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Dynamics of large wood in an eastern U.S. mountain stream

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ABSTRACT

Large wood (LW) is an important feature in many streams in northeastern North America, yet the dynamics (recruitment, movement, and export) of large wood remain largely undocumented for streams in this region. In this study we quantify the dynamics of LW in 400 m of a second-order, high gradient, boulder-dominated stream in the eastern Adirondack Mountains, NY. Characteristics and location of all LW (>1-m length, >10-cm diameter) in the 400-m study reach were initially recorded and pieces were individually tagged in November 2000. Subsequent surveys were conducted in late summer/fall of 2001, 2003, and 2004. Twenty-six% of the 112 pieces of LW initially tagged moved 5.0 m or more during the 4 years of this study. Mobile wood was, on average, shorter than non-mobile wood. Nearly all mobile wood was shorter than the 8.0-m bankfull width of the stream. From 2000 to 2004, 2.16 m^3 (0.54 m^3 100 m^{-1}; 43 pieces) of LW entered the study reach and 0.7 m^3 (0.18 m^3 100 m^{-1}; 13 pieces) left the stream. Retention of wood in debris dams was key to reducing potential export. For this stream, located within a second-growth mixed northern hardwood riparian forest that is approaching maturity, the net wood accumulation rate was estimated as ranging from 0.09 to 0.15 m^3 100 m^{-1} $year^{-1}$. Our data support previous observations that LW length strongly influences its potential to move in high gradient streams, though debris dams can reduce LW movement rates and movement distances for wood of all sizes.

1. Introduction

Several recent studies have documented the importance of large woody debris (large wood) in streams of northeastern North America. Large wood retains sediment and organic matter (Thompson, 1995), promotes habitat for fish (Warren and Kraft, 2003), contributes to pool formation (Keeton et al., 2007), and has been linked to nutrient uptake (Warren et al., 2007). However, the recruitment dynamics, movement, and short-term accumulation of wood in streams within this region remain largely unstudied. In this paper we characterize input, movement, and export of wood over 4 years in 400 m of a second-order stream in the eastern Adirondack Mountains of New York state.

Lienkaemper and Swanson (1987) and several subsequent studies (Bilby and Ward, 1989; Young, 1994; Diez et al., 2001; Martin, 2001) found that the length of a piece of wood relative to the bankfull width of the stream was the best predictor of wood movement in forested streams. Once stream width exceeds the length of a piece of wood, other factors dominate movement potential. Braudrick and Grant (2000) found that wood diameter was the most important factor influencing the propensity of wood to move in flume experiments. However, they noted that extrapolation of their results was likely limited to low-gradient alluvial systems and that other factors were likely to dominate in other stream types (Braudrick and Grant, 2000). For example, in higher-gradient, boulder-dominated streams of the Sierra Nevada (CA), other researchers have observed that the size and frequency of flood events strongly affected wood movement, as did the physical dimensions of the wood (Berg et al., 1998).

Several studies have highlighted that regional variability is an important consideration in quantifying wood dynamics in streams (Richmond and Fausch, 1995; Berg et al., 1998; Gurnell et al., 2002). Within the northeastern U.S., moderate- to high-gradient streams with abundant glacial till are common. Riparian forests range in age, but most are second-growth forests in the early to middle stages of maturity—recovering from historical logging or agricultural use (Lorimer and White, 2003). The amount of wood in a stream often varies with forest age, but few studies have attempted to measure whether the rate of wood recruitment to streams varies with forest stand age and associated stand structure. Warren and Kraft (2003) and Keeton et al. (2007) have suggested that in heavily glaciated northeastern North America the

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great abundance of boulders and glacial erratics leads to greater retention of wood recruited from the forest by these large in-channel features, thereby reducing wood export. Keeton et al. (2007) also speculated that ice flows in medium and large streams in this region may lead to more rapid physical break-up of wood with associated increases in export. To date, no measurements of wood movement or wood export rates have been reported for any streams in the northeastern U.S.

