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Primary Research Paper

Effects of large woody debris addition on stream habitat and brook trout populations in Appalachian streams

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Abstract

Large woody debris (LWD) was added to eight streams in the central Appalachians of West Virginia to determine if stream habitat could be enhanced and brook trout (*Salvelinus fontinalis*) populations increased. Brook trout populations were assessed one year prior to habitat manipulation and 3 years post-habitat manipulation. LWD was added by felling approximately 15 trees per 300 m stream reach. Four of the streams had LWD added to one 300 m reach with 300 m unmanipulated reaches upstream and downstream of the manipulated reach to observe within-stream effects of LWD additions on brook trout density. The remaining four streams had LWD added to three 300 m reaches and these streams were compared to those with only a single 300 m manipulated reach to observe the effects of the extent of habitat manipulation on brook trout density. New pools were formed by the addition of LWD, but overall pool area did not increase significantly in reaches where LWD was added. The relatively high gradient and coarse substrate of these streams may have precluded the added LWD from having a significant influence on stream channel morphology and habitat complexity. No pools were formed in the highest gradient stream, while the stream with the most pools formed had the lowest gradient. Brook trout populations fluctuated following habitat manipulations, and there was no overall effect of the LWD additions on within-stream variability in brook trout density. When there were significant differences among-streams with different extents of LWD additions, those streams receiving LWD additions over a large extent had the greatest brook trout densities. The full potential of added LWD to change stream habitat and influence on brook trout populations may take more time to develop than the 3 years post-manipulation period of this study.

Introduction

Large woody debris (LWD) plays an important role in structuring small stream habitat. The abundance of LWD helps to define the degree of habitat complexity through the formation of pools (Berg et al., 1998), creation of cover and refugia (Angermeier & Karr, 1984), sorting and storage of sediment, and increasing bank stability (Sheilds, 1998). It also influences stream trophic dynamics by increasing retention of organic matter (Smock et al., 1989; Raikow et al., 1995) which serves as substrate and food sources for macroinvertebrates. Debris dams decrease nutrient spiraling length in small streams and increase secondary production (Gurnell et al., 1995). Thus, LWD may influence key habitat components necessary to the life cycle of stream fish.

Several studies have shown a positive correlation between salmonid abundance and the amount of

LWD in streams. Berg et al. (1998) and Fausch & Northcote (1992) both found that fish abundance was strongly correlated with total pool volume within a stream reach, which was governed by the amount of boulders and LWD in western streams. Rates of occupancy by salmonids in a given habitat type (e.g. pool, riffle, glide) increase with the amount of LWD (Flebbe & Dolloff, 1995; Young 1996; Neumann & Wildman 2002). Riley & Fausch (1995) and Gowan & Fausch (1996a, b) found salmonid abundance increased in response to LWD addition. However, they found high rates of fish movement and suggest that the observed increase in abundance was primarily due to increased immigration rather than increased survival. Other habitat manipulation studies in which LWD has been added have shown mixed results with the effects on fish populations differing by species, age, and season (Solazzi et al., 2000; Roni & Quinn 2001). Warren & Kraft (2003) found no effect of the removal of LWD on brook trout populations in Adirondack Mountain streams (NY, U.S.A.).

Although salmonid abundance may be positively correlated with the amount of LWD within streams, fluctuations in flow and the frequency of drought and flood events are also important factors interacting with LWD to govern abundance of fish in small streams. Binns & Eiserman (1979) found strong correlations between late summer flow and annual stream flow variation and the standing crop of trout in Wyoming streams. Flood and drought events can significantly reduce the abundance of brook trout in Appalachian streams (Roghair et al., 2002; Carline & McCullough 2003; Hakala & Hartman 2004). Abundant LWD may dampen the effects of fluctuating flows on fish abundance in small streams. For example, LWD provides areas where fish may seek refuge from high current velocities during high stream flow events (Harvey et al. 1999). Also, during drought events, riffle area decreases more than pool area (Hakala & Hartman 2004) and as total pool area increases with LWD abundance, so does refugia during extreme low flow events.

The amount of LWD present in small streams is directly related to the past land-use of the surrounding riparian area. Streams in disturbed forests typically have lower amounts of LWD and lower pool numbers and area than streams in old-growth forests (Silsbee & Larson, 1983; Evans et al., 1993; Ralph et al., 1994). The forested riparian zone surrounding many central Appalachian streams was destructively logged during the late 19th and early 20th century, which depleted much of the source of LWD. Streamside management zones (SMZs) are now established to protect riparian vegetation and stream habitat (although compliance may not be mandatory in all regions). In the central Appalachian mountains of West Virginia, streamside management zones prohibit the construction of roads running parallel to the stream thereby reducing sedimentation. They also limit timber harvest to $\leq 50\%$ of the basal area thereby protecting the source of LWD. However, it may be many more years before secondary growth within these SMZs can reach the age required to contribute LWD in amounts equivalent to those seen in old-growth systems. (Mature stands in the central Appalachians are >90 years old, therefore they may not begin to contribute LWD in amounts seen in old growth until they reach 150–200 years.)

