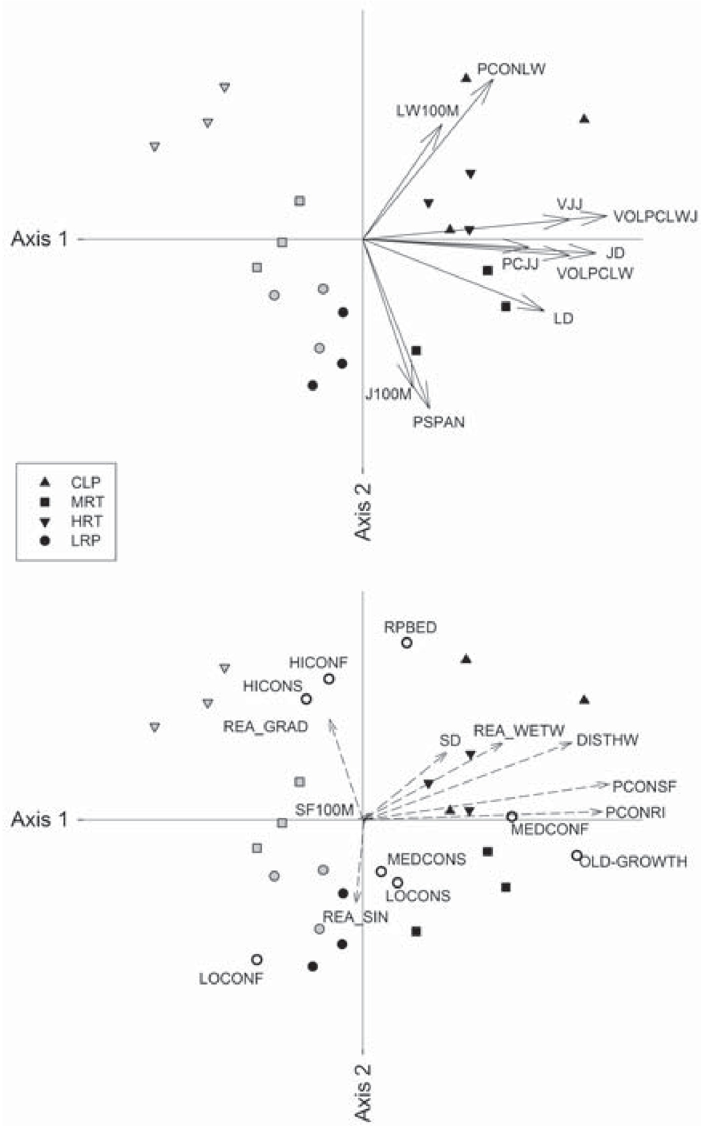

Figure 8. Redundancy analysis comparing LWJ and LW characteristics with geomorphic and riparian forest variables. Solid lines represent LWJ and LW characteristics (response variables). Dashed lines represent continuous environmental variables, and open circles represent categorical environmental variables. Three-letter codes in the legend refer to geomorphic sections. Black-filled symbols represent reaches from old-growth forest and gray-filled symbols represent reaches from second-growth forest. CLP is the clay-lake plain and MRT is the mid-gradient, HRT is the high-gradient and LRP is the low-gradient geomorphic section.

followed by distance from headwaters, gradient and sinuosity for LW characteristics (Table VII). Channel confinement was the next most important variable after channel wet width for splitting similar groups of LWJ characteristics. Rock-plane bedding was the only landscape-level factor with importance rankings greater than 75 for any LWJ or LW characteristics: it was the primary splitter (importance rank = 100) for the number of LWJs/100 m and percent of the channel spanned by LWJs.