We hypothesized that the average length of mobile large wood would be shorter than non-mobile wood and that mobile large wood would be shorter than the stream bankfull width. Given the high-gradient constrained channel of our study stream, we did not expect large wood diameter to be a major factor influencing wood movement. We also quantified wood export from and recruitment to the study reach during the 4 years of this study (2000–2004).

2. Study site

The study reach was a 400-m section of Rocky Branch, a second-order stream in the eastern Adirondack Mountains of northern New York with a mean bankfull width of 8.0 m and an overall gradient of approximately 6.5% (Fig. 1). The reach is dominated by boulders and large cobble and has an upstream watershed area of approximately 7.4 km^2. Sub-sections of this larger stream reach were subject to a wood manipulation experiment in 2000 (Warren and Kraft, 2003), and the amount of large wood removed as part of that study was quantified and is accounted for in the wood volume estimates reported here. Stream discharge in this system peaks in the spring during snowmelt, reaches its minimum in mid-summer, and experiences a slight increase in the fall. A more detailed description of the study region and a comparison of this study reach with seven other nearby streams are presented in Kraft et al. (2002) and Warren and Kraft (2003).

The forest adjacent to the 400-m section of stream was surveyed in 2000 during a study evaluating the impacts of a severe ice storm on Adirondack streams (Kraft et al., 2002). Our study reach was adjacent to four of the 5 m × 10 m plots established on Rocky Branch. A total of 44 trees of >5 cm diameter at breast height (DBH, 1.3 m) were surveyed in these plots. The dominant tree species was eastern hemlock (*Tsuga canadensis* (L.) Carr.) (27 individual trees) followed by white birch (*Betula paperifera* Marsh.) (8 individuals), green ash (*Fraxinus pennsylvanica*, Marsh.) (3), and sugar maple (*Acer sacherinum* Marsh.) (3). Surveys also included a single individual of balsam fir (*Abies balsamea* (L.) P. Mill.), aspen (*Populus* sp.), and white oak (*Quercus alba* L.). Overall, 40% of the trees were greater than 20 cm DBH. The largest tree was a hemlock 43.5 cm DBH. Stand age at this site has been estimated at 60–80 years of age, based on forest structure and logging history (Warren and Kraft, 2003).

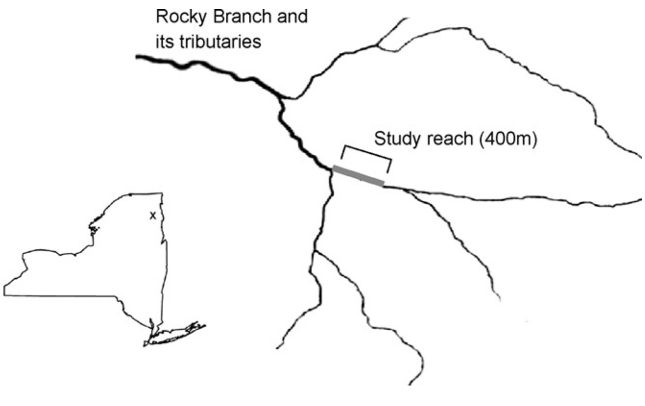

Fig. 1. Location of Rocky Branch in New York state and study reach location within the Rocky Branch tributary system.

3. Methods

3.1. Large wood surveys

We used the standard definition for large wood (LW) in this study: dead wood within the bankfull channel with diameter >10 cm and length >1 m. In November 2000, we surveyed all LW within a 400-m reach of the study stream. Each piece of LW received an individually numbered plastic tag and the following information was recorded: tag number, estimated length in the stream channel, estimated length outside the stream channel, maximum diameter, location (distance from the center of each piece to a permanent landmark at the beginning of the reach), and whether or not the LW was part of a debris dam. The length of LW was visually estimated and estimates were verified using a field tape for the first 10 pieces encountered. Thereafter, length was estimated by both members of the field crew to the nearest 0.5 m. If estimate discrepancies were large, the piece was measured using a measuring tape. All estimates of wood length outside the stream channel were visually estimated. Location was measured using multiple 100-m tapes set in the thalweg of the stream. A benchmark tag was set in a live tree about half way through the reach (175 m) for use in correcting subsequent distance measurements.