Stream habitat manipulation is widely used to mitigate the effects of degradation caused by past land-use. However, the effects of habitat manipulations are rarely tested in replicated field experiments. Studies are often pseudo-replicated within a stream with different treatments in different stream reaches (e.g. Cederholm et al., 1997) or are evaluated as 'before-and-after' type studies (e.g. Hunt, 1976). Accordingly, there is a need for more controlled field experimentation, replicated over several streams within a region, to gain a better understanding of the relationship between habitat and fish population dynamics.

The objectives of this study were to (1) determine the effectiveness of artificially adding LWD on the creation of pool habitat in eight streams of the central Appalachian Mountains of West Virginia; (2) assess the incorporation of added LWD into stream habitat (3) determine the effect of LWD additions on within-stream variation in brook trout density; and (4) determine the effect of the extent of LWD additions on brook trout populations among streams.

Study sites

This study was conducted in eight tributaries of the Middlefork River, Randolph Co., WV (Fig. 1).

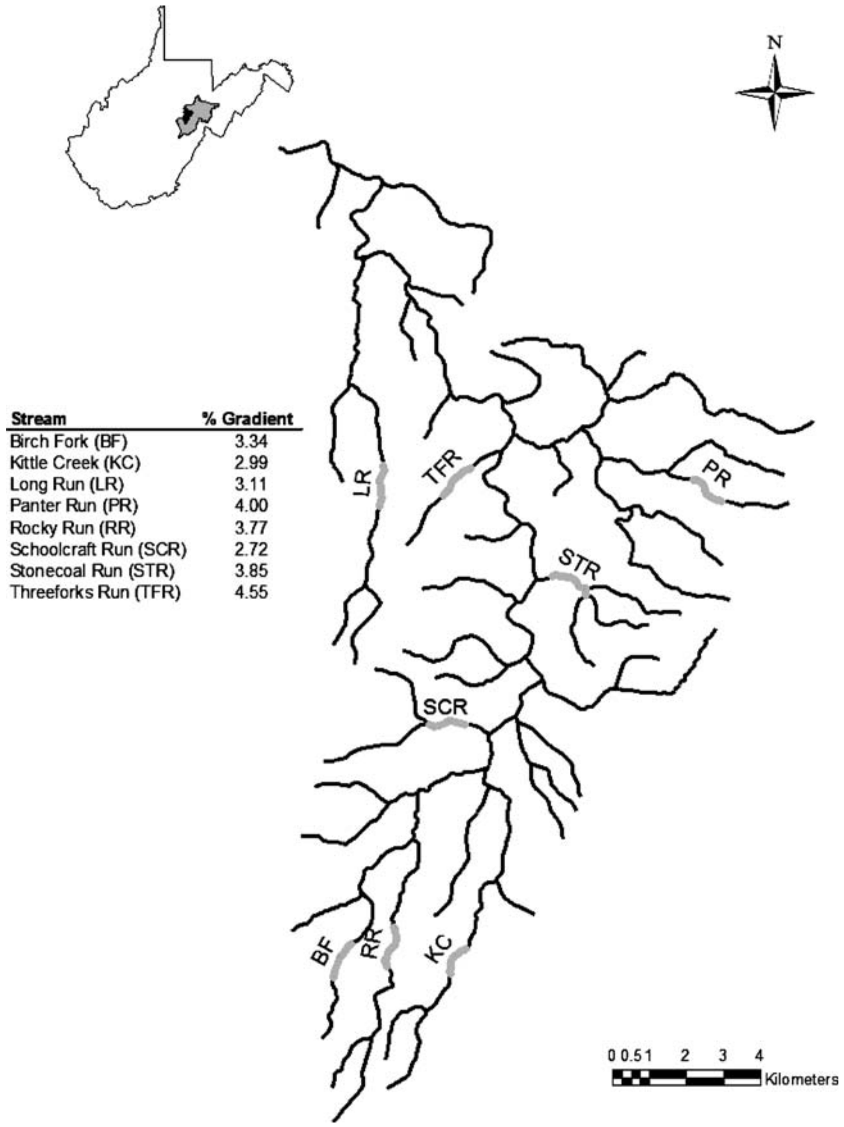

Figure 1. Middle Fork River watershed, Randolph Co., WV.

The watershed is located in the Allegheny Plateau physiographic province. All streams are small, low order, and relatively high gradient. Stream elevations ranged from 707 to 890 m. The percent canopy cover averaged 70–80%, and stream temperatures remained adequate for brook trout for the majority of the year with temperatures rarely exceeding 20 °C. Channel types could generally be considered Rosgen types A and B (Rosgen, 1994) and dominated by coarse substrate.

