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SPATIAL PATTERN, DENSITY AND CHARACTERISTICS OF LARGE WOOD IN CONNECTICUT STREAMS: IMPLICATIONS FOR STREAM RESTORATION PRIORITIES IN SOUTHERN NEW ENGLAND

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ABSTRACT

Many streams have been modified so extensively that river managers do not have clear reference conditions to frame targets for stream restoration. Large woody debris (LWD) has long been recognized as an important influence on both geomorphic and ecologic processes in stream channels; however, there have been few studies of LWD dynamics in New England. Although this region is heavily forested today, the forest is predominantly young (70–90 years old) regrowth following a historical episode of severe deforestation. This study presents the results of an extensive census of LWD and associated stream characteristics in over 16 river kilometres of northeastern Connecticut streams and represents the first reported inventory of wood loading and sorting in Southern New England. Results of this study indicate that wood loading and jam frequencies in the study region are low: 2.5–17.8 and 0.5–5.51 per 100 m, respectively. Orientation of LWD is predominantly parallel to flow, an indication that these streams are not retaining organic matter or sediment, which has important geomorphic and ecologic implications. Results imply that stream recruitment of LWD is still lagging from the massive forest conversions of the 18th and 19th centuries. Given the low wood loadings observed in the study reaches, manual wood addition and continued forest regeneration would likely improve both habitat diversity and organic matter and fine sediment retention in these systems. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: large woody debris; spatial distribution; wood jams; in-stream wood; stream restoration

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INTRODUCTION

Across the globe, fluvial structures and dynamics have been severely altered by widespread land use changes and direct river channel modifications. These physical changes have resulted in reduced ecological function and habitat simplification (e.g. Meyer *et al*., 2007; Nilsson *et al*., 2007). In attempts to address this ecosystem decline, large financial investments are made in river restoration projects (e.g. Bernhardt *et al*., 2005). Yet, in many cases, an appropriate reference target for restoration is absent because of the spatial and temporal extents of the disturbances. Such is the case in Southern New England, where most streams have been radically impacted by human activities for such a long time that river managers do not have clear reference conditions with which to frame targets for stream restoration. This problem is particularly acute with respect to understanding what predisturbance wood loadings might have been for the region's streams. New England was settled extensively after colonization and underwent widespread deforestation driven by conversion of forests to agricultural production, particularly to support grazing animals. Hardwoods also were logged extensively to fuel smelting of iron and brass, and hemlocks were logged and stripped of their bark for use in tanneries. These landscape level pressures resulted in the virtual elimination of old growth forests in Southern New England. Since the widespread agricultural abandonment in the late 19th and early 20th centuries, natural reforestation began but did not produce forests similar to those of pre-European conditions because of continuing low-intensity forests disturbances such as logging (Fuller *et al*., 1998; Motzkin *et al*., 1999). New England forests today are a patchwork of young regrowth stands, with the oldest patches still well short of the natural senescence age for common species. In the absence of age-related mortality, wood introduction to streams and rivers is largely dependent on episodic disturbances such as windthrow events, ice storms and bank erosion. The wood load present in Southern New England streams today does not show advanced decay, suggesting a relatively recent introduction to the system. It remains unknown whether the streams were historically cleared by people at the same time the forests were or whether the pre-European in-stream wood load simply transported out or decayed in place.

Large woody debris (LWD) has long been recognized as an important influence on both geomorphic and ecologic

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processes in stream channels. In systems of all orders and gradients, LWD has been shown to affect pool-riffle spacing and forms, channel geometry and channel planform (Robinson and Beschta, 1990a, 1990b; Gregory *et al*., 1994; Ralph *et al*., 1994; Gurnell *et al*., 1995; Montgomery *et al*., 1995; Richmond and Fausch, 1995; Abbe and Montgomery, 1996; Friedman *et al*., 1996; Myers and Swanson, 1997; Gurnell and Sweet, 1998; Buffington *et al*., 2002). LWD also can cause variations in the longitudinal profile of both the stream bed and the water surface by storing sediment, creating scour pools, anchoring pools or scour holes in place, or creating deep backwater pools (Maser and Sedell, 1994; Gurnell and Sweet, 1998).

Large woody debris structures modify the storage and transport of materials including sediment, organic matter and solutes throughout the stream system (Keller and Swanson, 1979; Assani and Petit, 1995; Gippel, 1995; Gurnell and Sweet, 1998), creating areas of low shear stress (Fetherston *et al*., 1995), increasing the roughness of the bed, increasing the shear stress required to initiate motion of particles, providing up to half of the total flow resistance (Assani and Petit, 1995; Magna and Kirchner, 2000), accumulating and retaining sediment (Raikow *et al*., 1995; Thompson, 1995; Daniels, 2006), increasing bank stability (Keller and Swanson, 1979) and creating gravel bars (Montgomery *et al*., 2003). If LWD structures are removed from a system, sediment is released from storage, resulting in rapid increases in sediment transport and export out of the system (Smith *et al*., 1993; Ralph *et al*., 1994; Gurnell *et al*., 1995), potentially leading to geomorphic instability, channel widening, bank erosion (Gippel *et al*., 1996), erosion of fine sediments from gravel substrates, contraction of pool areas and an overall reduction in physical habitat complexity (Lisle, 1995).