In September 2001, a second survey was conducted, and the location of all tagged wood within the reach was recorded. All new wood was tagged and data were collected from each piece. In addition to surveys within the study reach, we surveyed the channel downstream of the study reach to search for missing wood and confirm the absence of certain pieces. In September 2003 and September 2004, the reach was re-surveyed. The location of all tagged wood was recorded and all new wood was tagged and measured. Any failing tags were replaced and rotten wood was double tagged if we suspected that the existing tag was likely to be lost. Unless a piece of LW had clearly broken, the length and diameter of pieces tagged in 2000 or 2001 were not re-measured in the 2003 and 2004 surveys.

In August 2000, two debris dams were removed within the 400-m reach as part of a different study (Warren and Kraft, 2003). All large wood pieces removed in this process were measured and their former location and orientation were recorded for this survey. None of the four other debris dams of comparable size moved or were broken up during the course of this study, so we assumed for our analysis that the dams would have remained in place and that the associated LW would not have moved. These pieces were included in estimates of LW standing stock, but were not included in any of the wood movement analyses. Only a few pieces of LW passed through either dam removal location – and these highly mobile pieces also passed existing dams comparable in size to the two that were removed – therefore dam removal would have had only a limited influence upon wood mobility estimates.

Several pieces of wood unaccounted for in the 2001, 2003, and 2004 surveys were considered to have been buried in a debris dam with the tag inaccessible or out of view, based on the original wood location that often included partial or complete burial in a debris dam. Similarly, some pieces were recognized as being in the same place as in previous surveys, but no identification tag could be located. Using data on the length and diameter of wood observed in earlier surveys and using field notes, we determined which of the untagged wood pieces in the 2001, 2003, and 2004 surveys were older pieces from which tags had been lost and which were new pieces of wood that had entered the study reach. Many of the debris dams increased in size (most notably in 2003), thereby leading to wood burial. The assumption of wood burial was corroborated in at least one case in which wood was not observed in 2003, but observed again in a dam in 2004. Young (1994) also documented the burial of large wood in debris dams. In a few cases we had to make assumptions regarding movement of wood out of the study reach. Two pieces lost tags from 2000 to 2001, as did seven pieces from 2001 to 2003 and eight pieces from 2003 to 2004.

3.2. Analysis

We calculated median and maximum diameter of large wood in the study reach. We also calculated the median and maximum diameter of riparian trees adjacent to the study reach using the surveys conducted by Kraft et al. (2002). The loading rates for individual pieces of LW and total LW volume per 100 m per year were calculated for the reach using mass balance calculations (Benda and Sias, 2003). Individual LW volume was calculated assuming each piece was cylindrical and total LW volume was estimated by summing the volume of all wood measured.

Wood movement was determined based on changes in the location of each piece of LW relative to the downstream benchmark during each time interval. Movement that occurred beyond the stream reach was not incorporated into total movement analyses because the stream was significantly wider below the downstream endpoint of the study reach, which corresponded to a tributary entrance. Due to year-to-year variability in laying out the thalweg transect, movement distances less than 5 m were considered to be within the range of measurement error for determining wood locations (Berg et al., 1998). We determined the number, median length and median diameter of pieces of LW that did not move, as well as LW that moved distances greater than 5, 50, 100, and 150 m. Wood length estimates were $\log_{10}$ transformed to normalize the data and a single-factor ANOVA was conducted to compare mean lengths of mobile (all wood moving $>$5 m) versus immobile wood (movement $<$5 m). We also compared the length of highly mobile wood (defined as LW moving $>$50 m) to that of the immobile wood. Due to the limited number of mobile pieces of wood, these analyses were not well balanced; however, single-factor ANOVA remains relatively robust to the violation of this assumption (Shaw and Mitchellolds, 1993).

Given previous observations that large discharge events strongly influence wood movement in streams (Lienkaemper and Swanson, 1987; Berg et al., 1998), we used long-term data from a USGS gauging station on the mainstem Au Sable River – located approximately 25 km downstream from the study reach – to evaluate the relative size of peak flow events in each study year. Although the specific magnitude of discharge events recorded by this gauge are larger than those at the study site, this record is adequate to characterize storm events and year-to-year discharge variability in this upstream tributary.