The surrounding watersheds of all streams are privately owned and actively managed for timber production. Timber harvest activities occurred in all watersheds throughout the study. The surrounding forest ranged from 65 to 80 years old and was dominated by mixed hardwood species. All riparian areas have been logged in the past and most logging activity occurred in the early 1900's. Evidence of timber harvest activity prior to the establishment of SMZs was apparent along all steams with the presence of abandoned logging roads, railroad grades, stream crossings, and highly eroded streambanks in some areas. Although limited harvest is permitted in SMZs surrounding these streams, no such activity occurred along any of the streams during the course of our study. In terms of past and present land-use activity, these streams are typical of the central Appalachians.

Typical of Appalachian headwater streams, fish species diversity was low in all of the streams in this study. Brook trout were the dominant species. Other species found, in order decreasing of abundance, included: mottled sculpin (*Cottus bairdi*), blacknose dace (*Rhynichthys atratulus*), creek chub (*Semotilis atromaculatus*), white sucker (*Catostomus commersoni*), and longnose dace (*R. cataractae*).

Methods

Experimental design

Three-300 m study reaches (designated upstream, middle, and downstream reaches according to their relative position along the stream gradient) were established on each stream and these replicate reaches were separated by 100 m. Our study was divided into two experiments. In the first experiment (hereafter referred to as the 'within-stream experiment'), four of the eight streams were randomly selected to receive LWD additions to the middle 300 m reach, while the upstream and downstream 300 m reaches were un-manipulated, so as to examine the effect of LWD additions on within stream variation in brook trout density. In the second experiment (hereafter referred to as the 'among-stream experiment'), the four remaining streams had LWD added to all three 300 m reaches. These streams would then be compared to the streams in the first experiment to determine the effect of the extent of habitat manipulation on brook trout density. There was not a 'true' control stream without any habitat manipulation for the second experiment. Because several studies showed trout abundance was greatest in stream reaches with more LWD (Fausch & Northcote 1992; Flebbe & Dolloff 1995; Riley & Fausch 1995; Gowan & Fausch 1996a), we felt a more appropriate question to address was how the extent of habitat manipulation influenced brook trout density. Trout populations were then assessed during the fall (Sept.–Oct.) and spring (June) beginning in Sept. 1999 with the last assessment occurring in June 2003.

Habitat assessment

Habitat was surveyed each summer during baseflow conditions. Habitat units were classified as pools, riffles, or runs. Pools were considered areas of relatively deep areas with slow current velocity and laminar flow. Riffles were shallower with faster current velocity, and broken water surfaces. Runs were considered areas where the depth was shallower than pools and current velocity was swifter than pools, but still maintained laminar flow and unbroken water surfaces. The length of each habitat unit was measured along the thalweg to the nearest 0.1 m. Wetted and bankfull widths were visually estimated at transects established 0.25, 0.50, and 0.75 of the thalweg length. Depth was measured at three points along each transect to the nearest cm. At every fifth habitat unit, the wetted and bankfull widths were both estimated and verified by measuring to the nearest 0.1 m. The area of each habitat unit was estimated by multiplying the mean estimated wetted and/or bankfull width within a habitat unit by the length of the habitat unit. Estimated areas were then corrected by regression of verified area on estimated area and predicted values of the regression equation were used as the area of the habitat unit.

Large woody debris was considered any piece of wood within the bankfull channel, including 'spanners' which could be in the water or at the surface of the water under bankfull flow (Overton et al., 1997) and was a minimum of 10 cm diameter and 1 m length (Richmond & Fausch, 1995). Within each reach, we measured the diameter and length of each piece of LWD. Diameters (nearest cm) were measured at each end, and if the piece extended out of the bankfull channel, diameter was measured where the piece crossed the bankfull edge of the stream. Total lengths and lengths within the bankfull channel were measured on each piece. Total and bankfull volume (m^3) were calculated from the equation $V = \pi(D_1^2 + D_2^2)L/8$, where D_1 and D_2 are the diameters at each end, and L is the total or bankfull length (Richmond & Fausch 1995). In the case of branches extending from a central bole, only those branches conforming to the minimum size requirements were counted and measured.

Each piece of LWD in the channel was classified according to the primary function it appeared to be serving. The classification of bank stabilization was given to any piece which was embedded in the stream bank serving to reduce erosion. Pool formation was any piece that was directly responsible for scouring or damming action and the creation of pool habitat. Sediment storage was any piece influencing stream flow such that areas of deposition of fine sediment were created. Organic storage was any piece which created areas of leaf and fine woody debris accumulation. The classification of overhead cover was given to pieces that did not influence stream flow or channel morphology, but provided areas whereby fish could swim beneath for cover. Pieces which were unstable and would likely move during high flow events or did not apparently serve any of the above functions were classified as having no apparent function. The function of an individual piece of LWD may vary depending on flow, but we considered only the function at summer baseflow in this study.

