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The geomorphic function and characteristics of large woody debris in low gradient rivers, coastal Maine, USA

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Abstract

The role, function, and importance of large woody debris (LWD) in rivers depend strongly on environmental context and land use history. The coastal watersheds of central and northern Maine, northeastern U.S., are characterized by low gradients, moderate topography, and minimal influence of mass wasting processes, along with a history of intensive commercial timber harvest. In spite of the ecological importance of these rivers, which contain the last wild populations of Atlantic salmon (*Salmo salar*) in the U.S., we know little about LWD distribution, dynamics, and function in these systems. We conducted a cross-basin analysis in seven coastal Maine watersheds, documenting the size, frequency, volume, position, and orientation of LWD, as well as the association between LWD, pool formation, and sediment storage. In conjunction with these LWD surveys, we conducted extensive riparian vegetation surveys. We observed very low LWD frequencies and volumes across the 60 km of rivers surveyed. Frequency of LWD ≥ 20 cm diameter ranged from 15–50 pieces km^{-1} and wood volumes were commonly <10–20 m^3 km^{-1}. Moreover, most of this wood was located in the immediate low-flow channel zone, was oriented parallel to flow, and failed to span the stream channel. As a result, pool formation associated with LWD is generally lacking and $<20\%$ of the wood was associated with sediment storage. Low LWD volumes are consistent with the relatively young riparian stands we observed, with the large majority of trees <20 cm DBH. These results strongly reflect the legacy of intensive timber harvest and land clearing and suggest that the frequency and distribution of LWD may be considerably less than presettlement and/or future desired conditions.

Keywords: Large woody debris; Stream channel; Riparian; Watershed; Habitat; Aquatic ecology

1. Introduction

An extensive literature has emerged in the past decade on the function and importance of large woody debris (LWD) in fluvial systems. From an ecological perspective, LWD serves a vital role in biogeochemical cycling (cf. Bilby, 2003) and is an important structural element in aquatic habitats, providing cover and increasing habitat complexity, with resultant effects on fish and aquatic invertebrate abundance and diversity (cf. Dolloff and Warren, 2003). Geomorphologically, LWD influences pool formation, frequency, and type (Keller and Swanson, 1979; Andrus et al., 1988; Bilby

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and Ward, 1991; Montgomery et al., 1995; Abbe and Montgomery, 1996; Gurnell and Sweet, 1998; Rosenfeld and Huato, 2003; Kreutzweiser et al., 2005) and is commonly associated with increased sediment storage (Thompson, 1995; May and Gresswell, 2003; Daniels, 2006), enhanced flow resistance (Marston, 1982; Assani and Petit, 1995; Shields and Gippel, 1995; Gippel et al., 1996; Manga and Kirchner, 2000; Curran and Wohl, 2003; Hygelund and Manga, 2003; Bocchiola et al., 2006; Manners et al., 2007), reduced sediment transport (Bilby and Ward, 1989; Nakamura and Swanson, 1993), and increased longitudinal variation of both channel depth and width (Montgomery et al., 2003).

Unlike watersheds in other parts of the U.S., little is known about the function of wood in New England rivers, especially in coastal Maine (Fig. 1). This is an important area ecologically, as rivers in this region possess the few remaining native runs of federally endangered Atlantic salmon (*Salmo salar*) in the U.S. (National Research Council, 2004). Late twentieth century wild runs of Atlantic salmon have been drastically reduced in coastal Maine. These declines have been associated with a wide array of marine, riverine, and terrestrial impacts including overfishing, predation, disease, watershed fragmentation by dams, and habitat loss/degradation (National Research Council, 2004). In the juvenile freshwater phase, it appears that overwinter survival is very low, and factors influencing overwinter success have a strong influence on overall population dynamics (Maine Atlantic Salmon Task Force, 1997; Kircheis, 2001; National Research Council, 2004; National Marine Fisheries Service and U.S. Fish and Wildlife Service, 2005). At this life-history stage, stream salmonids have a strong requirement for cover to provide protection from predators and adverse environmental conditions (Cunjak, 1988), and availability of LWD appears to increase overwinter survival in some circumstances (Roni and Quinn, 2001). However, little information exists on the extent to which LWD provided this function in Maine Atlantic salmon streams.

These coastal watersheds have been heavily affected by historical and contemporary land use disturbance (Lorimer, 1977), especially hillslope and riparian logging that have likely reduced LWD recruitment. For example, based on sawmill surveys of white pine production in Bangor, Maine, from ca. 1830 to 1870 that generated ~8.5 million m^3 of sawtimber, Wilson (2005) estimated a presettlement standing volume of white pine of ~14.1 million m^3 in the Penobscot watershed. Current estimates for a similar region indicate that the presettlement standing volumes of white pine may have been at least three times greater than contemporary large pine volumes in Maine's eastern and northern regions (Wilson, 2005). More recently, harvest volumes have significantly declined, with corresponding increases in stand basal areas and individual tree sizes (USDA Forest Service, 2004). These trends are likely to be particularly manifested, both currently and in the future, in riparian zones because of recent regulation governing the intensity and extent of timber harvest within these zones (Maine Department of Environmental Protection, 2006). However, because of intrinsic lags between forest recovery and the stochastic processes that govern LWD recruitment, LWD recovery lags forest recovery by centuries (Bragg, 2000; Benda et al., 2003). These considerations suggest that current LWD levels are likely to be low, that LWD may have had an important effect on streams that is currently lacking, and that LWD abundance will increase in the future under existing management practices and regulations. However, we currently lack quantitative information on the current abundance, distribution, and functional role of LWD in these systems and on the characteristics of the riparian forests that will serve as LWD sources.

To establish baseline conditions for LWD distribution, abundance, and functional role in Maine rivers, we conducted extensive LWD and riparian forest surveys in seven major coastal Maine river systems (Figs. 1 and 2). We used these data to address four major questions: (i) what is the contemporary frequency, volume, and size distribution of LWD; (ii) how does LWD orientation, in-channel location, and geomorphic role vary longitudinally within and among basins; (iii) do watershed scale controls (such as gradient, flow, or sinuosity) explain the frequency, orientation, and broader distribution of LWD; and (iv) what is the relationship between riparian forest and LWD characteristics? Our primary goal is to contribute to a broader understanding of the role of LWD in reforesting low gradient watersheds where information in the literature is commonly lacking.