3.3. Large wood mass balance

In order to more accurately estimate wood loading specifically from the riparian area into our study reach, we created a mass balance wood budget for this system, using a modification of the approach described by Benda and Sias (2003). This method uses measurements of LW standing stocks, LW inputs, and LW outputs to estimate wood flux into and out of a stream reach. The mass balance equation for our study site is relatively simple, involving a wood recruitment metric with two components: (1) fluvial transport into the reach from upstream, and (2) recruitment into the stream from riparian trees. The wood export metric also involves two processes: (1) fluvial transport out of the reach, and (2) physical or biological breakdown of wood. We applied the equation from Benda and Sias (2003), modified as follows:

$$S_c = (L_i - L_o) + (Q_i - Q_o) - D \quad (1)$$

where S_c represents the standing stock of wood in a given section of stream, L_i represents loading from the riparian zone, L_o represents lateral wood export from the reach onto the adjacent streambank, Q_i represents wood transported into the reach from upstream via fluvial processes, and Q_o represents downstream wood transport out of the reach through fluvial processes. The symbol D represents the loss of wood from the reach as a result of decay (both physical and biological).

The primary metric of interest in our study was the rate of wood input from the riparian area (L_i). Although we had an accurate measure of the total amount of new wood in the study reach over the 4 years of this study (0.18 m^3 $year^{-1}$), we did not know whether wood entering the stream reach was derived from upstream transport or from the adjacent riparian area. Using data on wood movement and information from field notes (e.g. identifying instances in which a specific piece of wood originated from a specific tree adjacent to the stream) we were able to estimate recruitment from the riparian zone under two different scenarios. Under scenario number one, we assumed that transport into and out of the system was in balance ($Q_i = Q_o$), and we then simply used the total net wood accumulation rate to estimate riparian recruitment to the reach (L_i). This scenario assumed no loss of wood due to lateral transport onto the streambank and that no wood was lost due to decay. These assumptions are supported by the size of the discharge events during the study period (see below) and the relatively short duration of this study. The second scenario was intended to provide an estimate of maximum wood loading to the reach. In this scenario, we assumed that fluvial transport of wood originating outside the study area and passing through the upper half of the stream reach was low and therefore all new wood entering the reach via fluvial transport was restricted to this upper 200-m section. We then used the total volume of new wood from the lower 200 m to estimate an alternative riparian area wood recruitment rate, i.e. all new wood in the lower 200 was attributed to riparian recruitment from the forest adjacent to that reach.

4. Results

We tagged 112 pieces of LW in the study reach. This excluded an additional 10 LW pieces that were removed in 2000 in association with the earlier study (i.e. 122 pieces of LW were originally present in the stream reach). Excluding these 10 pieces, all LW in the 400-m study reach was considered potentially mobile wood (including the original 112 tagged pieces and any wood that entered the stream between 2000 and 2003). During the 4 years following our initial survey 43 pieces of LW entered the system, 13 pieces were carried out of the system, and 6 new pieces of LW were formed by breakage of pieces previously surveyed (Tables 1 and 2). The total estimated large wood volume within the study reach at the end of the study period (2004) was 14.1 m^3 (3.53 m^3 100 m^{-1})—a total that includes the LW removed in the earlier experiment. From 2000 to 2004, 2.16 m^3 of LW was recruited into the reach (0.13 m^3 100 m^{-1} $year^{-1}$) and 0.7 m^3 of LW exited the study reach (0.05 m^3 100 m^{-1} $year^{-1}$) for a net gain of approximately 0.36 m^3 per year (0.09 m^3 100 m^{-1} $year^{-1}$).