Brook trout populations estimates

Population estimates and resulting density estimates of brook trout were conducted in each reach of each stream during June and Sept.–Oct. during each year of the study. Within a 300 m stream reach, a 100 m sub-reach was randomly selected for sampling. Block nets were placed at the upstream and downstream ends and brook trout were captured using a pulsed DC backpack electrofishing unit and a standard three-pass removal technique. Brook trout from each pass were individually weighed to the nearest g, measured to the nearest mm total length, and released back into the area of capture following completion of the third electrofishing pass. Brook trout were separated into young-of-the-year and age-1 + age classes according to length frequency distributions and removal population estimators were determined for each age class using the program CAPTURE (White et al., 1982).

LWD additions

Large woody debris was added in August 2000. A minimum of 15 trees were targeted for felling in each reach. Occasionally more trees were felled if a target tree was hung on surrounding trees during felling. Felled trees were selected based on size (> 10 cm dbh), minimization of canopy cover removal, and ultimately by the ease with which the loggers could fell the tree into the stream channel. Often after felling, no portion of the tree came in contact with the streambed due to steep banks on either or both sides. In such cases the loggers bucked one of the ends of the tree so that at least some portion of the tree came in contact with the stream bed where it had the potential of altering channel morphology. Branches were left in place, except where removal was needed to get some portion of the tree in contact with the streambed.

Immediately after the trees were felled, the newly added LWD was quantified as described in the habitat measurement protocol. Each piece of LWD was individually double marked with two numbered aluminum tags and the location of each piece was determined by measuring the distance from the upstream end of the stream reach. In addition to the standard measurements to assess LWD, the horizontal angle of the added pieces relative to the thalweg was recorded, and the vertical angle of entry into the stream channel was measured with a clinometer. The dominant substrate type (e.g. boulder cobble, gravel, pebble) was noted at the location of each added piece. The bucking of trees to achieve contact with the streambed resulted in > 15 pieces of LWD being added in each stream reach. If the residual pieces from bucking met the minimum size requirements to be classified as LWD, they were also tagged and quantified as above. All measurements were repeated on each piece in subsequent summers each year to determine stability of the added pieces. Also upon re-assessment, the function of each added piece was noted.

Statistical analysis

Hypothesis tests in the within-stream experiment considered individual stream reaches as the experimental units. Conversely, hypothesis tests in the among-stream experiment considered the entire study area of each stream as the experimental unit and measurements were either summed across the three 300 m reaches on each stream or averaged among the three 300 m reaches on each stream prior to statistical analysis.

Pre-manipulation channel morphology, brook trout density, and brook trout size were analyzed to ensure that experimental units were equivalent at the beginning of the study. In the within-stream experiment, initial pool area and number of pools per 300 m stream reach, and initial brook trout density (#/100 m^2) were compared between stream reaches using a blocked ANOVA. The stream was the random block effect and the stream reach (LWD to be added vs. unmanipulated) was the treatment effect. In the among-stream experiment, pool area and the number of pools were summed over the three 300 m reaches and expressed as total pool area and total number of pools per 900 m of stream. Brook trout density was averaged over the three reaches in each stream. A one-way ANOVA was then used to determine if there were any pre-manipulation differences among streams to receive LWD additions to a single 300 m reach (small extent) vs. three 300 m reaches (large extent).

Post manipulation effects on stream habitat, brook trout density, and brook trout size were analyzed as a repeated measures ANOVA using the PROC MIXED procedure in SAS® version 8.3. In the within-stream experiment, the stream was used as a blocking factor and stream reach within treatment was used as the random subject effect. In the among-stream experiment, stream within treatment was used as the random subject effect.

Hypotheses specifically relating to the added LWD were also tested. The size (length and diameter) of added large woody debris (LWD_A) was compared to that of naturally occurring large woody debris (LWD_N) using a Wilcoxon rank sums test. Functionality of LWD_A was compared to LWD_N using a χ^2 test for homogeneity. Unstable pieces of LWD_A in this study were considered those that moved ≥ an arbitrary distance 5 m from 1 year to the next. Properties governing whether a piece of LWD_A was stable or not were assessed using logistic regression. The likelihood of a piece of LWD_A forming a pool was also assed using logistic regression. The number of pieces of LWD serving primary functions of bank stabilization, pool formation, sediment storage, organic storage, and overhead cover for trout were analyzed in the same manner as stream habitat and brook trout density using a blocked ANOVA to compare pre-manipulation numbers and repeated measured ANOVA for post manipulation numbers.

Results

Large woody debris

There was high variation in the abundance and volume of LWD_N prior to habitat manipulations. The overall average number of pieces per 300 m stream reach was 55 (range: 15–116) and the overall average volume of LWD per 300 m stream reach was 12.10 m^3 (range: 2.13–45.87 m^3). Under summer baseflow conditions, the bulk of LWD was assigned a primary function of serving in bank stability (28%) or in storing organic material (25%). Only 4% of the LWD was involved in the creation of pool habitat. Those pieces forming pools had a median total length of 4.6 m compared to 3.0 m for pieces not forming pools, and a median diameter of 18 cm compared to 15 cm for pieces not forming pools. These differences were significant (total length $p = 0.01$, mean diameter $p < 0.01$ by Wilcoxon rank sums test).