The role that LWD plays in structuring the complexity of physical habitats in streams does not alone fully represent the extent of its importance to stream ecosystem functioning. The input of LWD is a major linkage between aquatic and terrestrial ecosystems. LWD is recognized as an important structural component as well as an important nutrient source for the continuum of nutrient spiraling in stream ecosystems (Bilby and Likens, 1980; Cummins *et al*., 1983; Lienkaemper and Swanson, 1987) with clear ties to increased biodiversity (Piégay *et al*., 1999; Beisel *et al*., 2000; Lester *et al*., 2007). LWD structures help retain coarse particulate organic matter (CPOM) in the stream system long enough to be processed rather than being flushed downstream in coarse form (Bilby and Likens, 1980; Lamberti *et al*., 1989; Maser and Sedell, 1994). Any reduction in the organic matter retention capacity of a stream is thought to reduce the system's capability to process CPOM and consequently reduce the energy base of the ecosystem (Bilby and Likens, 1980; Maser and Sedell, 1994; Gurnell *et al*., 1995).

The orientation and arrangement of wood in streams can influence its functional role in the system. For example, wood orientations that are parallel to flow likely have a greatly reduced retention function compared with orientations perpendicular to flow and can be an indication that the LWD is not retaining organic matter or sediment because of the lack of resistance and associated pool formation (Magilligan *et al*., 2008). Clustering of LWD into jams influences in-channel hydraulics and channel pattern more than individual wood pieces (Keller and Swanson, 1979), and the density of jamming has been shown to influence the longitudinal geomorphic pattern of the system (Wohl and Jaeger, 2009). Key jam member pieces are those that anchor the debris jam (Keller and Tally, 1979; Nakamura and Swanson, 1993) and are crucial for the development of jams. The presence of jams is thought to be an indicator of wood transport capacity, with a high density of jams suggesting a lower wood transport capacity (Wohl and Jaeger, 2009), and is representative of a balance of recruitment and downstream movement. Jams can substantially increase the residence time of finer organic material by wedging and burying pieces of wood (Gurnell and Sweet, 1998; Cadol and Wohl, 2011) and creating upstream backwater habitats that result in increased organic matter and sediment storage (Daniels, 2006).

The characteristic dimensions of the LWD found in a given fluvial system are dependent on the climate, species, stand age, and forest management history in the environment the LWD was derived (Comiti *et al*., 2006). There is a long history of removing LWD from larger rivers and streams in the 19th and 20th centuries for navigation and to reduce flooding (Montgomery *et al*., 2003). However, in smaller streams, LWD loads also were radically altered by widespread land cover changes. In the USA, much of the forests east of the Appalachian Mountains underwent a dramatic conversion to agricultural and grazing lands during the 18th and 19th centuries to be replaced by the modern land cover of expanding second growth forest interspersed with urban settlements. Although many northeastern states are now densely populated, there remain vast areas of low-density development in states, such as Connecticut, that are largely covered by second growth forest. Very little old growth forest has survived. Recruitment of LWD is known to lag behind forest regeneration by centuries (Bragg, 2000; Benda *et al*., 2003); therefore, we hypothesized that current LWD conditions in the Connecticut streams surveyed in this study are lower than those observed in other regions outside the New England region.

Recent reviews of the literature (Cordova *et al*., 2007; Cadol *et al*., 2009) documented LWD loadings across many regions and nations with varying forest compositions and age structures, but only very recently have any studies examined LWD loading and dynamics in the Northeastern

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USA where forests are young and wood loadings are conspicuously lower than in other regions of the USA (Magilligan *et al*., 2008; Warren and Kraft, 2008; Laser *et al*., 2009; Warren *et al*., 2009). Although these studies have helped shed light on LWD characteristics in the Northeastern USA (upstate New York and Maine), no LWD census studies have been conducted in Southern New England where both natural vegetation distributions and anthropogenic land use change histories are quite different.

Many have noted that the speed and scale of investment in restoration appear to be resulting in management applications outpacing scientific developments in the fluvial sciences (Kondolf, 1995; Wohl *et al*., 1995; Bernhardt *et al*., 2005; Snyder *et al*., 2009; Wilkins and Snyder, 2010). In the case of large wood, our scientific understanding of loading densities and mechanisms is in its infancy and is based on regionally concentrated studies, whereas wood addition is an increasingly popular restoration strategy (Kasprak *et al*., 2010). It is with this imbalance in mind that we attempt to address the absence of a contextual understanding of wood loadings in Southern New England streams. We do this by evaluating how wood loadings in representative Southern New England streams compare with studies reported for other regions of the United States. To achieve this, we present the results of an extensive census of LWD and associated stream characteristics in northeastern Connecticut streams. We hypothesized the following: (i) that wood loadings would be among the lowest reported for the USA; and (ii) that there would be few geomorphically influential large pieces of wood or wood accumulations. Finally, we discuss how large wood loading in today's Southern New England streams compare with those observed in other regions and how river managers might use this increased scientific understanding to guide wood addition restoration efforts.