Twenty-five percent of the 142 potentially mobile pieces of LW (112 original plus 43 recruited minus 13 exported) moved at least 5 m from 2000 to 2004. Of the original 112 potentially mobile

Table 1
Large wood (LW) abundance in the 400-m section of Rocky Branch surveyed from 2000 to 2004

Reach characteristics	2000	2001	2003	2004
Total number of pieces of LW[a]	122	137	142	158
Number of pieces of LW/100 m[a]	30.5	34.25	35.5	39.5
Total number of debris dams	–	15	17	19
Number of debris dams/100 m	–	3.75	4.25	4.75
Number of pieces of LW in debris dams[a]	75	87	73	87
Proportion of LW in debris dams	0.61	0.64	0.51	0.55
Number of new pieces recruited	–	19	11	13
Number of pieces left or assumed to have left the system	–	5	4	4

[a] Including LW not found but assumed to be buried in debris dams and the LW that was removed in the August 2001 dam removal.

pieces of wood, 26% moved a distance greater than 5 m, 11% moved more than 50 m, 7% moved more than 100 m and 4% moved more than 150 m within the study reach (Table 2). The median length of mobile wood pieces was 3.5 m – which was less than that of stationary wood (4.0 m) – though the difference was not significant at $\alpha = 0.05$ (Table 2, Fig. 2; $p = 0.08$). The median length of the highly mobile wood was 2.2 m, and the analysis of log-transformed length data indicated that highly mobile wood was significantly shorter than immobile wood ($p = 0.008$; Fig. 2). Three pieces of large wood moved distances greater than 200 m within the study reach during the 4 years of this study, and one moved over 300 m. All three of the pieces moving over 200 m passed the locations where the dams were removed and also passed at least four other channel-spanning dams of comparable size that were not removed. Two additional pieces passed the downstream dam location. Both of these pieces were also highly mobile and passed channel-spanning dams elsewhere in the reach. If these pieces had been retained in the first of the removed dams that they encountered they would have still undergone considerable movement (28–100 m).

In the initial survey, 84% of all LW (including removed debris dams) and 83% of the potentially mobile LW (all wood excluding removed debris dams) was shorter than the mean bankfull width of the stream (8 m). Of the wood that did not move between 2000 and 2004, 20% of the pieces were longer than the bankfull width of the stream. Of all wood that was mobile during the 4 years of this study, only 7% of the LW was longer than the bankfull width, and no wood moving more than 50 m in the study reach was longer than the mean bankfull width (Table 2).

The median diameter of in-stream wood was not substantially different from corresponding dimensions of trees adjacent to the stream reach. The diameter of the largest piece of in-stream wood, however, was greater than the DBH of the largest tree. Large wood diameter was not different between the mobile and immobile wood. Even the highly mobile wood was not significantly different in diameter from the immobile wood ($p > 0.4$; Table 2), and overall, no significant differences in LW diameter were found among the mobility categories ($p > 0.5$; Table 2).

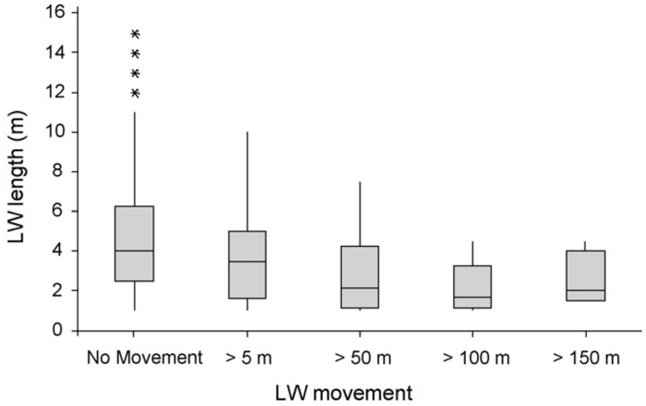

Fig. 2. Box plots of large wood (LW) length in each of five movement categories for the original 112 pieces of potentially mobile LW present in the 400-m study reach in 2000. Movement distances are based on changes in position of LW from 2000 to 2004. Movement categories were as follows: no movement (<5 m difference in distance among years, $n = 85$); movement >5 m ($n = 28$); movement >50 m ($n = 12$); movement >100 m ($n = 8$) and movement >150 m ($n = 4$). All wood that moved >50 m are included in the plot of wood moving greater than 5 m. All wood moving >100 m are included in the plot of wood moving greater than 50 m, and so on. The horizontal line in each box represents the median length of large wood in each movement category. Boxes represent the middle 50% of the length values and bars represent the upper and lower quartiles. Outliers are denoted by asterisks.