2. Geomorphic and geologic setting

Fluvial properties of coastal and Downeast Maine rivers are strongly controlled by geologic processes where, for example, lithologic variation and bedrock strike, in combination with sediment supply from Pleistocene deposits, largely control the quality and frequency of salmon rearing and spawning habitat (Fisher et al., 2006). While there is evidence for early Paleozoic collisional events in northern and western Maine (i.e., Penobscottian and Taconic orogenies), the dominant structural grain of the bedrock and the distribution of metamorphism and plutonic rocks in the state is the result

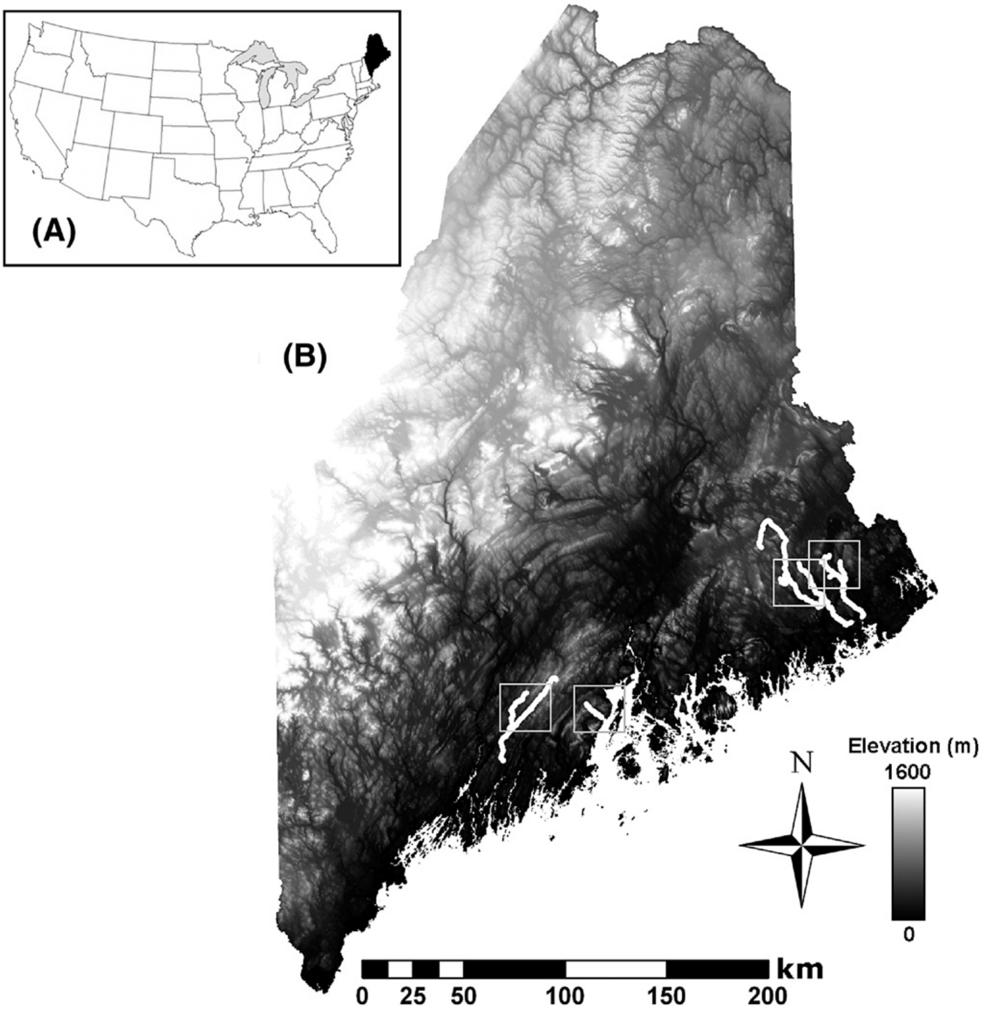

Fig. 1. (A) Map of the United States showing location of Maine in black. (B) Digital elevation model of Maine showing the surveyed tributaries and their mainstems in white with gray boxes delineating shaded relief drainage maps in Fig. 2.

of the Silurian–Devonian Acadian orogeny (Osberg et al., 1989). Coastal Maine is essentially characterized by NE-trending belts of strongly deformed and metamorphosed Paleozoic sedimentary (mostly) and volcanic rocks that have been intruded by a wide variety of plutons ranging in age from Ordovician to Cretaceous (although most are Silurian–Devonian).

The legacy of Pleistocene glaciation still has a pronounced influence on channel properties. Ice covered during the Last Glacial Maximum (LGM), coastal Maine contains various Pleistocene deposits including well-sorted fluvial–glacial deposits such as eskers and kames, poorly sorted till and morainal deposits, and fine- and coarse-grained marine deposits following post-glacial marine transgression (Smith, 1985; Stone and Borns, 1986). Moreover, channel gradient and the magnitude of and variation in valley confinement are largely controlled by the presence and type of Pleistocene deposits (Fisher et al., 2006).

3. Methods

Under the direction of the Maine Atlantic Salmon Commission and the U.S. Fish and Wildlife Service — Gulf of Maine Coastal Program, over 60 km of river length was inventoried for LWD between 2004 and 2006 in coastal Maine following the protocols outlined by Schuett-Hames et al. (1999) where each piece of wood ≥ 10 cm in the broader channel and riparian zone was identified and measured. Survey teams documented the total length and diameter of each piece of LWD for seven different watersheds; and they further measured and identified the proportion of the total length of LWD existing in each channel zone (Fig. 3), its orientation

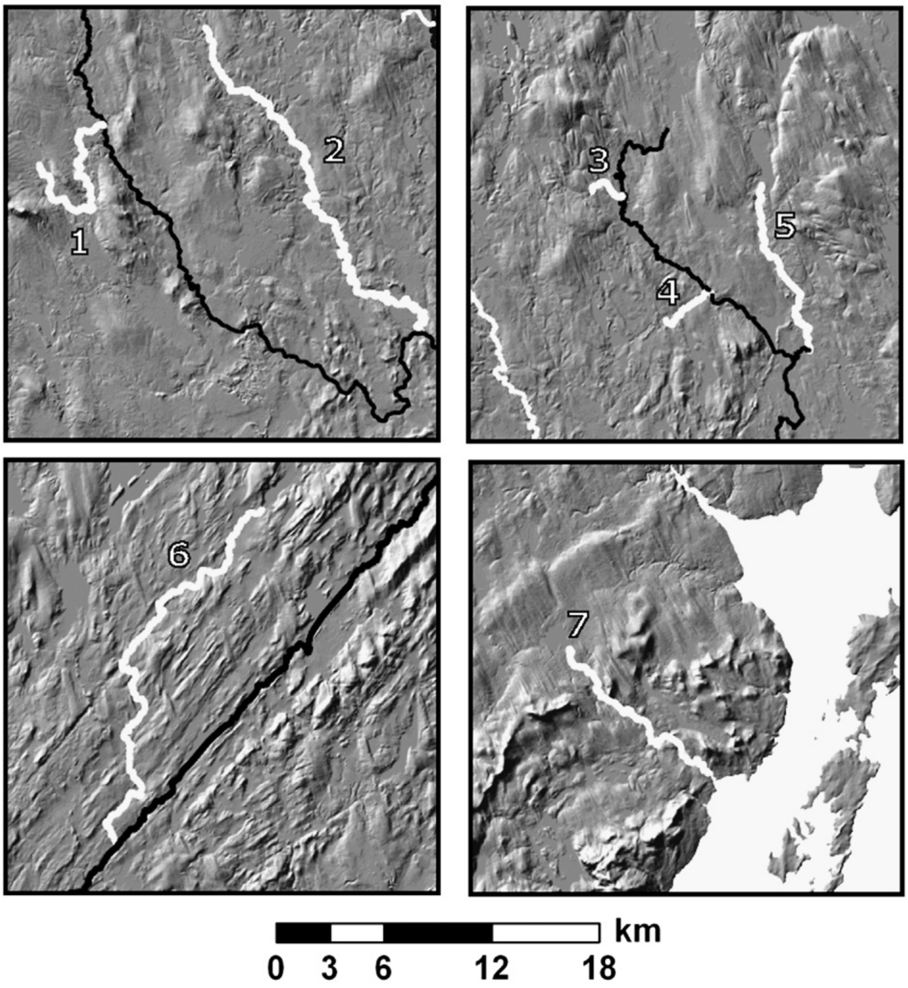

Fig. 2. Shaded relief maps of surveyed tributaries (white) and mainstem rivers (black). 1 — Crooked River; 2 — Old Stream; 3 — Beaverdam Stream; 4 — Seavey Stream; 5 — Northern Stream; 6 — West Branch of the Sheepscot River; 7 — Ducktrap River.