MATERIALS AND METHODS

Study region

Over 16 km of river length were inventoried for LWD in seven Connecticut streams (Figure 1). The study river segments are all part of the larger Thames River watershed in the Eastern Highlands of Connecticut and ultimately drain to the Long Island Sound. Mean annual precipitation is 115 cm $\pm$ a standard deviation (SD) of 18.5 cm, with snowfall being a minor component because of the proximity of the Thames River watershed to the Atlantic Ocean (Miller *et al*., 2002). Each of the study segments are single-thread channels with little lateral mobility within developed floodplains. Stream gradients ranged from 0.009 to 0.1%, and channel widths ranged from 4.22 to 30.3 m (see Table I for full study site descriptions).

Surficial geology in the watershed is composed of strongly foliated metamorphic bedrock dating to the Paleozoic Era (Abrams and Riley, 2002) and surficial deposits of glacial till ranging from 0 to 15.2 m thick (Warren and Stone, 1986), although generally less than 4.5 m thick. Modern day soils are largely developed from a layer of aeolian sand and silts that overlay the glacial till (Stone *et al*., 2005). Glacial retreat occurred between 18 000 and 16 000 years ago (Stone and Borns, 1986), and the region continues a glacio-isostatic rebound of 0.9 mm per year (Koteff *et al*., 1988). Riparian forests were all classified as mixed northern hardwoods with a mix of coniferous and deciduous trees with no large scale current anthropogenic disturbances documented.

The area did experience a large scale land use and land cover conversion in the 18th and 19th centuries, but since the 1940s, the forests have largely been left to naturally regenerate; however, anthropogenic disturbances to the area are still occurring today. Small run-of-the-river dams (less than 1–20 m in height) are quite numerous in the region, including within the Thames River watershed (McCusker and Daniels, 2009). These dams are primarily relics of Connecticut's water-powered industry of the 1700 s–1900s and are increasingly the target of dam removal efforts. Although the Thames River watershed has some of the highest percentages of riparian forest cover in Connecticut, since 1985, there has been a net conversion of riparian cover to urban development (CLEAR, 2006). All of the study reaches selected for this research have well developed forests and no urban development within the riparian zone. Reaches also were selected to minimize road crossings, geological channel confinement and impoundments (including active beaver colonies).

Study design

Sampled river segments ranged from 576 to 5700 m and were divided into sampling reaches based on the uniformity of mesohabitats. Mesohabitats were defined based on uniformity of slope, planform configuration, bed material and channel unit types (eg. step-pool, riffle-run). Ten representative measurements of bankfull depths and widths, as identified in the field based on channel morphology, were recorded throughout each reach. For each reach, the gradient, sinuosity, bed material, prominent bank vegetation and floodplain size were determined. Stream segments were classified by watershed areas as defined from the furthest downstream limit of the sampled reach and by the Strahler stream order (Strahler, 1957) as a measure of stream size.

All pieces of LWD contained within the active floodplain, defined as the flat portion of the valley immediately adjacent to the channel that is constructed by the present river under the present climate (Leopold, 1994), and over 0.05 m in diameter and greater than 0.3 m in length (Comiti *et al*., 2006)

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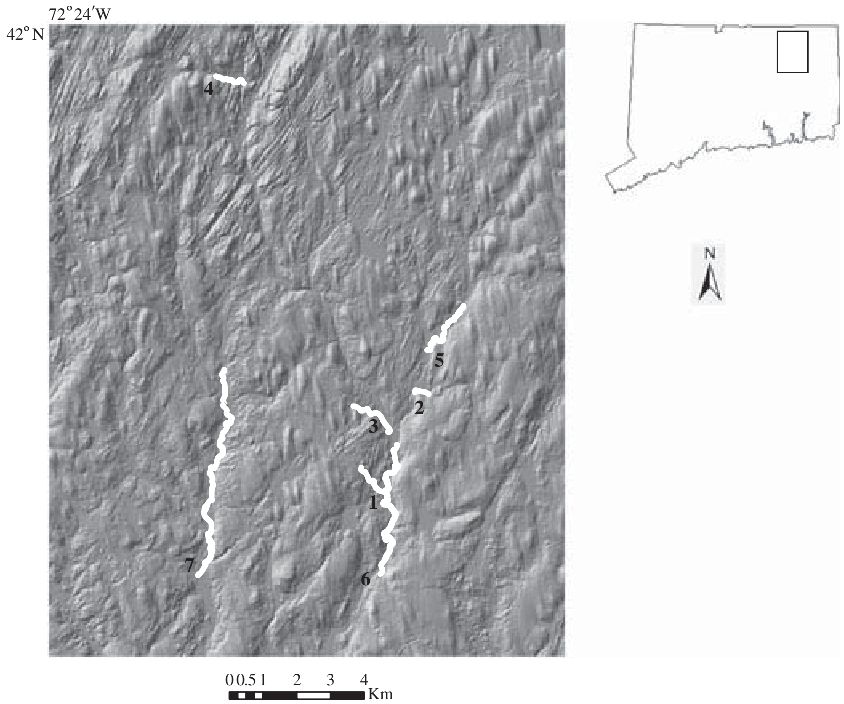