During the 4 years of this study, peak discharge events within the broader watershed that encompasses our study stream were slightly below average, but close to the median peak discharge. The yearly maximum discharge at the Au Sable Forks gauge was 356, 305, 178, and 235 $m^3 s^{-1}$ for the years 2001, 2002, 2003, and 2004, respectively. The median of all peak discharges for the previous 10 years (1991–2000) was 306 $m^3 s^{-1}$ (range: 160–1059 $m^3 s^{-1}$) and the median peak discharge for the entire period of record (1911–1968 and 1990–2005) was 284 $m^3 s^{-1}$ (range: 93–1059 $m^3 s^{-1}$). The largest number of pieces of LW that moved between sampling periods occurred between the 2001 and 2003 surveys, but because this encompassed 2 years of potential movement we could not correlate wood movement to peak discharge in any particular interval.

Mass balance results from scenario one (fluvial input rates equal fluvial output rates) led to an estimated wood loading rate of 0.09 m^3 100 m^{-1} $year^{-1}$, which corresponded to an increase of 2.5% of the entire standing stock for the 400-m reach. Under scenario two large wood was recruited at a rate of 0.15 m^3 100 m^{-1} $year^{-1}$.

5. Discussion

5.1. Large wood movement

Twenty-five percent of the large wood in our study system moved >5 m between 2000 and 2004. Consistent with wood

Table 2
Movement and characteristics of LW in a 400-m reach of Rocky Branch over 4 years

	All wood 2000–2001	All wood 2001–2003	All wood 2003–2004	Original wood, total movement 2000–2004	Median LW length for original wood (m)	Median LW diameter for original wood (m)	Proportion of original LW shorter than bankfull
Pieces surveyed and capable of movement	112	132	139	113	4.0	0.13	0.83
No movement	98	113	125	85	4.0	0.14	0.80
LW pieces moving >5 m	14	19	14	28	3.5	0.13	0.93
LW pieces moving >50 m	4	7	7	12	2.2	0.13	1.00
LW pieces moving >100 m	1	5	3	8	1.7	0.13	1.00
LW pieces moving >150 m	0	2	1	4	2.0	0.12	1.00

Note: The 2000–2004 summary analysis includes a piece of LW that broke in two early in the study.

movement studies from other regions, mobile wood was almost always shorter than the bankfull width of the stream (Lienkaemper and Swanson, 1987; Berg et al., 1998). Yet if wood lengths shorter than bankfull width were the sole indicator of wood mobility, we would have expected a much higher proportion of mobile wood because the majority of LW in our study reach was shorter than the bankfull channel width of the stream. Our results indicate that retention of wood in debris dams was an important factor in restricting LW movement in Rocky Branch. This is similar to results from a Wyoming stream (Crow Creek) with similar riparian forest and geomorphic characteristics (bankfull width, 7.0 m; gradient, 5.5%) to our study site. Young (1994) found that 18% of tagged wood in Crow Creek moved from 1 year to the next. Stable wood in Crow Creek was found to be significantly longer than mobile wood, and these longer pieces were also reported as more likely to have been buried in stream substrates or the banks of the stream. Although the number of tagged pieces that were actually retained in dams was limited in the Crow Creek study, some wood retention was observed in debris dams (Young, 1994).

Most wood that moved during the course of our study was retained in dams and no debris dams broke apart during the 4 years of observation. The observation of wood retention in debris dams supports the contention by Martin and Benda (2001) that the spacing of debris dams – and the length of intervals between debris dams – is the primary influence on the distance of LW transport in streams. Based on this assumption and their evaluations of dam spacing in an Alaskan watershed, Martin and Benda (2001) estimated that >90% of the LW in small streams moved at least 50 m (in no specific timeframe), and about 10% of the LW moved over 300 m. In our study reach we have previously reported observing a random distribution of debris dams in Rocky Branch in 2000 with a subsequent trend in 2001 toward regular spacing of dams at 55–90-m intervals (Kraft and Warren, 2003). This latter observation suggests a slightly greater distance of typical wood movement than results from this study indicating a median wood movement distance of 35 m. Significant absence of wood from certain stream reaches in our earlier analysis indicated that at a specified distance interval from any given debris dam the probability of encountering another dam was lower than would be expected if dams were distributed randomly. Our wood distribution metric provides a quantitative estimate of the scale and regularity of consistent patterns in the spacing of intervals without debris dams.