As examples of the association of different geomorphic factors with LW and LWJ characteristics, consider the abundance of LW, the abundance of LWJs and the percent of the channel spanned by LWJs. Channel gradient less than 0·7% corresponded to four reaches with a mean of $3{\cdot}8 \pm 3{\cdot}8$ pieces of LW/100 m while gradient equaling or exceeding 0·7% corresponded to 20 reaches with a mean of $18{\cdot}7 \pm 5{\cdot}4$ pieces LW/100 m (Figure 10(A)). CART analysis also indicated that wet width or distance from the headwaters would have been good surrogates for stream gradient in this case, suggesting that these geomorphic factors were the most important variables corresponding to the abundance of

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Table VII. Importance of explanatory variables in splitting groups of LWJ and LW characteristics in regression tree analyses. Importance is computed relative to the most important environmental variable by row, which is the variable used to make the most splits with least amount of heterogeneity in child nodes compared to parent nodes for that target variable (row). The importance reflects the occurrence of a variable as a primary splitter and as a surrogate splitter in the optimum (minimum cost) tree

Variable	Sinuosity	Gradient	Wet width	BFC width	Valley constraint	Channel confinement	Rock-plane bedding	Distance from headwaters	Forest mgmt	Bedrock geology	Quaternary geology
J100M	63	17	64	12	0	49	100	0	0	0	0
PCJJ	4	29	4	29	22	100	0	4	0	4	0
VJJ	53	69	53	69	5	100	0	53	0	53	0
JD	20	26	85	91	12	14	20	100	26	12	1
VPCLWJ[1]	2	79	100	30	2	5	3	27	23	2	0
PSPAN	75	43	70	78	0	42	100	59	54	0	42
LW100M	66	100	99	0	0	0	0	99	0	0	0
LD	100	78	78	0	0	0	0	78	0	0	0
VOLPCLW	96	52	100	42	0	10	1	79	18	0	0
PCONLW	6	42	77	77	0	100	0	77	0	0	0

[1] No optimal tree found for VPCLWJ.

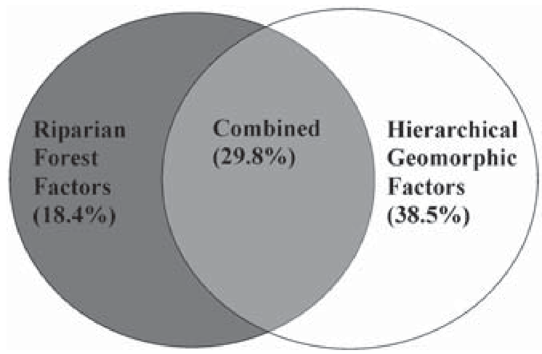

Figure 9. Results of RDA variance partitioning based on redundancy analyses of LW and LWJ characteristics as constrained by hierarchical geomorphic factors and riparian forest characteristics of streams.