(Fig. 4), and type of wood (softwood, hardwood, or unknown). For LWD jams, the total number of pieces in each jam was tallied, and the size, position, and orientation of key pieces in each jam were measured. Moreover, for each piece of LWD or for each LWD jam, survey teams determined whether the piece or jam was associated with either sediment storage or with pool formation. Lastly, for each identified piece of LWD, survey teams took GPS readings to be subsequently incorporated into a GIS database. The State of Maine has readily available 30-m DEMs (http://seamless.usgs.gov) that were used to determine longitudinal profiles, calculate channel gradients, and determine cumulative watershed drainage area.

Watersheds were selected primarily on the basis of their importance to Atlantic salmon conservation and restoration efforts. The goal was to characterize LWD in salmon rearing waters (generally 3rd–4th order rivers draining between 20 and 200 km^2) across a wide spatial scale. The reaches surveyed spanned known Atlantic salmon rearing habitat (primarily riffles and runs with $>1\%$ slope) but were not limited to these habitats. All of the stream lengths were surveyed without regard to habitat type once the extent of the reach was established. Survey reaches typically went from major access point to major access point, although in some cases the survey began or ended at a critical biological location, and we opted to survey more streams rather than survey longer and longer sections of the same stream.

In conjunction with LWD surveys, we measured riparian forest conditions along study reaches. At 100-m intervals along LWD survey reaches we established belt transects for vegetation sampling. Each transect was 5 m wide and 20 m long starting at bankfull width and

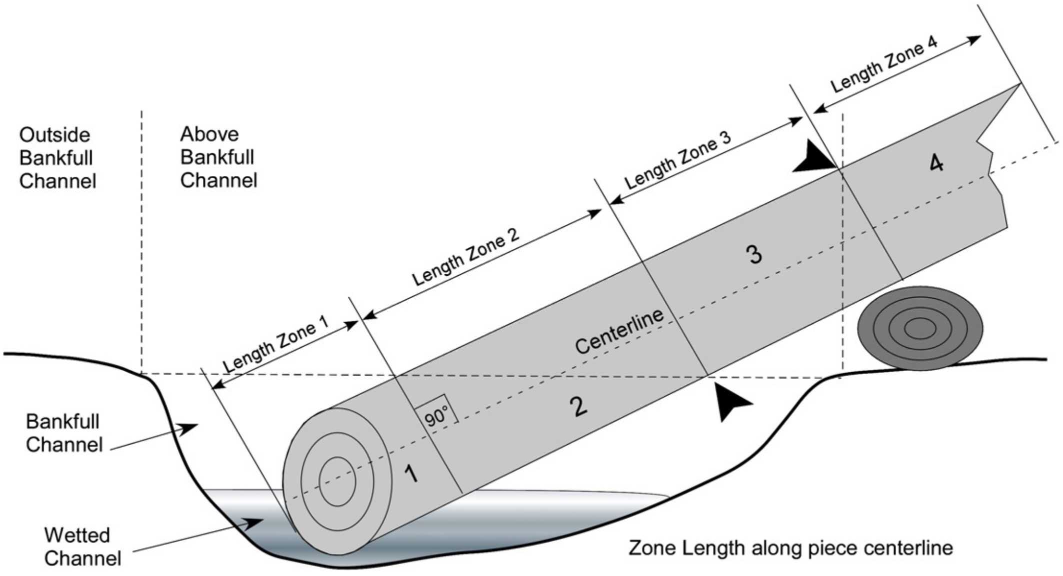

Fig. 3. Location of LWD by zone. For LWD frequency, this documents how much wood exists in a particular zone and how many zones it spans across. For wood volume, this accounting represents how much of each segment of wood exists in each zone. Adapted from Schuett-Hames et al. (1999).

extending both river left and right at each 100-m interval The bearing of the line and the transect slope were recorded. All standing trees (living and dead) within the transect having a diameter at breast height (DBH) >12 cm were tallied. Species, DBH and distance from bankfull width were recorded. Along with the species (if known), DBH and distance from bankfull width, the decay stage was recorded using the established protocol. Both upstream and downstream photos were taken from the center of the channel at each transect.

Numerous U.S. Geological Survey (USGS) stream gages exist across the region and these provided the base data for flood frequency analyses. For each station, the annual peak flood series was used to calculate the magnitude of the 2-yr bankfull discharge using the log Pearson Type III method. These flow data were used in conjunction with measured channel properties to calculate the bankfull channel dimensions for an array of local gages ranging in drainage area from 37 to 1190 km^2 across coastal Maine.

Reaches were delineated for each watershed based primarily on variations in gradient (Grant and Swanson, 1995; Bisson and Montgomery, 1996). For each reach, we determined watershed and reach-scale variables, including channel gradient from DEMs, reach length, reach-averaged channel width, sinuosity, and the drainage area and elevation at both the upstream and downstream ends of the reach. We then tested whether these variables were associated with the abundance (pieces km^{-1}) of all LWD and of LWD pieces ≥20 cm DBH, using General Linear Models (GLMs) with river, slope, drainage area, sinuosity, and bankfull width as predictors. Further, we used χ^2 tests to determine whether the distribution of LWD over size classes differed significantly among orientations and

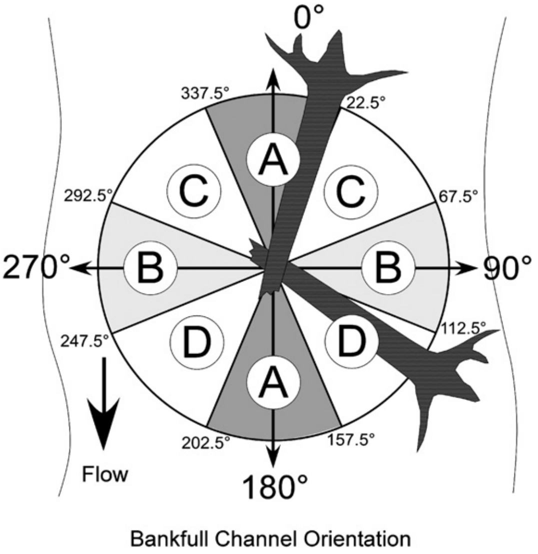

Fig. 4. Orientation of LWD by zone. Zone A is parallel to flow irrespective of rootwad orientation. Zone B is oriented perpendicular to flow. Zone C is oblique to flow with rootwad oriented upstream, while Zone D is LWD oriented oblique to flow with rootwad oriented downstream. Adapted from Schuett-Hames et al. (1999).

Table 1
Site characteristics for sampled watersheds (see Fig. 1 for locations)

River	Total watershed area (km^2)	Watershed area at survey beginning (km^2)	Watershed area at survey end (km^2)	Total river length (km)	River length sampled (km)
Old Stream	285.9	60.9	153.0	44.0	18.40
Ducktrap	94.2	20.7	94.2	15.4	15.40
Northern Stream	84.3	37.1	75.0	16.43	9.50
Crooked River	46.1	43.2	46.1	22.0	2.03
Seavey Stream	46.8	29.3	45.0	12.0	3.96
West Branch Sheepscot	132.7	35.8	41.8	33.7	2.75
Beaverdam Stream	34.7	N/A	N/A	12.0	6.72

positions. Lastly, several pieces of buried wood were collected in the Ducktrap River and sent to Beta Analytic, Inc. for radiocarbon dating. This buried wood comes from the base of streambanks at modern water level in a section of the Ducktrap River where ~50 pieces of buried logs exist along a 300 m section of the mid-valley.