Wood movement in any given year is strongly influenced by the frequency and magnitude of flood events (Lienkaemper and Swanson, 1987). For example, the link between wood movement and discharge was evident in high-gradient boulder-dominated streams in the Sierra Nevada, CA in which Berg et al. (1998) found no movement of 206 pieces of tagged LW in the first year of their study, but found that 11 pieces of wood moved in the second study year following a large flood event. Based on discharge measurements from a nearby gauging station, the observed wood movements in our study reach reflected conditions during typical annual flood regimes. No high discharge events occurred during the 4 years of our study, with peak discharge during 2 years of the study slightly greater than the long-term median and 2 years of discharge slightly below the long-term median. Because we did not measure wood movement in 2002, we cannot specifically tie wood movement to peak flow in any particular study year.

Although removal of the two debris dams in a previous study could have influenced some aspects of wood movement in this stream reach, we do not believe that dam removal strongly affected our study with regard to the questions addressed herein. None of the pieces that moved from 2000 to 2001 passed through the stream sections where the debris dams had been removed. From 2001 to 2003, two pieces moved through locations where the debris dams had been removed in August 2001. And from 2003 to 2004, only two pieces of LW passed these sections. It is important to note that these highly mobile pieces of large wood also passed channel-spanning dams of comparable size that remained in the stream during that period.

5.2. Wood loading

Consistent with the conceptual models for wood accumulation in stream systems with riparian forest in the aggrading phase of stand development, we found a net increase in LW volume and frequency over the 4 years of our study (Likens and Bilby, 1982; Valett et al., 2002; Benda and Sias, 2003). Total (gross) wood loading rates in our system were low (1.4 m^3 km^{-1} $year^{-1}$) relative to older forests in the Pacific Northwest. Lienkaemper and Swanson (1987) reported wood loading rates of 4.9 and 4.7 m^3 km^{-1} $year^{-1}$ from two headwater streams in old-growth forests at the H.J. Andrews Experimental Forest, OR. In an old-growth system in coastal Alaska, Martin and Benda (2001) estimated an average wood recruitment rate of 3.8 m^3 km^{-1} $year^{-1}$. It is important to recognize that trees in old-growth forests in the Pacific Northwest region can be very large, therefore the addition of a small number of trees can substantially increase wood loading. For example, Lienkaemper and Swanson (1987) attributed most of the new wood recruited to one of their study streams to two individual trees that entered the stream during an 8-year period. In a wood tagging study across multiple watersheds in northern Spain, Diez et al. (2001) found an average wood recruitment rate of 2.0 m^3 km^{-1} $year^{-1}$ for streams bordered by young and mature deciduous riparian forests and with bankfull widths ranging from 3.5 to 7.3 m. Although the mean input rate for the Iberian streams was relatively comparable to our estimate from Rocky Branch, input rates in these European streams were highly variable—particularly in their two largest streams. Specifically, one stream with a low wood loading rate (0.2 m^3 km^{-1} $year^{-1}$) in the Diez et al. (2001) study was located in a young forest with no trees greater than 30 cm DBH (the stream bankfull width was 5.8 m). This contrasted with a wider stream (7.3 m bankfull width) bordered by an older riparian forest containing many trees >30 cm diameter in which wood loading was 38 times greater (7.6 m^3 km^{-1} $year^{-1}$). Overall, these studies illustrate the variability in wood loading to streams and they confirm the important influence of tree size and stand age on wood loading to streams.