Figure 1. Shaded relief map showing location of study sites in white lines, the streams are numbered as they appear in Table I

were inventoried to document the full range of ecologic and geomorphically important woody debris. For each piece of LWD, we measured mid-length diameter and total length using a caliper and measuring tape, respectively. Volume (V, m^3) was calculated based on the mid-length diameter and the length of the log based on the assumption of a cylinder where

$$V = \pi r^2 h$$

r is the mean radius (m) and h is the length (m) of the woody debris. We also recorded the jam status and orientation of the LWD to flow; orientation delineations are as follows, with 180° being the main flow direction: parallel (A) 337.5–22.5°

Table I. Site characteristics of sampled watersheds

	School House Brook	Goodwin Brook	Eldridge Brook	Yale Forest	Beaver Dam Brook	Fenton River	Willimantic River
Surveyed length (km)	1.03	0.57	1.74	0.94	1.53	4.77	5.7
Watershed area (km^2)	2.18	2.3	6.31	6.58	8.43	88.86	242.77
Strahler order	2	2	3	3	3	4	6
Mean slope ($m \cdot m^{-1}$)	0.06	0.1	0.03	0.04	0.03	0.01	0.009
Mean bankfull channel width (m)	4.41	4.22	7.73	4.26	4.91	8.62	30.3
Mean bankfull channel depth (m)	0.34	0.43	0.49	0.37	0.45	0.55	Not measured
N reaches	31	7	27	32	20	41	17
N pieces in channel	145	101	236	145	241	671	137
N pieces in active floodplain	32	0	18	12	1	38	6
N pieces total	177	101	254	157	242	709	143
N jams	54	29	94	43	94	244	31
Mean length (m)	4.14	3.25	6.32	6.84	7.42	4.79	7.38
Mean diameter (cm)	13.84	14.73	13.69	14.75	15.86	21.65	19.65
Volume (m^3 per 100 m)	1.63	1.8	3	4.71	4.59	5.38	1.74
Pieces/100 m	17.19	17.8	14.62	16.65	13.8	14.88	2.51
Jam/100 m	5.24	5.11	5.41	4.56	5.36	5.12	0.54

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and 157.5–202.5°, perpendicular (B) 67.5–112.5° and 247.5–292.5°, oblique downstream (C) 22.5–67.5° and 292.5–337.5° and oblique upstream (D) 112.5–157.5° and 202.5–247.5° (e.g. Schuett-Hams *et al*., 1999; Magilligan *et al*., 2008). Location of the LWD was inventoried and categorized as follows: (i) in channel, those that are completely unattached from the banks; (ii) ramps, with one side of the LWD resting on a bank; (iii) bridging, with the LWD resting fully on the channel's banks; and (iv) in the active flood plain as wood that is completely out of water and not bridging the channel. Wood load was calculated as pieces per square meter, and wood frequency was calculated as pieces per 100 m.

Jams are considered herein as accumulations of two or more pieces of LWD; if a jam was present, the number of pieces in the jam was recorded as well as the percentage of channel area obstructed by the jam. Stream blockage was estimated using segment average channel depths and widths as well as the length of the key member piece of woody debris in the jam. We also evaluated the longitudinal distribution of wood by using GPS to document the location of each piece of wood in each study reach. Within ArcGIS, study reaches were divided into 25-m long segments (sensu Wohl and Jaeger, 2009), and segment averaged gradients were recorded in the field with clinometers.

RESULTS

Large woody debris piece characteristics

A total of 1783 LWD pieces were inventoried in the over 16 km of sampled stream reaches. The average wood frequency is 13.9 pieces per 100 m, with a rage of 2.51–17.8 pieces per 100 m (Table I). The largest ordered stream, the Willimantic River, had the lowest wood frequency, and the two second order streams, School House Brook and Goodwin Brook, had the highest frequencies of wood, with 17.19 and 17.8 pieces per 100 m, respectively.

Large woody debris diameters ranged from 13.17 to 21.6 cm (Figure 2a) with the LWD diameters of the Fenton and Willimantic Rivers significantly different ($p < 0.01$) from other inventoried streams but not significantly different from each other (p 0.39). LWD lengths ranged from 3.25 to 7.42 m (Figure 2b) with no significant relationship between wood lengths and stream orders ($p > 0.05$). Wood volume per 100 m ($m^3 m^{-1}$) ranged from 1.63 to 5.38 through the river reaches, with an average of 3.26 (Table I). The third and fourth order streams, Eldridge Brook, Yale Forest, Beaver Dam Brook, and the Fenton River, have the largest wood volumes per 100 m. The smallest as well as the largest ordered streams inventoried in this study have the lowest wood volumes. Wood load (pieces per square meter channel) decreases with channel width (Figure 2c) and increases with average gradient (Figure 2d) at the segment scale.