4. Results

Based on the extensive river surveys of seven watersheds, field teams measured ~5000 pieces of LWD in coastal Maine (Table 1). In general, LWD physical dimensions were consistent across watersheds, averaging between 5 and 6.2 m in length and between

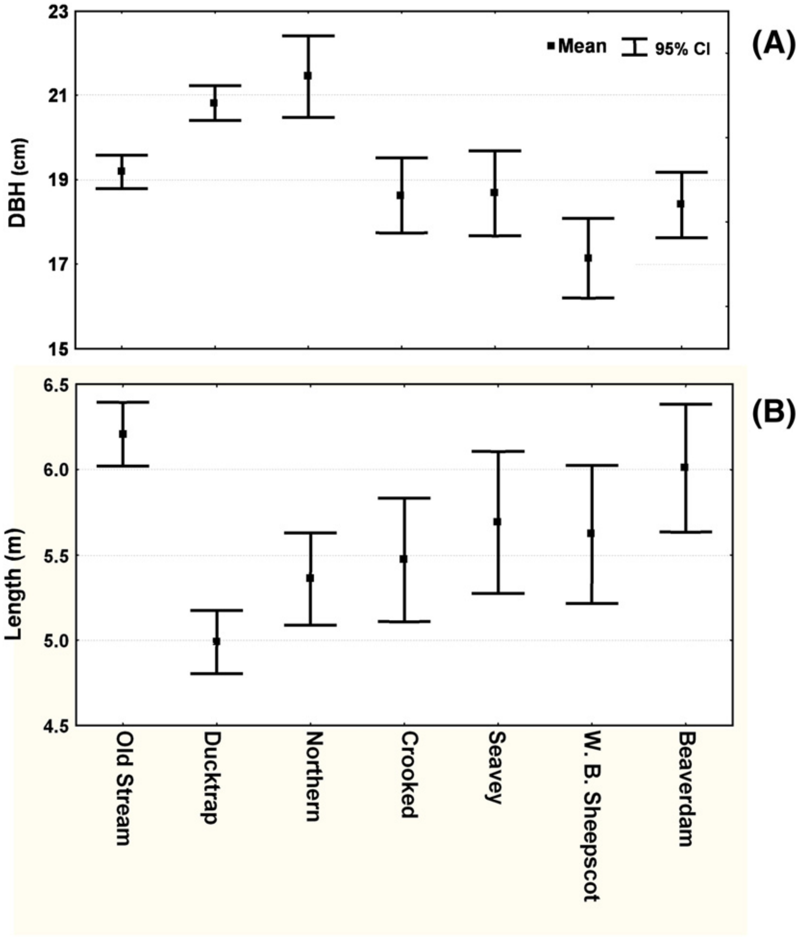

Fig. 5. Box plots of (A) LWD diameter by basin and (B) LWD length by basin. Sequence of basins goes from a large watershed size on the left to decreasing watershed size based on maximum drainage area of surveyed reach.

Table 2
Variation in LWD tree type by watershed

Watershed	% conifer	% deciduous	% unknown
Old Stream	45.9	21.8	32.3
Ducktrap	33.4	40.2	26.4
Northern	36.2	18.9	45.0
Crooked	58.7	23.4	17.9
Seavey	54.9	28.6	16.6
W.B. Sheepscot	55.7	37.6	6.7
Beaverdam	41.0	43.9	15.2

17.1 and 21. 4 cm in diameter (Fig. 5). Moreover, most of the LWD is coniferous except for the Ducktrap River which is predominantly deciduous (Table 2). We will first discuss the frequency and distribution of LWD by piece and by volume. This will be followed by data on orientation and relation to channel zones. Lastly, we present the analysis of watershed controls on LWD distribution.

4.1. LWD frequency

On average, the frequency of LWD across all the drainages is remarkably low, and this is consistent whether considering total pieces (all pieces ≥ 10 cm), medium and large (≥ 20 cm) pieces, or just large (≥ 50 cm) pieces. The total number of pieces of LWD of all sizes and in all zones range from 175 to 1550 pieces per basin (Fig. 6), but most of these are small (10–20 cm). The total number of pieces does not necessarily scale with basin size; Old Stream and the Ducktrap River had the greatest number of pieces, but Northern Stream, despite having 10 of its 16.5-km length surveyed, still has relatively little wood along its length (<300 pieces) as does the ~ 2-km surveyed stretch of the West Branch of the Sheepscot. Pieces of LWD ≥ 20 cm range from 56 to 750 per basin, generating a frequency of 14–55 pieces of LWD km^{-1} (Fig. 6). Again, the frequency of wood does not necessarily trend with basin length as the Ducktrap River has a much greater frequency of LWD ≥ 20 cm than rivers its size or smaller (Fig. 6). For all basins, there is a virtual absence of large pieces of LWD, with most drainages having less than 1 piece ≥ 50 cm diameter km^{-1}. The small size of instream and riparian LWD reflects the small size of riparian forest trees, with the large majority of stems <20 cm DBH (Fig. 7A). These riparian forests were typical Acadian forest assemblages, reflecting a mixture of spruce–fir and northern hardwood elements (Fig. 7B), and varied little among watersheds. Balsam fir (*Abies balsamifera*) was the most abundant tree (>40% of trees surveyed). In terms of basal area, red maple (*Acer rubrum*) was dominant, and white pine (*Pinus strobus*) was the largest tree species.

Almost all of the wood (60–80%) is located in the immediate low-flow channel zone (Fig. 8). Very little of

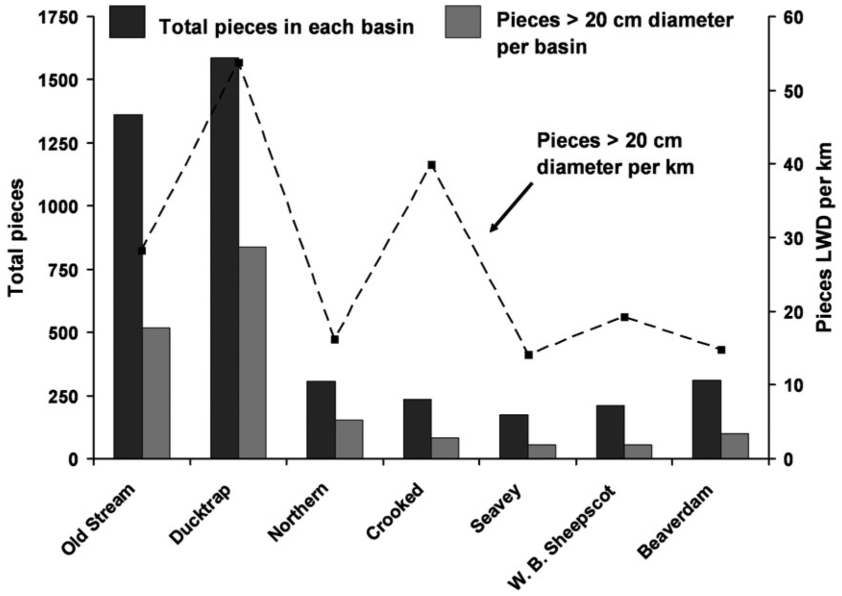

Fig. 6. Total pieces of wood by stream (left y axis) ≥ 10 cm (black bar) and for wood ≥ 20 cm (gray bar) in diameter and frequency of LWD ≥ 20 cm km^{-1} (dashed line and right y axis). Sequence of basins goes from a large watershed size on the left to decreasing watershed size based on maximum drainage area of surveyed reach.