The estimated volume of LW standing stock in our study reach was slightly lower but comparable to other streams in watersheds dominated by second-growth forests (Richmond and Fausch, 1995; Gomi et al., 2001; Morris et al., 2007; Warren et al., 2007); however, the frequency of large wood (~39 pieces per 100 m in 2004) was comparable to streams associated with old-growth forests (Richmond and Fausch, 1995; Martin and Benda, 2001; Young et al., 2006; Morris et al., 2007). The high abundance but low relative volume of LW in this stream likely resulted from a severe ice storm that occurred in this region in 1998. The ice storm brought down tree limbs and contributed abundant smaller LW to many streams in the region, including Rocky Branch (Kraft et al., 2002). Due to increased LW deposition from this ice storm that occurred throughout portions of the northeastern U.S. and southern Canada, LW frequency and volume reported in this study are likely higher than streams of comparable forest age in unaffected parts of the region (Kraft et al., 2002). Because ice storms tend to “prune” branches from trees, most of the wood that entered our study stream as a result of the ice storm was shorter than the bankfull width. While much of this new wood was likely to have been carried into debris dams in the 2 years prior to this study, the abundance of shorter wood in the system as a whole may lead to a slightly greater proportion of mobile wood in these systems relative to comparable streams in the northeastern U.S. that were not strongly impacted by the ice storm. An abundance of shorter LW trapped in debris dams may account for the smaller overall mean length of LW. Smaller wood retained in dams may also account for the lack of a significant difference between mobile and stationary wood.

The 1998 ice storm could have impacted wood input in two opposing ways. First, by pruning branches and killing some trees, the ice storm could have deposited wood into the stream all at once shortly after the storm, but depleted potential LW sources for the future and thereby diminished wood loading over the 4 years of our study. Alternatively, given that the ice storm did not directly kill many trees – yet caused severe damage that could subsequently lead to disease, insect infestation, and rot (Takahashi et al., 2007) – post-ice storm mortality of entire trees or tree branches could have increased in-stream LW recruitment during the study period. We cannot clearly determine if either of these two factors affected wood inputs to Rocky Branch in the current study.

5.3. Large wood mass balance

Wood loading rates were similar under both scenarios examined (0.09–0.15 m^3 100 m^{-1} $year^{-1}$), yet were greater than the long-term input rate calculated by Warren et al. (2007) in a space-for-time assessment of small streams in second-growth forests of New Hampshire (0.03 m^3 100 m^{-1} $year^{-1}$). We consider the wood loading estimates from our two scenarios as representative of the likely upper and lower bounds for recent wood input rates to the study stream. The age of streamside forests in the previous space-for-time study ranged from approximately 30–85 years. The older forests in that study are similar to the estimated age of dominant streamside trees at the Rocky Branch study site (60–80 years). Yet the current study estimated recent wood input rates from streamside forests to be greater than the previously published evaluation of in-stream wood accumulation that estimated inputs over a longer timespan (Warren et al., 2007). The long-term estimate integrated wood inputs over a time period spanning wood loading that occurred early in forest succession – when wood inputs to streams were likely to be low due to an absence of large trees – with more recent conditions of greater wood inputs (as measured in this study). The difference in estimated wood loading between the current study and the previous space-for-time analysis supports the idea that wood recruitment rates change as forests mature.

6. Conclusions

Our data support the broadly applicable concept that LW length strongly influences its potential to move within a stream (Lienkaemper and Swanson, 1987; Young et al., 1994; Berg et al., 1998; Martin, 2001). However, wood shorter than bankfull width does not always move and a high frequency of debris dams can reduce LW movement rates and movement distances for wood of all sizes. Large wood input was greater than LW export within our study reach, and overall large wood recruitment during the 4 study years was greater than the recruitment rate inferred from a broader space-for-time analyses of second-growth forests in New Hampshire. This likely resulted from the low wood loading rates in young forests typical of our study site. Wood recruitment from the mature hardwood forest adjacent to Rocky Branch was lower than recruitment rates from old-growth forests of the coastal Pacific Northwest, and within the range reported for second-growth hardwood forest system in Spain. Given the absence of major wood input events during our study period, wood input measurements reflect input rates associated with natural mortality and branchfall. Periodic disturbance events in the riparian area would likely increase wood input beyond the rates reported here.

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