Abundance and volume of LWD_N was compared among stream reaches (in the case of the within-stream experiment) or among streams (in the case of the among-stream experiment) prior to habitat manipulation. In the within-stream experiment, both abundance and volume of LWD_N were equivalent between treatment reaches (abundance: $F_{1,3} = 5.17$, $p = 0.11$; volume: $F_{1,3} = 1.82$, $p = 0.27$). Likewise, the total abundance and volume in 900 m of stream were equivalent between small and large extent streams in the among-stream experiment (abundance: $F_{1,7} = 2.22$, $p = 0.19$; volume: $F_{1,7} = 0.28$, $p = 0.61$).

Loggers added an average of 22 (range: 18–26) pieces of LWD to those stream reaches receiving habitat manipulations in August 2000. The dominant species of LWD added were yellow birch (29%), yellow poplar (13%), black birch (13%), and sugar maple (9%). Following the addition of LWD in August 2000, the reaches receiving LWD additions in the within-stream experiment had

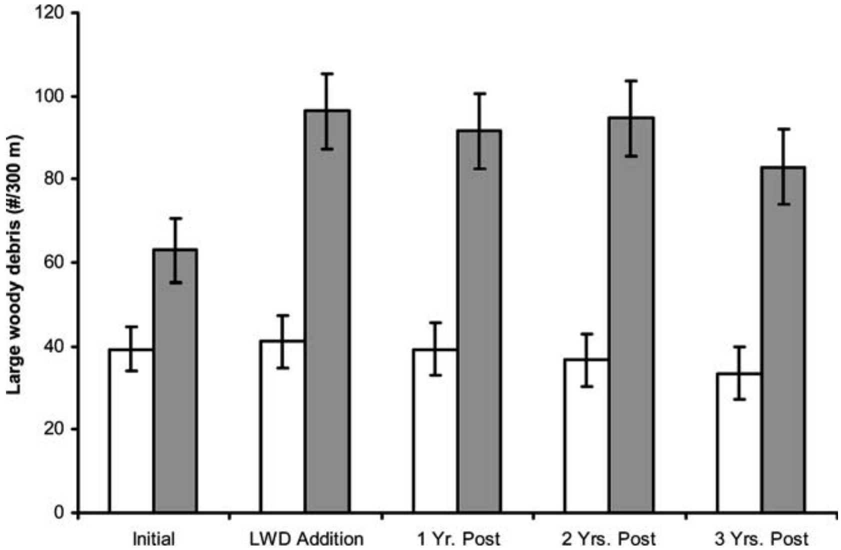

Figure 2. Abundance of LWD in the within-stream experiment prior to, and following the addition of LWD (2000–2003). Open bars correspond to unmanipulated reaches and shaded bars correspond to reaches were LWD was added. Error bars correspond to standard errors.

significantly more total LWD than the un-manipulated reaches throughout the remainder of the study period (Fig. 2; abundance: $F_{1,5} = 29.62$, $p < 0.01$; volume: $F_{1,5} = 12.55$, $p = 0.02$). In the among-stream experiment, the total abundance and volume of total LWD per 900 m of stream did not increase significantly following the LWD additions (abundance: $F_{1,6} = 1.36$, $p = 0.29$; volume: $F_{1,6} = 3.04$, $p = 0.13$). There was much variation among-streams in the amount of LWD_N which appeared to negate any treatment effect. However, the size of the LWD_A was significantly larger than that of LWD_N with the median total length of LWD_A equaling 9.3 m compared to 3.0 for LWD_N , and median diameter equaling 22 cm compared to 15 cm for LWD_N ($p < 0.01$ in both cases by Wilcoxon rank sums test). If we use the median length and diameter of LWD_N that was involved in the creation of pools (4.6 m total length and 18 cm diameter) as a minimum size criteria for the LWD which can potentially modify stream habitat by forming pools, then the abundance and volume of this large size class of LWD was greater in the large extent streams than in the small extent streams following habitat manipulations (Fig. 3; abundance: $F_{1,6} = 21.80$, $p < 0.01$; volume: $F_{1,6} = 21.21$, $p < 0.01$).

In reaches where LWD was added (both experiments combined), many of the added pieces became functional one year after addition and the percentage of total LWD serving some sort of function increased following habitat manipulation ($F_{3,60} = 18.29$, $p < 0.01$). The percentage of functional pieces of LWD increased from 49 ± 6% in 2000, prior to manipulation, to 69 ± 5% by 2001. This percentage remained fairly constant in the remaining years of the study with 71 ± 6% and 70 ± 4% serving some sort of function in 2002 and 2003, respectively. Functionality of LWD_A differed significantly from the functionality of LWD_N each year post manipulation ($p < 0.01$ in all cases; Table 1). The largest discrepancy between LWD_A and LWD_N was in the proportion of pieces functioning in bank stabilization. A higher proportion of LWD_A was involved in the formation of pools than LWD_N. This is likely because the mean volume of a piece of LWD_A (1.00 ± 0.66 m^3) was significantly greater than that of LWD_N (0.14 ± 0.01 m^3) (Wilcoxon two-sample test, $p < 0.01$).