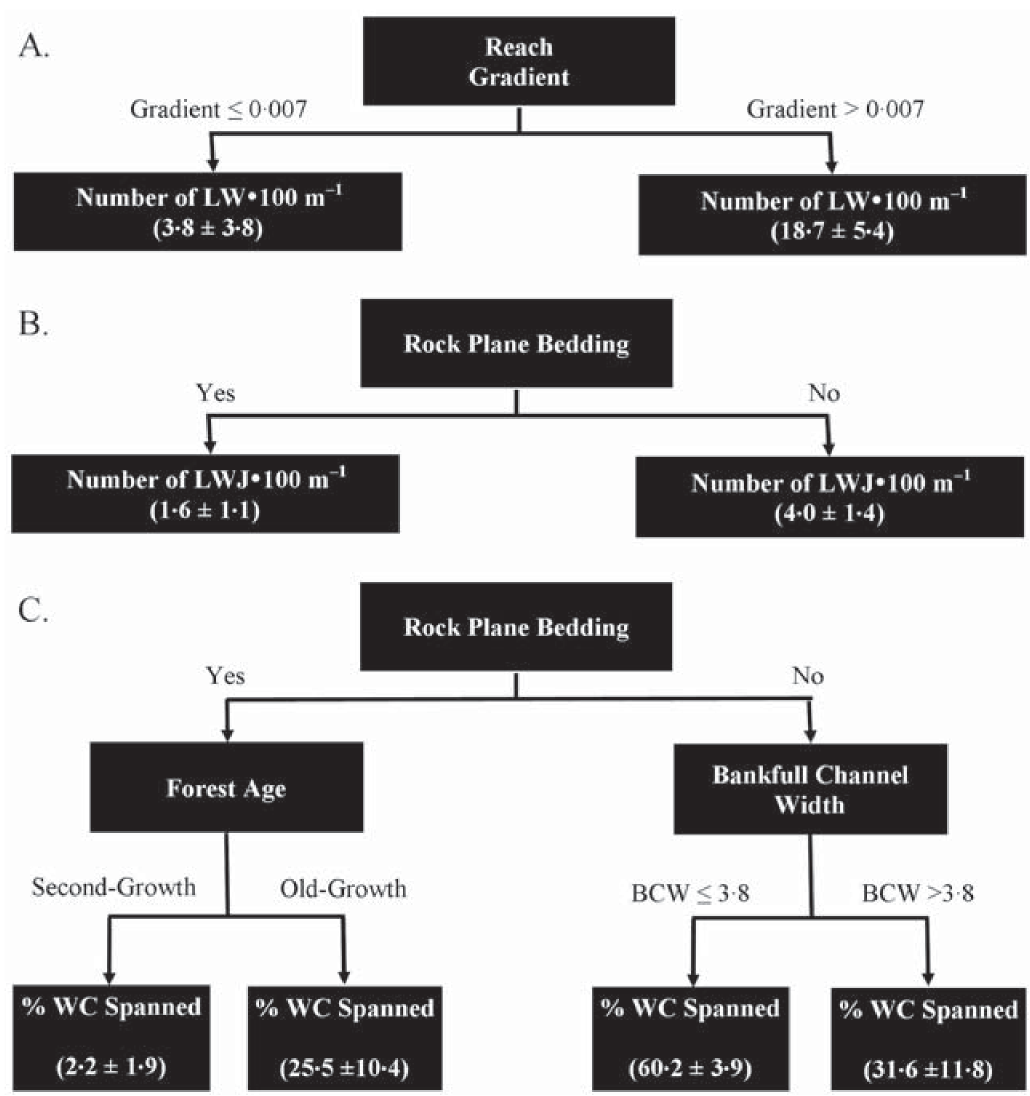

Figure 10. Regression trees explaining the abundance of LW/100 m (A), abundance of LWJs/100 m (B) and percent of the channel spanned by LWJs (C) in terms of geomorphic and forest variables. See Table VIII for a summary of regression tree analyses.

Table VIII. Summary of regression tree models relating characteristics of large-wood jams (LWJs) to geomorphic variables