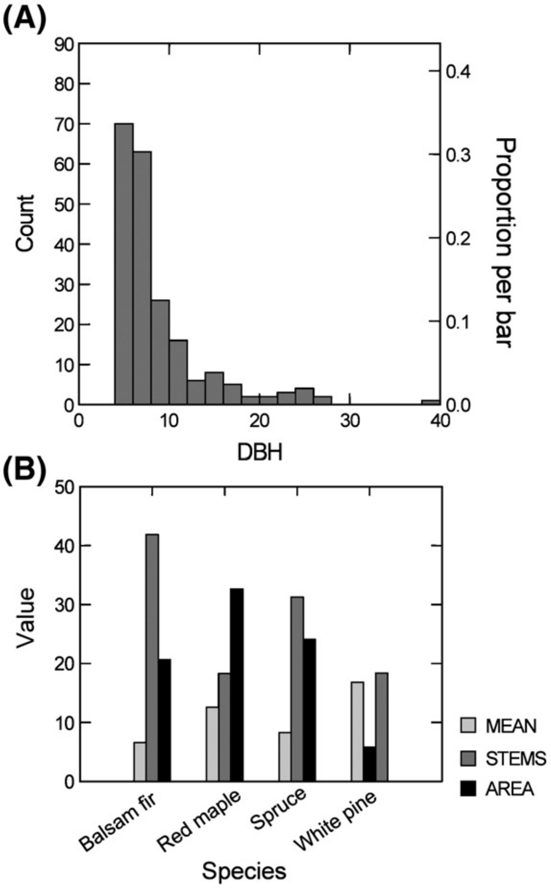

Fig. 7. (A) Composite DBH results of riparian surveys across sample plots of watersheds in coastal Maine. (B) Size and abundance of dominant tree species encountered in riparian surveys in coastal Maine. 'Mean' = mean DBH (cm), 'Stems' = percentage of total individual trees belonging to the species, 'Area' = percentage of total basal area accounted for by the species.

this wood spans across other zones, and when it does, it is primarily restricted to within the bankfull channel as wood spanning across zones 1–3 or 1–4 is rare (Fig. 8). As basin size decreases there is an associated increase in the number of pieces that span into other zones, but again it is dominated by wood spanning zones 1–2 (immediate low-flow channel to within bankfull channel).

4.2. LWD volume

For some ecological functions, LWD within the channel and riparian zone is best expressed in terms of volume. For the drainages in coastal and Downeast Maine, most of the wood volume is in the immediate low-flow in-channel zone (zone 1), especially for the larger basins (Fig. 9) where upwards of 60% of the total LWD volume occurs in the immediate low-flow channel. For the smaller basins, such as Seavey Stream and Beaverdam Stream, a greater percentage of wood volume is in other zones, especially zone 2 (Fig. 9) and a greater proportion of wood volume exists on adjacent floodplain and riparian surfaces (zone 4). Like wood frequency, the total volume of wood per km is very low, ranging from 10 to 60 m^3 km^{-1} (Fig. 9).

4.3. LWD orientation

LWD orientation controls the potential for flow convergence and divergence ultimately controlling pool formation and sites for sediment storage. For watersheds in coastal Maine, the dominant orientations for all pieces of LWD, irrespective of size, are either parallel to flow (orientation A) or oriented oblique to flow with rootwads pointing upstream (orientation C) (Figs. 4 and 10). Except for the West Branch of the Sheepscot, larger rivers tend to have most of the LWD oriented parallel to flow, generally approaching 40–50%. As basin size decreases, an increasing tendency exists for the wood to be more oblique to flow with values approaching 30–35% such as for both Beaverdam Stream and Seavey Stream. In general, large basins tend to be more unidirectional for LWD orientation, while smaller basins tend to be more multidirectional.

4.4. Geomorphic function of LWD

In many regions, LWD has an important role in pool formation and in sediment storage. In contrast, for coastal Maine watersheds pool formation associated with LWD is limited (Fig. 11), with the exception of the Ducktrap River (~12% of LWD associated with pools). The importance of LWD in sediment storage is more apparent with 5–20% of the wood serving some function of storing sediment, especially for Old Stream and Crooked River (Fig. 11). LWD in the smaller streams seems to be less important in storing sediment compared to the larger streams.

4.5. Reach-scale spatial distribution of LWD

LWD was patchily distributed in some of the surveyed rivers. This is especially evident along the 14-km reach of the Ducktrap River where ~75% of the 1550 pieces of LWD were found along a 4-km section (Fig. 12) corresponding to an extensive flat water section that is controlled by the bedrock strike. In contrast, along an 18-km reach of Old Stream (Fig. 13), LWD was distributed relatively evenly, irrespective of

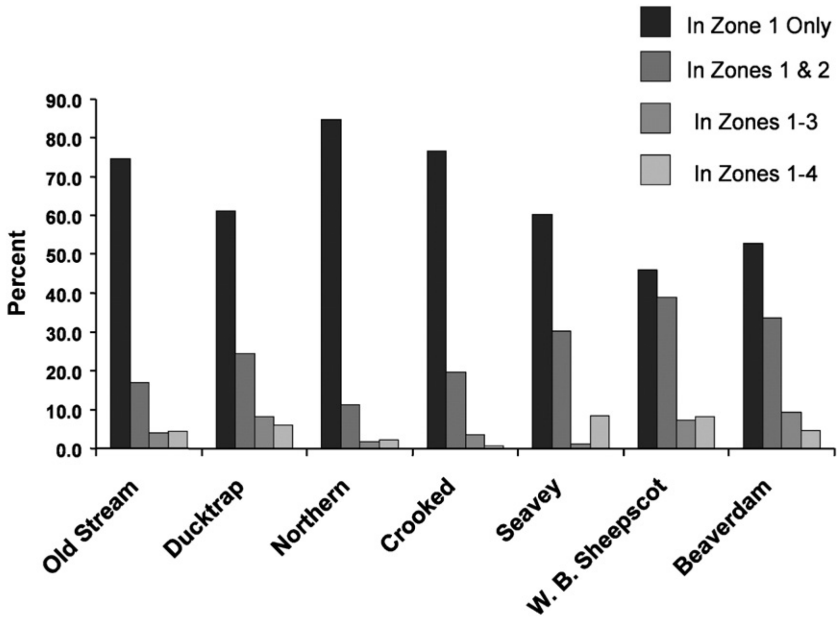

Fig. 8. Primary location of LWD by zone. Black bar represents LWD in zone 1; dark gray represents LWD spanning zones 1 and 2; medium gray bar represents LWD spanning zones 1–3; and light gray represents LWD spanning zones 1–4 (see Fig. 2 for location of zones). Sequence of basins goes from a large watershed size on the left to decreasing watershed size based on maximum drainage area of surveyed reach.