The number of total pieces of LWD serving to provide overhead cover for brook trout increased following the additions. These pieces could have been pieces which were added or newly recruited

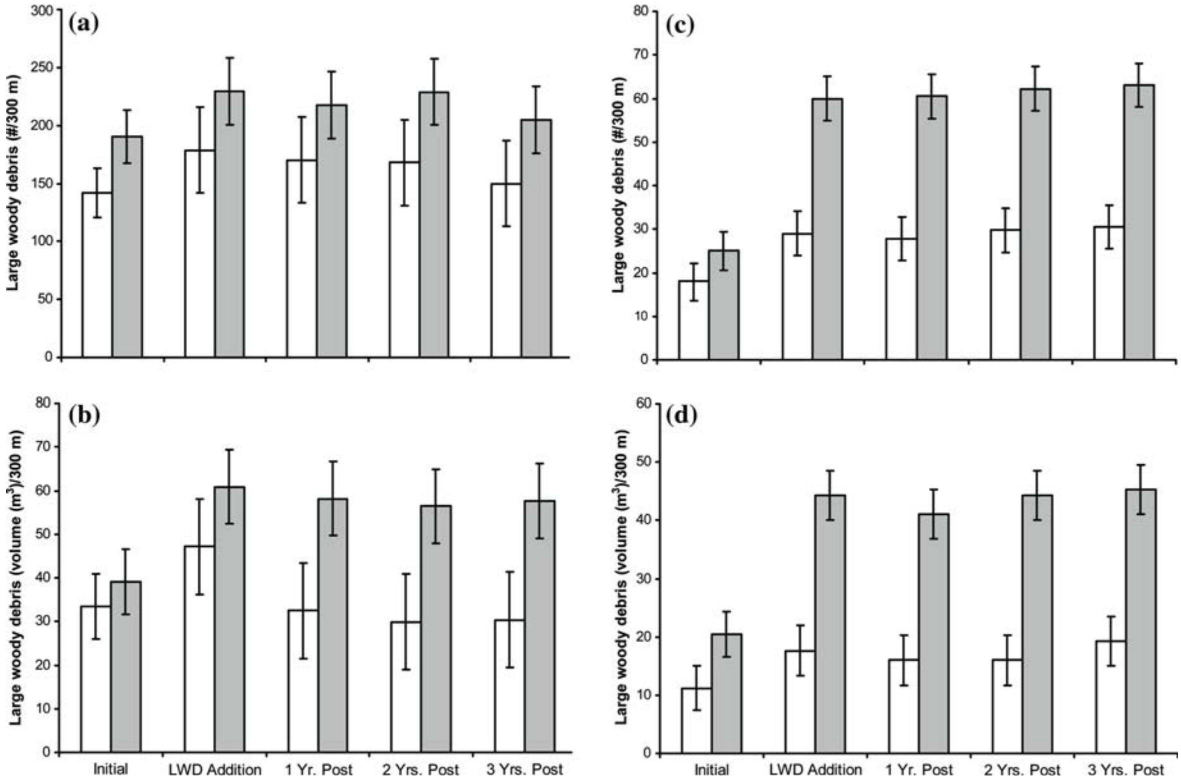

Figure 3. Abundance and volume of LWD in the among-stream experiment prior to and following the addition of LWD (2000–2003). Panels a & b show total LWD while panels c & d show amounts of LWD greater than the median size of naturally occurring LWD involved in pool formation prior to habitat manipulation (Meidan size = 4.6 m total length and 18 cm diameter). Open bars correspond to streams where LWD was added to one 300 m reach and shaded bars correspond to streams where LWD was added to three 300 m reaches. Error bars correspond to standard errors.

pieces which were captured by added pieces. In the within-stream experiment, pre-manipulation numbers were equivalent between reference and manipulated reaches ($F_{1,3} = 0.18$, $p = 0.70$). Also, pre-manipulation numbers were equivalent between extents of habitat manipulation in the among-stream experiment ($F_{1,7} = 1.54$, $p = 0.26$). Following the addition of LWD, the number of pieces involved in providing areas of overhead cover tended to increase in manipulated stream reaches in the within-stream experiment (0.75 ± 0.41 vs. 5.00 ± 2.4 per 300 m) , but the results weren't significant at the $a = 0.05$ level ($F_{1,7} = 4.10$, $p = 0.08$). However, in the among-stream experiment, the number of pieces of LWD providing overhead cover was significantly higher in streams where LWD was added to 900 m compared to 300 m ($F_{1,6} = 13.71$, $p = 0.01$). Total numbers of pieces providing overhead cover were 18.50 ± 3.71 and 9.25 ± 3.77 in large and small extents of manipulation, respectively. The total number of pieces of LWD serving other functions did not differ significantly following habitat manipulation in either the within or among-stream experiments.