LWJ variable	Relative error of optimal tree	Branch splitting rules[1]	Terminal node Mean ± SD	No. reaches in terminal node
J100M	0·936 ± 0·269	RPBED = yes	1·6 ± 1·1	12
		RPBED = no	4·0 ± 1·4	12
PCJJ	0·442 ± 0·088	CONFIN = high, low	6·7 ± 3·0	17
		CONFIN = med and GRAD ≤ 0·016	28·9 ± 3·7	2
		CONFIN = med and GRAD > 0·016	15·7 ± 4·0	4
VJJ	0·405 ± 0·160	CONFIN = high, low	1·8 ± 1·3 m^3	17
		CONFIN = med and GRAD ≤ 0·016	13·1 ± 2·2 m^3	2
		CONFIN = med and GRAD > 0·016	4·6 ± 2 m^3	4
JD	0·460 ± 0·158	BFCW ≤ 6·447 and GRAD ≤ 0·024 and SINU ≤ 1·231	25·3 ± 0·1 cm	2
		BFCW ≤ 6·447 and GRAD ≤ 0·024 and SINU > 1·231	22·0 ± 1·1 cm	5
		BFCW ≤ 6·447 and GRAD > 0·024	17·6 ± 1·7 cm	4
		BFCW > 6·447 and DISTHW ≤ 17·141 and SINU < 1·129	29·9 ± 1·2 cm	3
		BFCW > 6·447 and DISTHW ≤ 17·141 and SINU > 1·129	26·9 ± 1·0 cm	6
		BFCW > 6·447 and DISTHW > 17·141	34·1 ± 0·8 cm	3
PSPAN	0·926 ± 0·221	RPBED = yes and FOREST = second-growth	2·2 ± 1·9%	6
		RPBED = yes and FOREST = old-growth	25·5 ± 10·4%	6
		RPBED = no and BFCW ≤ 3·778	60·2 ± 3·9%	2
		RPBED = no and BFCW > 3·778	31·5 ± 11·7%	10
LW100M	0·685 ± 0·241	GRAD ≤ 0·007	3·8 ± 3·8	4
		GRAD > 0·007	18·7 ± 5·4	20
LD	0·770 ± 0·264	SINU ≤ 1·667	41·3 ± 1·7 cm	2
		SINU > 1·667	22·3 ± 3·8 cm	22
VPCLW	0·626 ± 0·167	SINU ≤ 1·063 and SINU ≤ 1·028	1·3 ± 0·0 m^3	1
		SINU ≤ 1·063 and SINU > 1·028	0·7 ± 0·1 m^3	2
		SINU > 1·063 and DISTHW ≤ 7·682	0·2 ± 0·1 m^3	12
		SINU > 1·063 and DISTHW > 7·682	0·4 ± 0·1 m^3	9
PCONLW	0·544 ± 0·095	CONFIN = low	31·4 ± 10·5%	10
		CONFIN = med, high	54·7 ± 10·6%	14

[1] 'Branch splitting rules' indicate criteria for splitting data; e.g., for LW100M, four reaches with gradient (GRAD) less than or equal to 0·007 had an average of 3.8 pieces of LW. The other (20) reaches had an average of 18·7 pieces of LW.

LW (see Table VIII). In contrast, the presence of rock-plane bedding corresponded to 12 reaches containing a mean of 1.6 ± 1·1 LWJs/100 m compared with 12 reaches without rock-plane bedding that contained a mean of 4·0 ± 1·4 LWJs/100 m (Figure 10(B)). There were no strong surrogates for rock-plane bedding in this case, suggesting that rock-plane bedding rather than stream gradient or width was the geomorphic factor most closely associated with the abundance of LWJs in this study. Finally, the presence of rock-plane bedding was an important factor for predicting the percent of the bankfull channel spanned by LWJs. For those streams with rock-plane bedding, second-growth streams had LWJs that spanned 2·2 ± 1·9% of the channel, while old-growth streams spanned 25·5 ± 10·4% of the channel (Figure 10(C)). In contrast, in streams with no rock-plane bedding, BFC width was the most important factor determining the percentage of the channel spanned by LWJs. In streams without rock-plane bedding and a BFC width of ≤3·8 m, LWJs spanned 60·2 ± 3·9% of the stream channel while in streams with a BFC width >3·8 m LWJs spanned on average 31·6 ± 11·8% of the stream channel (Figure 10(C)).

Discussion

LW and LWJ abundance, diameter and volume reflect integrated geomorphic, hydrologic and forest factors in the Porcupine Mountains as they do elsewhere (Swanson, 2003). The range of evaluated conditions influences factors identified as most highly associated with LW and LWJ characteristics in any geographic area, and present limits to comparisons of trends identified in this study with other studies. We evaluated small streams that increased by about 10 m in width in the study area. Topographic variability in our study area, while high relative to other portions of the northern Lake States, was less than in many mountainous regions, so we studied a moderate range of stream gradients