As watershed area increases, wood tends to be either fully contained within the channel or positioned as ramps, with very few bridging pieces observed (Figure 3). Goodwin Brook and Yale Forest were the only watersheds dominated by ramps. The Willimantic River had, by far, the greatest percent of wood fully contained to the channel and had no wood bridging the channel. The Fenton River, the second largest ordered stream, had the second lowest amount of wood bridging the channel as was also dominated by wood that was fully contained to the channel. The low order river reaches had the largest proportions of LWD in the floodplain or bridging the channel. The reaches surveyed in this study were typically dominated by parallel LWD orientations (orientation A), with the exception of the Fenton River where more LWD was oriented perpendicular (orientation B) to the channel (Figure 4). In general LWD orientations were primarily unidirectional in larger streams and multidirectional in smaller streams.

Jam characteristics

The Willimantic River had the lowest jam frequency of 0.54 jams per 100 m, whereas the other watersheds ranged from 4.56 to 5.41 per 100 m (Table I). All watersheds were dominated by debris jams that were two to five pieces in size (Figure 5). Although the Willimantic River had the lowest proportion of debris jams, it had the highest proportion of the largest jam class, 16+ pieces. Eldridge Brook had the largest proportion of mid-sized jams between 6–10 and 11–15 pieces. Key member LWD pieces were measured for their lengths and diameters. The lengths of the key members range from 3.75 to 9.39 m. Key member jam pieces tended to be larger than the average LWD size in a given sampling segment (Figure 6), with the exception of School House Brook. Eldridge Brook, Yale Forest and the Willimantic River all had key members over 0.6 m longer than the average LWD for each respective reach. The concentration of LWD pieces into jams decreased as both channel gradient and watershed area increased (Figure 7). The overall longitudinal distribution of LWD from upstream to downstream was influenced by local channel slope; high slope reaches contain low numbers of LWD pieces, but after transitions from high to lower slope reaches, there are large peaks in the number of LWD pieces (Figure 8).

DISCUSSION AND CONCLUSION

This study documents wood loadings in Connecticut streams that rank among the lowest reported nationally. Cordova *et al*. (2007) conducted a comprehensive review of published LWD frequencies from a number of regions

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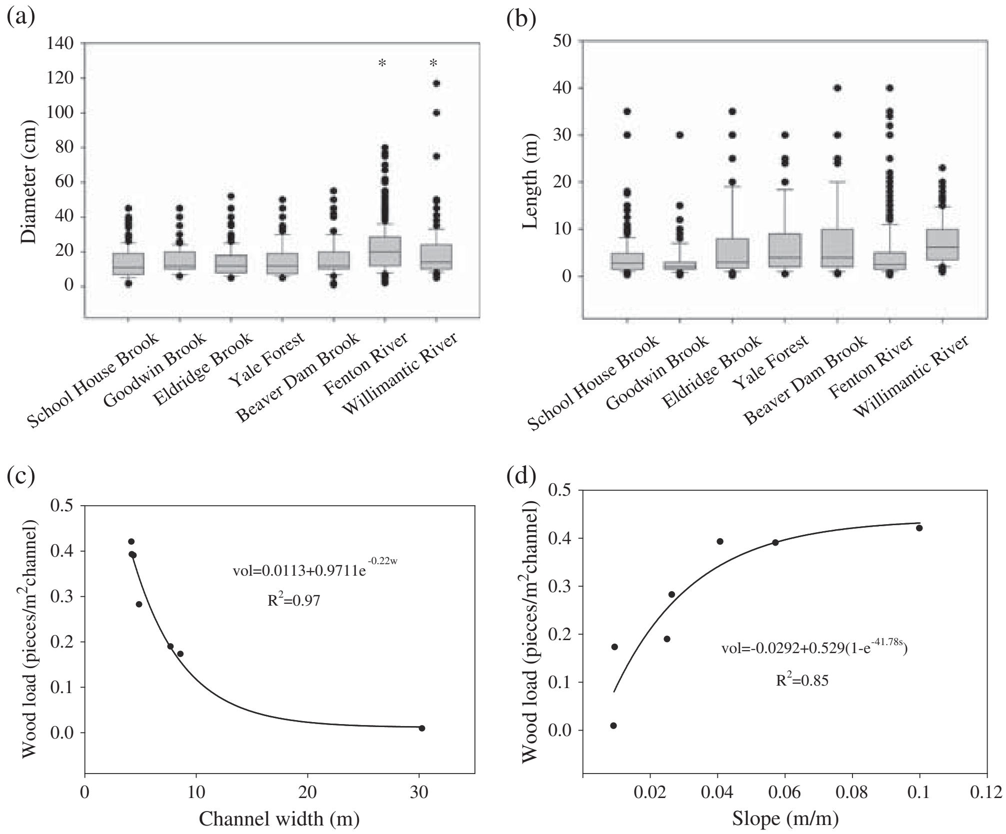