The majority of LWD_A was considered stable, and did not move > 5 m from its original location in the stream channel. The percentage of unstable pieces of LWD_A was 3.40% between 2000 and 2001, 2.87% between 2001 and 2002, and 4.13% between 2002 and 2003. Logistic regression was used to identify properties governing the stability of LWD_A. One of the assumptions of logistic regression, similar to linear regression, is that the independent variables are not correlated. Several of the variables measured on each piece of LWD_A were correlated, therefore a reduced set of uncorrelated variables consisting of total length,

Table 1. Numbers of pieces of natural and added LWD serving various functions in the stream channels of eight tributaries of the Middle Fork River, WV

Year	Function	Natural	Added	X^2	p
2001	None Apparent	360 (28.67)	132 (37.22)	116.9	< 0.01
	Bank stability	237 (18.93)	2 (0.57)		
	Overhead cover	68 (5.43)	57 (16.19)		
	Organic Storage	436 (34.74)	117 (32.95)		
	Pool formation	45 (3.59)	23 (6.53)		
	Sediment storage	108 (8.63)	23 (6.53)		
2002	None Apparent	354 (26.98)	130 (36.65)	95.7	< 0.01
	Bank stability	231 (17.61)	2 (0.57)		
	Overhead cover	48 (3.66)	31 (8.81)		
	Organic Storage	529 (40.32)	141 (39.77)		
	Pool formation	38 (2.90)	25 (7.10)		
	Sediment storage	112 (8.54)	25 (7.10)		
2003	None Apparent	348 (30.55)	116 (32.67)	98.6	< 0.01
	Bank stability	196 (17.21)	2 (0.57)		
	Overhead cover	52 (4.57)	41 (11.65)		
	Organic Storage	432 (37.93)	133 (37.50)		
	Pool formation	40 (3.51)	33 (9.38)		
	Sediment storage	71 (6.23)	29 (8.24)		

Overall functionality differed significantly between sources of LWD. Numbers in parentheses correspond to percentages.

dominant substrate size at the original location, the horizontal angle of the piece in relation to the stream channel, and the vertical angle of entry into the stream channel were used. Of these, only total length showed a significant influence on the likelihood of a piece remaining stable (Wald $X^2 = 9.60$, $p < 0.01$, odds ratio = 1.15). The odds of a piece remaining stable increased by 15% with a 1 m increase in total length.

Stream channel morphology

The initial number and area of pools was compared between treatments prior to the addition of LWD. The number of pools and area of pools was equivalent between reaches to receive LWD additions and those to remain unmanipulated in the within-stream experiment (number: $F_{1,3} = 0.22$, $p = 0.67$; area: $F_{1,3} = 0.79$, $p = 0.43$), and was equivalent between extents of habitat manipulation in the among-stream experiment (number: $F_{1,6} = 2.19$, $p = 0.19$; area: $F_{1,6} = 0.33$, $p = 0.59$).

The addition of LWD created pools in all streams except for Threeforks Run. In the streams where LWD was added to a single 300 m reach, between 0 and 2 pools were created by LWD_A by 2003. As expected, more pools were created by LWD_A in the streams where LWD was added to three 300 m reaches and the total number of pools created by the end of the study ranged from 2 to 8 pools. The number of pools created varied over time as pools formed in one year reverted to riffle or run habitat in following years. There was a marginally significant correlation between the number of pools created per 300 m stream reach and average stream gradient with the number of pools created decreasing as stream gradient increased ($r = -0.64$, $p = 0.08$).

Logistic regression was used to determine what properties of a piece of LWD_A increased the likelihood of creating a pool. The variables used in this analysis were bankfull length of an LWD_A piece, mean bankfull diameter, dominant substrate size, the horizontal angle of the piece in relation to the stream channel, and the vertical angle of entry into the stream channel. Of these, only bankfull length showed a significant influence on the likelihood of a piece forming a pool (Wald $X^2 = 4.37$, $p = 0.04$, odds ratio = 1.23). The odds of a piece forming a pool increased by 23% with a 1 m increase in bankfull length.