channel gradient or lithologic control. Overall, watershed and reach-scale variables were poor predictors of LWD distribution. There were no significant effects of river or significant interactions between river and slope, drainage area, sinuosity, or bankfull width on LWD pieces km^{-1} or pieces m^{-2} (all F values <2, all p values >0.2). Even after discarding these terms, subsequent models accounted for a very low proportion

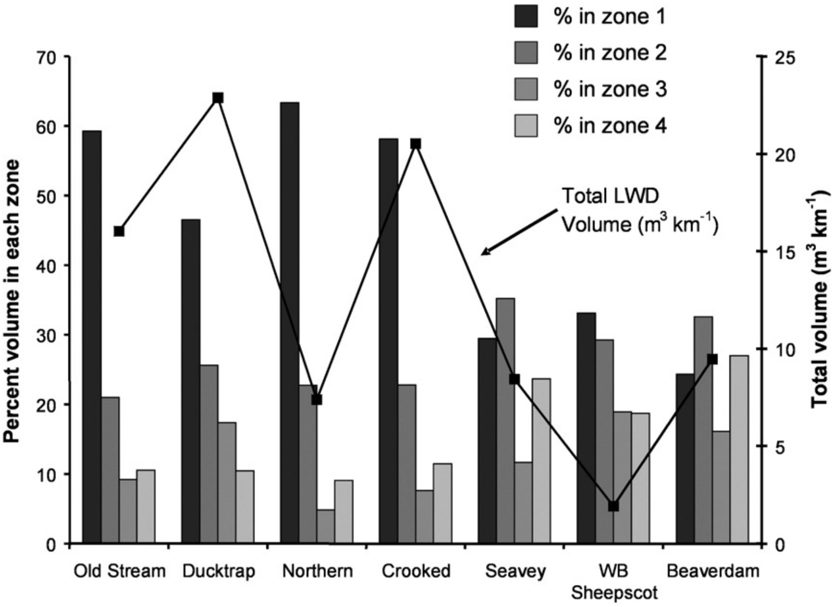

Fig. 9. LWD volume by percent in each zone. The black bars represent the LWD volume just in zone 1; the dark gray bar represents the LWD volume just in zone 2; the medium gray represents the LWD volume just in zone 3; and the light gray represents the LWD volume just in zone 4 (see Fig. 2 for location of zones). Sequence of basins goes from a large watershed size on the left to decreasing watershed size based on maximum drainage area of surveyed reach.

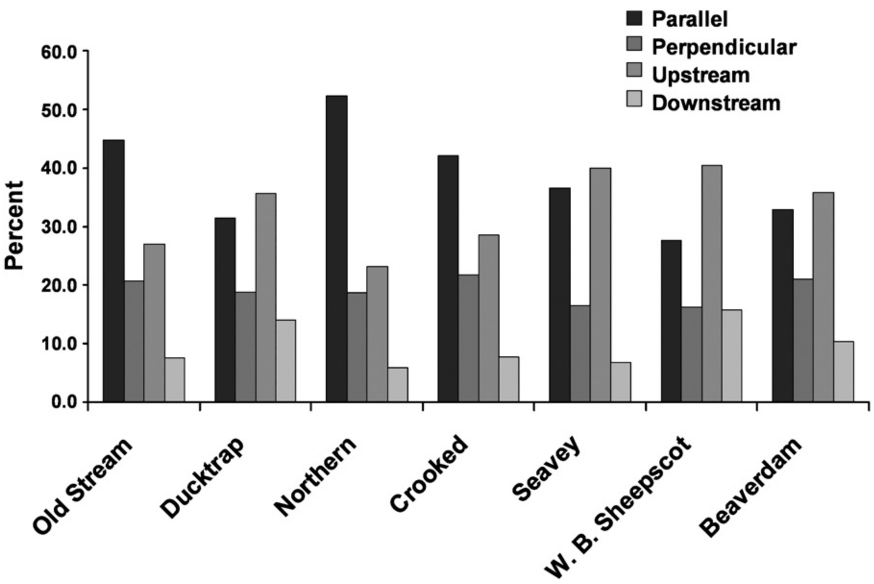

Fig. 10. Spatial orientation of LWD by percent. The black line is percent of LWD oriented parallel to flow; the dark gray bar is the percent of LWD oriented perpendicular to flow; the medium gray bar is percent LWD oriented oblique to flow with rootwad pointing upstream; and the light gray bar is the percent of LWD oriented with rootwad oriented downstream (see Fig. 3 for orientations). Sequence of basins goes from a large watershed size on the left to decreasing watershed size based on maximum drainage area of surveyed reach.

of the variation in LWD distribution (<15%) with no significant main effects or interactions (all p values > 0.2). In addition, while it appears that a somewhat higher proportion of large pieces were in stable orientations compared to small pieces (Fig. 10), differences in LWD distributions by size and orientation were not significant ($\chi^2 = 1.83$, $p = 0.176$).

4.6. Characteristics of LWD jams

Besides the metrics associated with individual pieces, we also categorized and measured LWD features related to debris jams. The number of jams varies from one to 21 across the drainages, which corresponds to a general frequency of ~1 jam km^{-1} (Table 3), although there is

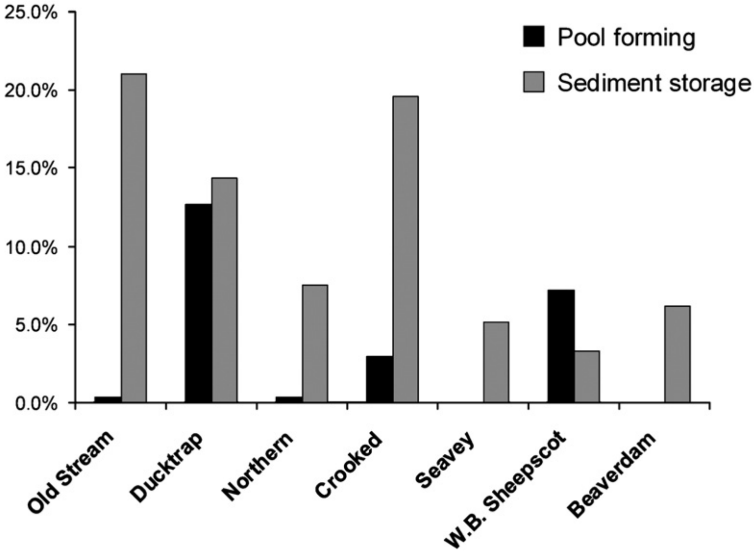

Fig. 11. Percent of all LWD associated with pool formation and with sediment storage. Sequence of basins goes from a large watershed size on the left to decreasing watershed size based on maximum drainage area of surveyed reach.