Figure 2. Large woody debris box plots of (a) diameter and (b) length, and wood load in relation to (c) channel width and (d) slope at the watershed scale, watershed size increases to the right (a and b). A * dentoes that the sites are significantly different from the other sites ($p < 0.01$) but not significantly different from each other. For the box plots, the line within each box signifies the median value and the ends are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles, and the dots are extreme values

throughout the USA, and Cadol *et al*. (2009) also published a review of LWD frequencies in old growth forests for a number of regions and countries, but none were available from Northeastern or New England states. Our Connecticut survey produced LWD loadings (2.51–17.8 pieces per 100 m) lower than those in most of the US regions reviewed in Cordova *et al*. (2007), with the exception of the Southeast and Central regions of the USA (Georgia, North Carolina,

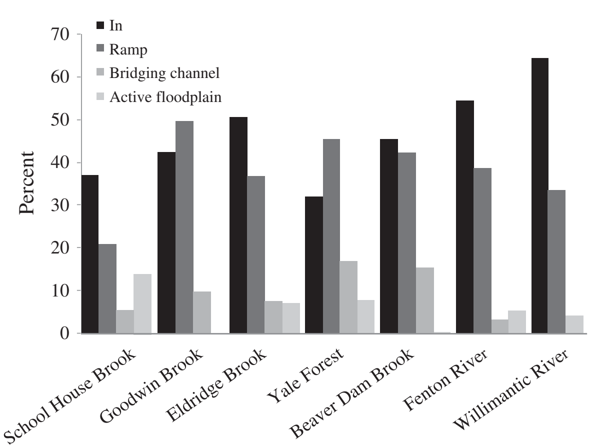

Figure 3. Channel position of the LWD pieces with watershed size increasing to the right

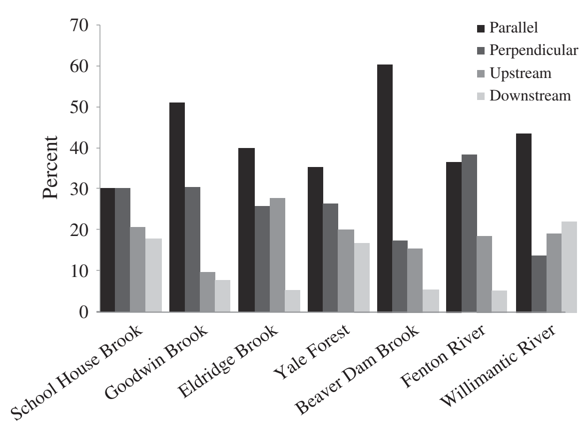

Figure 4. Orientation to flow for LWD by watershed with increasing watershed size to the right

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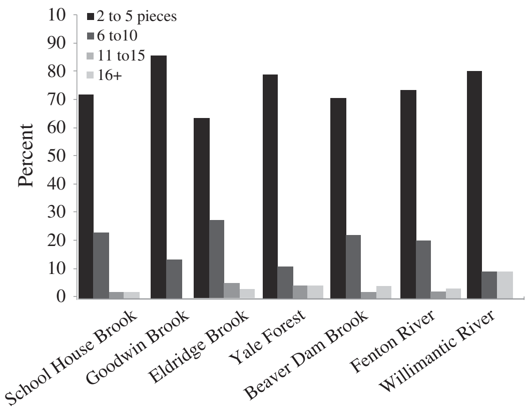

Figure 5. Size classification of woody debris jams with watershed size increasing to the right

Tennessee and Virginia) where abundances ranged from 0.4 to 16.3 per 100 m and volumes ranged from 0.25 to 3 m^3 per 100 m^2. This in unsurprising because the Southeast has experienced similar land cover transformations to the Northeast, and the Central region was never heavily forested. In contrast, Upper Midwest abundance ranges from 9 to 64, with an average of 32.6 pieces per 100 m, with volume ranging from 0 to 3.12, with an average of 0.77 m^3 per 100 m^2; Alaska abundance ranges from 8 to 40.9, with an average of 25.1 pieces per 100 m, with volume ranging from 0.36 to 18.02, with an average of 4.27 m^3 per 100 m^2; West and West North Central United States (California and Montana) abundance ranges from 5.2 to 91.2, with an average of 32.6 pieces per 100 m, with volume ranging from 0.03 to 5.2, with an average of 1.71 m^3 per 100 m^2; Pacific Northwest (Oregon and Washington) abundance ranges from 0.5 to 239, with an average of 36.2 pieces per 100 meters, with volume ranging from 0.1 to 8.12, with an average of 5.04 m^3 per 100 m^2; and Mid-Atlantic (Pennsylvania and West Virginia) abundance ranges from 6 to 34, with an average of 16.1 pieces per 100 m (Cordova *et al*., 2007).