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(1–5% gradients). The metastructure of landscape patches along a stream may also influence the patterns of LW recruitment and retention visible as patterns of LW and LWJ structure (Swanson, 2003). Streams we studied in the Porcupine Mountains generally began in low-gradient settings and flowed briefly through steep channels far downstream from the headwaters, which is different from river landscapes described in many other mountainous regions, where steep headwater streams flatten and enlarge downstream (Nakamura and Swanson, 2003). Finally, the forests of the Porcupine Mountains represent mixed deciduous–conifer forests, which have smaller trees than are typical for the conifer forests of the Pacific Northwest, and are characterized by different forest stand dynamics. The height of the tallest trees in the Porcupine Mountains was approximately 40 m, compared to the typical height of 70–80 m for Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), 50–65 m for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and 45–70 m for noble fir (*Abies procera* Rehd.), the often numerically dominant tree species in forests of the Pacific Northwest, USA (Waring and Franklin, 1979). Trends identified in our study directly apply to similar conditions in small streams of the Great Lakes Region, USA. Nevertheless, even from within the range of conditions evaluated during this study, patterns of relationships between environmental factors and LW and LWJ characteristics emerged that correspond with and help to clarify trends identified in studies from other areas.

Influence of hierarchical geomorphic factors

Our analyses suggest that LWJ and LW characteristics are strongly related to hierarchical geomorphic factors in the Porcupine Mountains. At the landscape scale, our multivariate analyses suggest that the presence of rock-plane bedding was an important predictor of the number of LWJs and the percent of channel spanned by LWJs. Both the number of LWJs and the percent of channel spanned by LWJs most likely relate to landscape setting because both relate strongly to the ability of a stream channel to transport and retain LWJs, which is a function of integrated forest, hydrologic and geomorphic factors. The presence of rock-plane bedding indicates a strong probability for transport conditions (i.e. poor retention) because these channels corresponded to high channel confinement and occurred where water power was high due to high stream gradient (in the HRT sections) and large channel size (in the CLP sections), and where there were relatively few trapping structures in the channel. As streams flow through highly confined channels over the smooth substrate of rock-plane bedding, retention of LWJs is low relative to other geomorphic settings. Therefore, the presence of rock-plane bedding seems to be a strong landscape-scale indicator for combinations of factors that influence LWJ numbers and span of the channel in the Porcupine Mountains.

Reach-scale factors also strongly influenced LW and LWJ structure, suggesting that much of the control of individual LW and LWJ characteristics derives from the small-scale setting in the Porcupine Mountains. Of the reach-scale factors we measured, variability in channel width ranked the highest overall as a predictor variable in regression tree analysis, followed by distance from the headwaters, gradient and sinuosity. Distance from the headwaters (which we used to represent overall changes in a downstream direction) was less important than channel wet width at predicting LW and LWJ characteristics, except for predicting the diameter of pieces in LWJs. Distance from the headwaters correlated strongly with larger diameter of pieces in LWJs because larger riparian trees occurred further downstream in our study area. Although channel width and distance from the headwaters were highly correlated (distance from the headwaters with wet width $r = 0{\cdot}93$), channel width corresponded more strongly with LW and LWJ characteristics than did distance from the headwaters because of variations in channel width at the reach scale that did not correspond to distance from the headwaters. Channel gradient and sinuosity did not correlate very strongly with distance from the headwaters, showing that geomorphic factors corresponding to LW and LWJ structure did not just vary in a downstream direction.

Other studies have associated changes in LW abundance or volume with stream width, size or order (see, e.g., Bilby and Ward, 1989; Nakamura and Swanson, 1994; Gurnell *et al.*, 2002; Gurnell, 2003). Although we found that channel width ranked highly among factors explaining variability of LW and LWJ characteristics, we also found that width alone was only responsible for 17% of the observed variability in LW and LWJ characteristics in the RDA. The importance of other geomorphic factors (such as channel gradient) highlights interactions with channel width that influence physical structures and processes involving large-wood recruitment and transport (Piégay and Gurnell, 1997; Palik *et al.*, 1998; Martin, 2001).