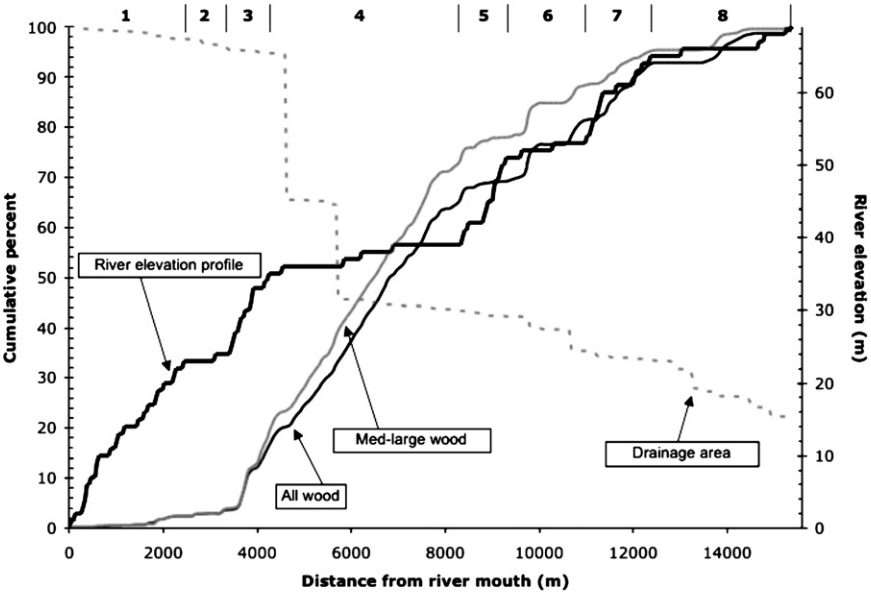

Fig. 12. Cumulative accumulation of all wood ≥ 10 cm (black line) and ≥ 20 cm (dark gray line) on the Ducktrap River by longitudinal profile (thick black line), reach (by gradient; see segment number at top of graph), and cumulative drainage area (stippled gray line).

one major outlier, Crooked River, that has 5.4 jams km^{-1} and one minor outlier, West Branch of Sheepscot, that only has one jam along its 2.75 km surveyed reach. For Crooked River, the surveyed reach occurs in the lower 2 km of the watershed where high sinuosities exist and channel gradients are quite low. The remaining watersheds (other than the West Branch of the Sheepscot) tend to have generally similar frequencies irrespective of length surveyed or location of the survey within the watershed. Similarities also exist for the average number of pieces within each debris jam (~ 10–16 jams^{-1}) and in the dominance of small pieces (10–20 cm diameter), which represent ~65% of all the pieces in the jams with the remaining 35% represented by medium-sized pieces (20–50 cm). Although previous research documents the important geomorphic function

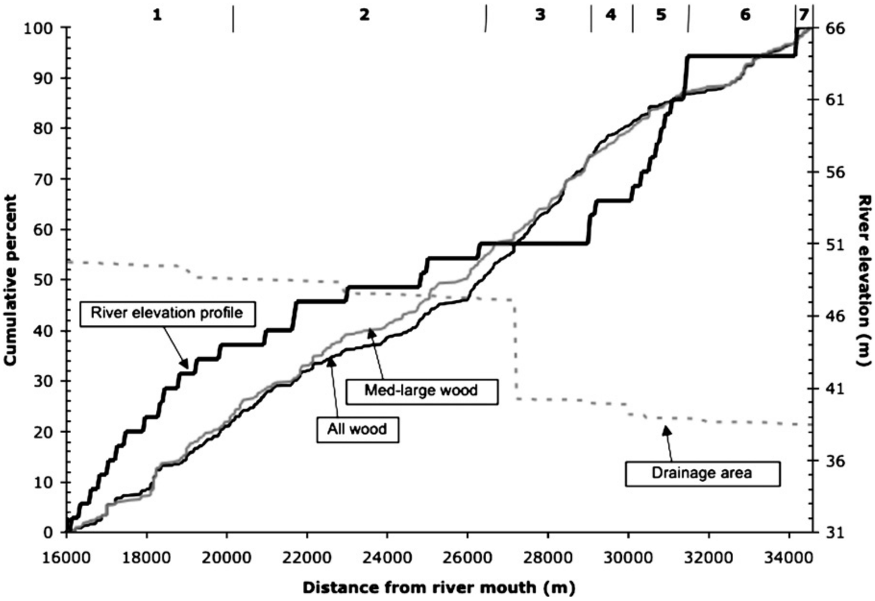

Fig. 13. Cumulative accumulation of all wood ≥ 10 cm (black line) and ≥ 20 cm (dark gray line) on Old Stream by longitudinal profile (thick black line), reach (by gradient; see segment number at top of graph), and cumulative drainage area (stippled gray line).

Table 3
LWD characteristics in jams

River	Total # of jams	Jams km^{-1}	Average # of pieces per jam	Standard deviation	Percent small pieces in jam	Percent medium pieces in jam	Percent large pieces in jam	Percent of jams that are pool forming
Old Stream	21	1.14	15.14	5.8	59.95	40.05	0.00	9.5
Ducktrap	16	1.03	16.88	6.7	62.22	37.41	0.37	62.5
Northern	11	1.16	14.55	6.5	68.34	31.66	0.00	0.0
Crooked	11	5.42	12.72	2.2	63.52	36.48	0.00	18.2
Seavey	3	0.76	15.67	4.5	52.46	47.54	0.00	0.0
W.B. Sheepscot	1	0.36	10.00	N/A	70.00	30.00	0.00	0.0
Beaverdam Creek	6	0.89	14.67	7.1	69.84	29.55	0.62	16.7

of LWD jams (cf. Abbe and Montgomery, 1996, 2003), very few of the LWD jams in Downeast Maine are associated with pools of any kind (Table 3) except for the Ducktrap River where 10 of the 16 jams are associated with pools, but this contrasts with the other rivers which have limited pool formation associated with LWD jams.

5. Discussion

Within the broader watershed and regional context, these results point to the low abundance and limited geomorphic significance of LWD in coastal and Downeast Maine. From a broad perspective, the most salient result of this cross-watershed analysis indicates that there is limited wood in coastal Maine watersheds and that the LWD present is extremely small both in terms of piece size and total volume. The frequency of wood is remarkably limited with values on the order of 15–50 pieces ≥ 20 cm km^{-1}, and essentially no pieces >50 cm in diameter. The lack of wood in general and the lack of large wood specifically are likely due to several different factors. Lacking rugged topography and high relief, hillslopes in coastal Maine are less likely to contribute LWD, a dominant recruitment mechanism in western U.S. watersheds (cf. May and Gresswell, 2003). In Maine, adjacent hillsides are generally thickly mantled, well-drained Pleistocene deposits lacking the frequent contribution of debris flows or other mass wasting processes that provide LWD to stream channels. Moreover, because of the regional geology most river channels flow along a continuous NW–SE strike with limited sinuosity, and many streambanks contain coarse-textured fluvioglacial sediments that essentially armor the banks, preventing lateral migration and LWD recruitment via bank erosion. LWD frequency and volume in Maine coastal rivers were also unassociated with watershed and reach-scale variables that generally exert considerable control on LWD dynamics (cf. Dufour et al., 2005). This lack of a relationship may, in part, be due to overall low LWD frequencies, which limit the statistical power of predictive models. However, these findings may also indicate that LWD recruitment and distribution are dominated by local factors such as individual tree mortality from small-scale disturbances such as wind or ice damage, coupled with small-scale geophysical factors such as local bank failure.

The geomorphic limitations on LWD recruitment are exacerbated by local forest conditions. Riparian surveys indicate that most of the trees in the riparian zone are similarly small having an average diameter <10 cm (Fig. 7A). This lack of large wood results in part from the legacy of nineteenth and twentieth century logging, along with current timber harvest in these watersheds, in which industrial timberlands still have a large ownership. Thus, even when the stream has the ability to recruit wood, most of this wood is small because of the immature riparian forest stands. Given current restrictions on riparian logging (Maine Department of Environmental Protection, 2006), increased future tree size should increase the availability of stable LWD in channels and riparian zones.