Our Connecticut findings are similar to those observed in other more recent studies of wood loading in the Northeastern USA (Magilligan *et al*., 2008; Warren and Kraft, 2008; Laser *et al*., 2009; Warren *et al*., 2009). Wood frequencies reported in coastal Maine were 3.2–11.5 pieces per 100 m for pieces equal or greater to 10 cm in diameter (Magilligan *et al*., 2008), and wood frequencies of inland Maine are 7.78 pieces per 100 m (Laser *et al*., 2009). Although our observed wood loadings are comparable to those reported by Magilligan *et al*. (2008) and Laser *et al*. (2009), wood lengths and diameters varied considerably more. Laser *et al*. (2009) report wood lengths with a mean of 5.62 m and a SD of 2.47 m and mean diameters of 0.21 m and a SD of 0.11 m, Magilligan *et al*. (2008) report wood lengths with a mean averaging between 5 and 6.2 m and a SD of at most 1 m and mean diameters averaging between 0.17 and 0.21 m and a SD of at most 0.03, whereas the Connecticut streams inventoried here have a mean length of 5.6 m and a SD of 6.36 m and mean diameter of 0.12 m and a SD of 0.18 m. Measured LWD jam frequencies also were quite low and comparable to other studies in the Northeast (Warren *et al*., 2009). The differences in size of LWD between Connecticut and Maine are likely because of the stochastic weather events more common in coastal Maine (e.g. ice storms and hurricanes) (Laser *et al*., 2009), slow maturation of trees in coastal Maine (Laser *et al*., 2009) and continued timber harvesting (Magilligan *et al*., 2008), all of which produce recruited wood that is much smaller than reported herein for Connecticut. LWD frequency tended to decrease with increasing stream size, which is consistent with previous findings from across the USA (Bilby and Ward, 1989; Montgomery *et al*., 1995).

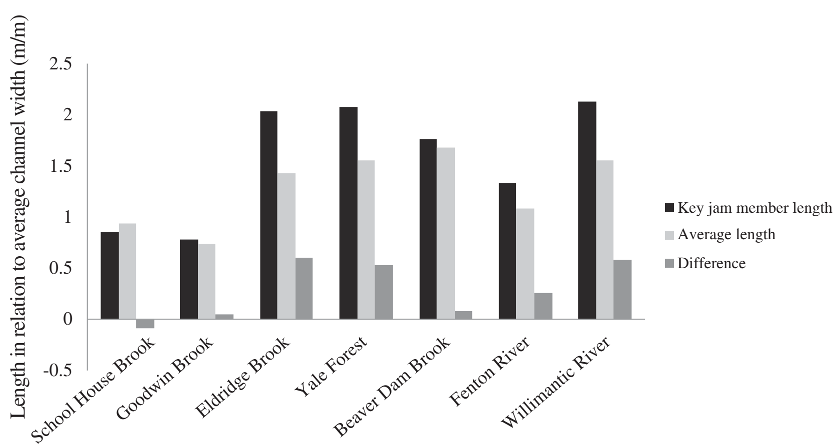

Figure 6. Jam key memeber length, average length, and difference in lengths as a proportion of average channel lengths at the segment scale by watershed where watershed size increases to the right

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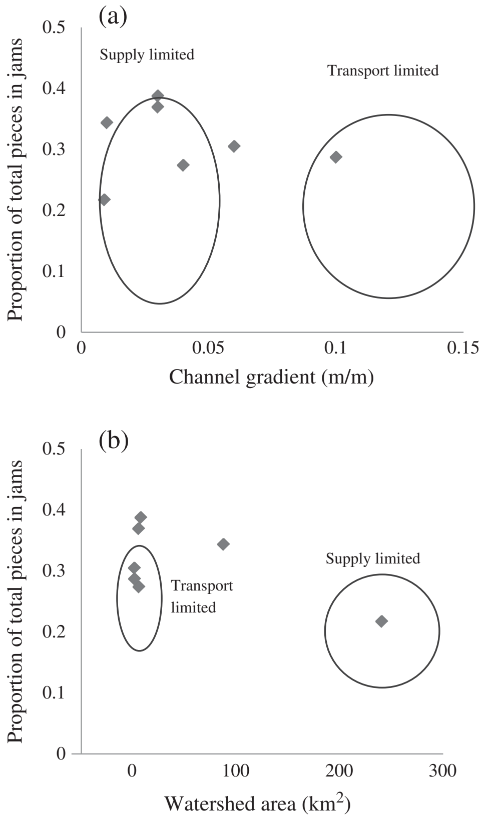

Figure 7. Proportion of total pieces of wood in jams at the segment scale that are supply or transported in relation to (a) channel gradient and (b) watershed as defined by Wohl and Jaeger (2009)

In all of our study reaches, regardless of stream order, LWD pieces were dominated by parallel orientations (Figure 4), but small-sized and intermediate-sized streams did have higher proportions of wood perpendicular to flow, a finding similar to that of Magilligan *et al*. (2008). Laser *et al*. (2009) also reported the majority of LWD in downstream or parallel orientations, both of which are unstable and not conducive to retention of organic matter and sediments. The preponderance of unstable orientations suggests that the majority of LWD in Connecticut streams is small enough to be mobilized and transported by these systems.

The predominance of fully contained wood and ramped wood pieces, combined with the absence of bridging pieces (Figure 3), also is likely a result of the low recruitment of large mature trees. Woods introduced into the stream channels are simply too small to effectively bridge channels and/or resist transport by the stream. Other studies have demonstrated that retention of smaller than channel-spanning pieces may be dependent on the presence of large anchored pieces of LWD, such as trees with intact soil–root boles (e.g. Daniels, 2006). In the absence of such structures, all but the largest LWD pieces may be transported and redeposited into parallel or ramped configurations as flow subsides. With orientations that are predominantly parallel to flow and low wood volumes, it is highly likely that these streams are not effectively retaining organic matter and fine sediment (Magilligan *et al*., 2008).