Variability in LW and LWJ structural characteristics in the Porcupine Mountains corresponds to a suite of environmental variables including those at both large and small scales together. Variance partitioning to compare the correspondence of riparian forest factors and geomorphic factors with LW and LWJ structure indicated that geomorphic factors uniquely corresponded to 38·5% of the variability in total LW and LWJ structure and were redundant with riparian forest factors for another 29·8% of the variability, showing that geomorphic variables alone could be used to explain 68·3% of the total variability in LW and LWJ structure that we observed. Single-factor RDA indicated, however, that no single environmental variable uniquely accounted for more than 30% of the variability in the entire

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suite of LW and LWJ characteristics, suggesting that environmental factors influenced wood characteristics differently. Regression tree analyses show differences in relationships between geomorphic factors and LW and LWJ structure, suggesting that individual geomorphic factors corresponded most strongly to different LW and LWJ characteristics. For example, stream gradient, wet width and distance from the headwaters corresponded to the abundance of LW, while rock-plane bedding corresponded to the abundance of LWJs. Conclusions about the relative importance of individual environmental factors on LW and LWJ structure are based on a fairly small data set of geomorphic settings in this study, so they require further evaluation with additional data.

There have been two recent studies that quantified LW correspondence to large-scale geomorphology (Rot *et al.*, 2000; Wing and Skaugset, 2002). Comparison of our study with the studies of Rot *et al.* (2000) and Wing and Skaugset (2002) illustrates comparisons between trends we identified in the Porcupine Mountains and trends from the Pacific Northwest, USA, where much research on LW has been done in North America (Gurnell, 2003). Rot *et al.* (2000) found that more LW occurred in relatively unconstrained valley types with extensive alluvial landforms and where bedrock channel substrate was absent (16 pieces/100 m) compared to constrained bedrock and plane bed channels where alluvial landform development was minimal (10–11 pieces/100 m) in small, low-gradient channels surrounded by mid- to late successional plant communities in western Washington. Studies in Alaska have also found more LW in unconfined, alluvial channels than in confined, bedrock channels (see, e.g., Murphy and Koski, 1989; Martin, 2001). We generally found more LW in settings without rock-plane bedding and with low channel confinement, but this was largely in LWJs, the abundance of which corresponded strongly to channel confinement and rock-plane bedding in the Porcupine Mountains. We found that LW not in LWJs typically occurred in greater abundance in steeper, confined, rock-plane bedded channels than in other channels, but these differences probably result simply from the greater chance of LW being involved with other pieces of LW as LWJs in the relatively low-gradient, unconfined channels without rock-plane bedding.

Wing and Skaugset (2002) used regression tree analysis with 3793 stream reaches in western Oregon to determine that in forested streams LW abundance was best predicted by stream gradient and BFC width, and that the volume and size of LW also corresponded to stream width. In comparison, we found that channel gradient, wet width, rock-plane bedding and channel confinement appeared to be important factors for predicting the abundance of LW and LWJs in the Porcupine Mountains. The importance of geomorphic variables for predicting the abundance of LW in our study, even though the range of environmental conditions was different in our study from that evaluated by Wing and Skaugset (2002), supports the assertion of Wing and Skaugset (2002) that the most important factor related to LW abundance is the geomorphology of stream reaches and surrounding landscapes.

With regard to LWJs, previous studies have identified that LWJs typically develop in certain locations, and that LWJ configuration often reflects geomorphic setting or location in the watershed (e.g. Zimmerman *et al.*, 1967; Keller and Swanson, 1979; Palik *et al.*, 1998; Wallerstein *et al.*, 2001; Abbe *et al.*, 2003). Our study in the Porcupine Mountains complements previous work by confirming that the size of pieces of LW in LWJs and the span of LWJs correspond to geomorphic attributes of the channel. In addition, geomorphic attributes that we found to correspond most strongly to LWJ attributes were similar to the predictive factors of channel geomorphology reported in the very complete evaluation of LWJ configuration by Abbe *et al.* (2003) following work by Abbe (2000).