The small size of this LWD has important ecogeomorphic consequences. At a large-scale level, it tends to have limited geomorphic function, such as pool formation or sediment storage (Fig. 11). The lack of pool formation results, of course, from the limited size of the existing LWD but also because of its constrained geometry and orientation. Pool shape, magnitude, and occurrence result not only from the presence of LWD but also from its ability to exert a first-order control on flow convergence (Montgomery et al., 1995). For coastal Maine, very little of the LWD is stable because of its small size (Fig. 6): it exists primarily in the immediate low-flow channel (Fig. 8), does not span across multiple zones (Fig. 8), and is oriented primarily parallel to flow (Fig. 10). The combined effects of this geometry means that the existing LWD lacks the appropriate size, geometry, and overall stability to create either dammed backwater pools or deep scour pools associated with flow convergence.

Table 4
Channel dimensions at the 2-yr bankfull discharge

River	Drainage area (km^2)	Q_2 (m^3 s^{-1})	Bankfull width (m)	Bankfull depth (m)	Ratio of bankfull depth to mean LWD diameter[a]
Machias River at Whitneyville	1186.22	167.54	54.41	3.27	16.37
Narraguagus River at Cherryville	587.93	110.26	39.25	1.75	8.77
Sheepscot at N. Whitefield	375.55	54.65	23.09	1.25	6.23
Pleasant River at Epping	156.95	22.17	23.10	1.14	5.69
Old Stream near Wesley	75.37	12.24	19.34	0.65	3.23
Ducktrap River at Lincolnville	37.30	10.91	10.43	0.87	4.33

Calculated bankfull discharges (Q_2) and channel dimensions for channel cross sections at USGS stream gages in coastal Maine (the last column presents the ratio of bankfull depth to the mean diameter to estimate potential entrainment of wood by bankfull discharges).

[a] Assumes mean LWD diameter = 0.2 m.

The small size of the wood indicates that localized hydraulics control its position, geometry, and stability. Recent research (Braudrick et al., 1997; Braudrick and Grant, 2000, 2001) has shown that the stability of wood, and thus its localized importance in pool formation, relates to either its ability to be channel spanning or transportable, with the former controlled primarily by LWD length and the latter controlled by the combination of wood characteristics (e.g., density, diameter, etc.) and hydraulic characteristics (velocity, gradient, flow depth). Although no definitive threshold exists, wood begins to float and get transported when flow depths or velocity is sufficient to enhance buoyancy and entrainment — at flow depths approximating LWD diameter, depending upon presence/absence of rootwads, gradient, etc. (Braudrick and Grant, 2000). For Downeast Maine, flow depths at the bankfull, 2-yr flood greatly exceed average LWD diameters (~20 cm) by a factor of 4–12, depending on drainage area (Table 4). This striking difference between flow depths and LWD diameter across the range of drainage areas represented in our cross-basin stream survey indicate the high mobility of LWD for these watersheds, thus explaining the instream dominance of LWD within zone 1 (Fig. 8), the absence of multiple zone-spanning LWD (Fig. 8), and the dominance of wood oriented parallel to flow (Fig. 10).

6. Conclusions

The low wood volumes in coastal Maine underscore the long-term effects of land clearing, the lack of recruitable riparian wood of sufficient size, and commonly occurring entraining flows. No data exists for pre-European contact wood loadings, but wood was probably a common feature of channel and riparian settings pre-contact. Buried logs along the Ducktrap River evidence the common occurrence of in-channel wood during the prehistorical period where ~50 pieces of buried logs occur along a 300 m section (Table 5), yet prehistorical wood loadings are impossible to calculate nor are there any unimpacted “natural” settings nearby to establish base conditions. Moreover, contemporary comparisons are difficult as there is a dearth of literature on wood loadings from low gradient, humid climates of moderate relief. Comparison to other settings is further limited by a lack of comparable metrics as minimal uniformity of metrics or descriptors exist as some researches have differing diameter classifications, volume expressions, or measuring criteria.

Despite these limitations, it is possible to assemble a somewhat comprehensive analysis from the literature to permit some comparison. Cordova et al. (2007) compiled LWD regional frequency data for the US and found a range between 60 and 362 pieces of LWD km^{-1}. For various ecological, management, and land use reasons, the Pacific NW has the highest LWD mean frequency of ~362 pieces km^{-1}. LWD frequency was comparatively low elsewhere in the U.S. with midwestern streams having the second highest LWD frequencies of 326 pieces km^{-1} and streams in the eastern U.S. having strikingly lower mean LWD frequencies of 61–161 pieces km^{-1} (Cordova et al., 2007). Within this

Table 5
Radiocarbon dates from the Ducktrap River

Site ID	Latitude (°N)	Longitude (°W)	Conventional radiocarbon age (^{14}C yr BP)	Calibrated radiocarbon age (cal. AD)	1 Sigma calibrated radiocarbon age (cal. AD)	Lab ID
Duck_S#1_2006	44.3269	69.0572	870 ± 40	1180	1160–1220	Beta-218325
Duck_S#2_2006	44.3355	69.0764	250 ± 40	1650	1640–1660	Beta-219592

broader context, LWD frequencies in coastal Maine are even conspicuously lower, especially considering that we tallied LWD across all four channel zones, which was not necessarily the case in the studies presented by Cordova et al. (2007). The range of LWD frequencies in our seven-watershed analysis of 32–115 pieces of LWD km^{-1}, for all pieces ≥10 cm, and 14–53 km^{-1} for pieces ≥20 cm (Fig. 6) are some of the lowest reported values in the U.S.

These watersheds in Maine represent an interesting position in the range of types of watersheds studied globally. Although these watersheds in Maine do not have the topography nor the wood dimensions of those reported in watersheds in the Pacific NW, they do share a common focus in that they have been sites of intensive and fairly recent (within the last 200 years) commercial logging. In contrast to the long (>1000 year) history of agricultural conversion in lowland Europe, agriculture was and is a minor component of the land use history of these Maine watersheds. However, the low gradients manifested in these watersheds are approximate to those of lowland Europe, but the frequency of LWD in Maine of 32–115 pieces ≥10 cm km^{-1} still falls below documented wood loadings in similar geomorphic settings in Europe. For example Hering et al. (2000) found the frequency of LWD≥10 cm to be ~125 pieces km^{-1} in a 7 watershed cross-basin analysis in Central Europe while Comiti et al. (2006) reported LWD frequencies of 120–320 pieces of LWD≥5 cm km^{-1}. Similarly, LWD volumes in Maine correspond to the low values reported by Piégay and Gurnell (1997) and from a geomorphic perspective, LWD in Maine has a limited effect on pool formation (Fig. 11) as is commonly true of many low gradient French rivers (Piégay et al., 1999).

In essence, the diminished size and frequency of LWD across the 60-km reaches reported herein suggests that the legacy of logging and other land uses still exerts a significant control on LWD distribution and thus ecogeomorphic function. Given this legacy, and in the absence of appropriate reference conditions, it is difficult to understand the past, or predict the future ecogeomorphic role of LWD in coastal Maine systems. This understanding is critical to help guide forest and aquatic resource management in the region and will likely require an innovative combination of monitoring, modeling, and experimentation as these landscapes continue to change over time.

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