The most plausible explanation for these finding is low wood recruitment from riparian forests, which can be attributed to two primary factors: (i) the history of land use/land cover change resulting in young riparian forests containing trees of considerably smaller size; and (ii) the lack of steep riparian slopes (Magilligan *et al*., 2008), which limits the systems' ability to recruit wood through debris flow or mass wasting processes. Furthermore, because wood that is recruited to stream channels in the Northeast is primarily from natural mortality and branch fall in young forests (Warren and Kraft, 2008), it generally lacks sufficient size to be retained (Magilligan *et al*., 2008), contributing to overall low wood volumes. In addition, the forest in Laser *et al*. (2009) is in

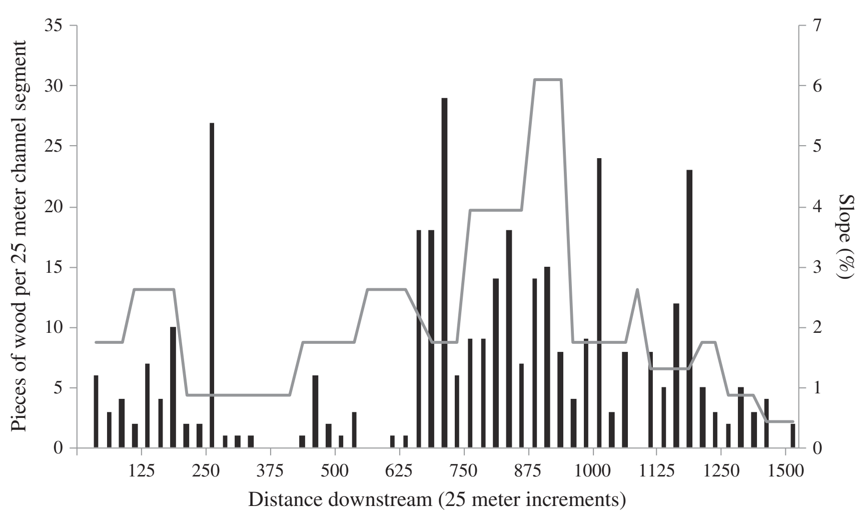

Figure 8. Number of pieces of wood in successive 25 meter increments and the slope of the river at each segment for Beaver Dam Brook

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an intermediate successional state; the trees in their study are more resilient to stochastic weather events, and the wood that is recruited is generally too small to be retained in the system.

Although there is a rich literature set for LWD influence on channel morphology and hydraulics, few studies have examined the longitudinal distribution of wood (Wohl and Jaeger, 2009). Wohl and Jaeger (2009) developed a conceptual model that suggests a progressive decrease in wood load as a response to drainage area, elevation, channel width, bed gradient and total stream power and suggest that the intermediate size streams should have the maximum number of jams. Because of strong local influences, the results of our study do not follow this conceptual model, with small and intermediate streams having relatively similar jam loads (Table I). In using the Wohl and Jaeger (2009) slope criteria, one stream is transport limited, and three are supply limited (Figure 7a); in using their watershed area criteria, one stream is supply limited, and three are transport limited (Figure 7b). The longitudinal distribution of LWD from upstream to downstream appears to be patchy and strongly influenced by slope; high slope segments contain low numbers of LWD pieces, but after transitions from high to lower slope segments, there are large peaks in the number of LWD pieces (Figure 8). However, with limited sample sizes, it is difficult to draw any firm conclusions regarding the wider applicability of the Wohl and Jaeger (2009) model. Our results for the longitudinal distribution of wood through Beaver Dam Brook (Figure 8) indicate that, in addition to riparian forest condition, the segment averaged slope is likely a locally important determinant of wood loading at discrete segment scales.

In summary, our findings support the suggestion by others (Magilligan *et al*., 2008; Laser *et al*., 2009) that wood loads and debris jams in the New England region are still being influenced by the land clearing of the 18th and 19th centuries. Although no pre-European settlement data about LWD exists for this region (Magilligan *et al*., 2008), it is widely recognized that the addition of woody debris to streams in this region will contribute to the quality of the streams both ecologically (Neumann and Wildman, 2002) and geomorphically (Magilligan *et al*., 2008; Warren *et al*., 2009). The implications of these findings are important for stream management and restoration efforts throughout Southern New England. Clearly, given what we know about the positive effects of wood in stream channels, the relative scarcity of LWD is likely limiting stream ecosystem function and should be a primary target for river restoration and management efforts. Efforts to increase wood loading in New England streams could include felling selected mature trees into the stream to retentive, stable, configurations (perpendicular to flow, cabled to one back, pinned in place with natural boulders, etc.), constructing jams using in-steam wood retention structures such as wood piles and protecting riparian forests to encourage continued regrowth and natural recruitment (Laser *et al*., 2009).

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