Influence of riparian forests and stand age

Forest management also influences LW characteristics as it influences the types and amounts of wood available to the stream, riparian forest dynamics and hydrologic processes (Hedman *et al.*, 1996; Slaymaker, 2000; Boyer *et al.*, 2003). The size of pieces of wood relative to the size of the channel strongly influences the transport or retention of wood in the channel (Hilderbrand *et al.*, 1998; Abbe *et al.*, 2003). Harvesting riparian forests generally results in smaller LW in streams (Baille *et al.*, 1999; Elosegi *et al.*, 1999; Rot *et al.*, 2000; Slaymaker, 2000; Collins *et al.*, 2002), and repeated harvesting near streams can lead to decreased amounts of wood in streams (Hering *et al.*, 2000; Díez *et al.*, 2001). In contrast, some researchers have shown that logging may lead to increased wood in streams over the short term as slash is recruited to streams or as forest dynamics change (e.g. increased windthrow in riparian buffer strips along streams; Grizzel and Wolff, 1998; Baille *et al.*, 1999; Gomi *et al.*, 2001). However, there is evidence from the southern Appalachians that as forests recover from disturbance, in this case the loss of American chestnut (*Castanea dentata* (Marsh.) Borkh.), there may be a decline in the LW loadings in the stream system over the long term (Hedman *et al.*, 1996). We found that streams in the second-growth forests contained less volume of LW, and generally fewer pieces of LW in LWJ, than in old-growth forests in the Porcupine Mountains. Old-growth forests also contained more abundant conifers and overall larger trees than did second-growth forests, a trend also observed in the southern Appalachians (Hedman *et al.*, 1996), so the source-pool of wood in old-growth forest contained large potential LW likely to decompose slowly in streams (Hyatt and Naiman, 2001).

Imminent recruits represented wood that would enter the stream individually within a few years. The number of imminent recruits related only poorly to any LW or LWJ characteristics, showing that current individual inputs of LW do not represent the standing stock of LW (in and out of LWJs) in the stream, which is not surprising given the potential for mass inputs from slope failures, breakage of wood on entering the stream and long retention times of wood in streams (Hyatt and Naiman, 2001). Rot *et al.* (2000) reported that the diameter of LW in streams of old-growth forests in western Washington exceeded the diameter of trees in riparian forests. We found, however, that the diameter of riparian snags almost always exceeded the diameter of LW and LW in LWJs in the Little Carp River, and hypothesize that differences exist because of breakage of pieces when entering the river (leading to higher numbers of small-diameter pieces in the stream than out of the stream) coupled with fairly high retention of LW. Finally, we found that the percent of conifers in the riparian forest was higher than the percent of conifers in LW in the streams of old-growth forests while in many reaches in second-growth forest more conifer occurred in LW than occurred in the forest. Conifer in LW in second-growth forests, therefore, probably represents historical inputs.

Restoration implications

Bisson *et al.* (2003) reported a current trend of recognition that one prescription for the amount of LW to restore throughout a stream will not suffice. The need for more than one prescription for wood abundance is especially true for channels where forests and streams show longitudinal geomorphic discontinuities as they do in the Porcupine Mountains. Recognizing LW and LWJ characteristics that correspond to both large-scale and small-scale geomorphology will allow stream restoration practitioners to plan wood additions that create spatial and temporal variation typical of natural systems.

The results of our study show how variable LW and LWJ characteristics can be in old-growth ecosystems. Variability in LW and LWJ structure corresponding to combinations of landscape-scale and reach-scale geomorphology would best represent a system like the Little Carp River. Monitoring the success of restoration would also only be effective if large enough sections of river were evaluated to represent different settings of stream valley geomorphology. The patchy nature of streams with inherent complexity as shown by the streams in the Porcupine Mountains indicates some of the difficulty in planning direct manipulations of LW in streams to emulate natural processes and suggests that managing riparian forests to favor natural wood additions (passive restoration) is desirable from a practical standpoint where stream geomorphology remains intact enough to self-regulate LW distribution (Collins and Montgomery, 2002; Bisson *et al.*, 2003; Boyer *et al.*, 2003).

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