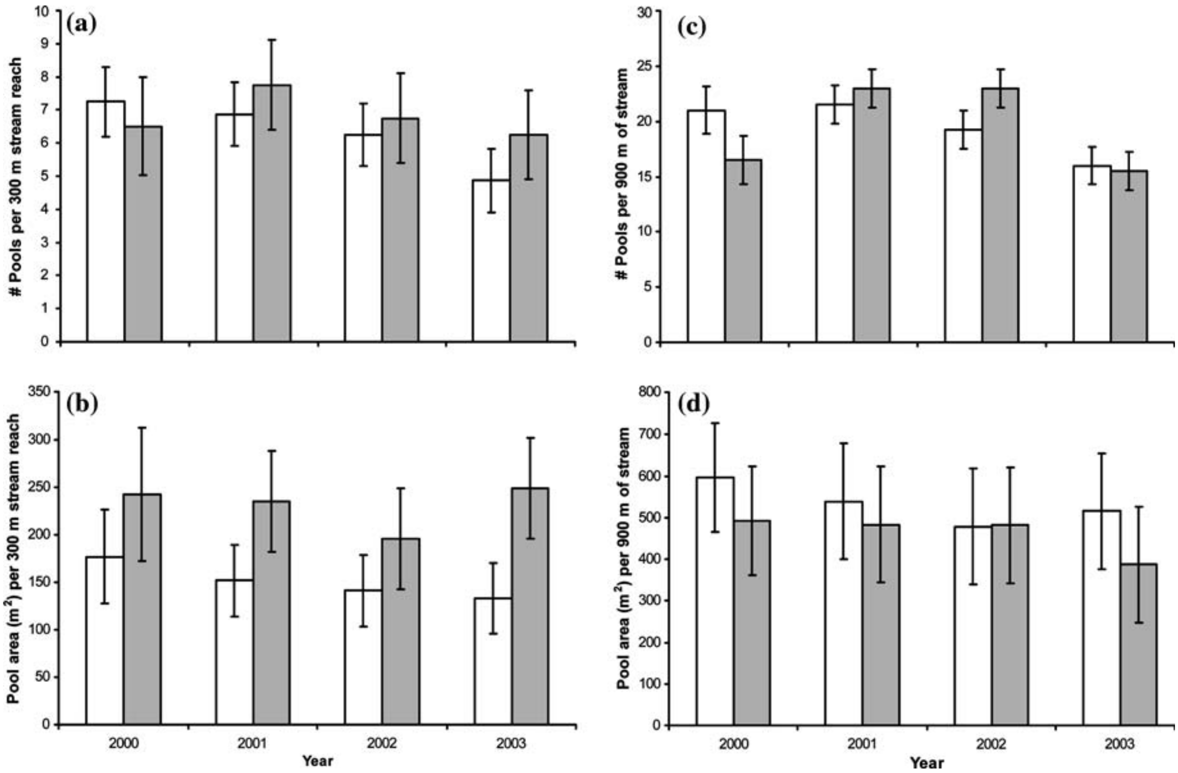

Figure 4. Number and area of pools in the within-stream experiment (panels a & b; open bars = unmanipulated reaches, shaded bars = LWD added reaches) and in the among-stream experiment (panels c & d; open bars = LWD added to one 300 m reach, shaded bars = LWD added to three 300 m reahes). LWD additions occurred following the initial habitat assessments in 2000. Error bars correspond to standard errors.

Despite the creation of some pools by the LWD_A , there was no significant overall change in channel morphology. In the within-stream experiment, pool number and area did not differ between reaches where LWD was added compared to unmanipulated reaches following the addition in 2000 (Fig. 4; number: $F_{1,7} = 0.41$, $p = 0.54$; area: $F_{1,7} = 2.10$, $p = 0.19$). Likewise, there was no difference following habitat manipulation between the small and large extent treatments in the among-stream experiment (Fig. 4; number: $F_{1,6} = 0.49$, $p = 0.51$; area: $F_{1,6} = 0.10$, $p = 0.76$). The loss of some naturally occurring pools appeared to offset the addition of pools from LWD_A in overall net habitat change.

Brook trout density

Young-of-the-year brook trout density data collected in the spring seasons was dropped from the statistical analysis because YOY brook trout at this time are generally < 60 mm (total length) and it was felt that low catchability of this small size class at this time of the year resulted in negatively biased density estimates.

Large woody debris additions had little effect on brook trout densities. Prior to habitat manipulation, initial YOY and age 1 + brook trout densities were equivalent between reaches that were to receive LWD additions and reaches that were to be unmanipulated in the within-stream experiment (YOY: $F_{1,3} = 0.23$, $p = 0.66$; Fall Age 1 +: $F_{1,3} = 0.17$, $p = 0.71$; Spring Age 1 +: $F_{1,3} = 1.41$, $p = 0.32$). In the among-stream experiment, initial YOY and age 1 + brook trout densities were also equivalent between extents of habitat manipulation (YOY: $F_{1,6} = 0.38$, $p = 0.38$; Fall Age 1 +: $F_{1,6} = 0.39$, $p = 0.56$; Spring Age 1 +: $F_{1,6} = 0.16$, $p = 0.70$). Young-of-the-year and age 1 + trout densities fluctuated over time, and the time effect was significant ($p < 0.01$) in the repeated measures ANOVA for both within and among-stream experiments, but there was no consistent increase in the post-manipulation years in either the within or among-stream experiments (Figs. 5 & 6). Also, there was no significant treatment effect in either the within or among-stream experiments. In the among-stream experiment, there was a significant treatment × time interaction ($F_{2,12} = 7.56$, $p < 0.01$) for YOY and age 1+ brook trout density. Fisher's LSD multiple comparison test showed YOY density was greater in the large extent streams compared to the small extent streams during the fall 2001. This trend continued through the spring 2002 where the density of age 1+ brook trout was highest in the streams receiving the large extent of habitat manipulation ($p < 0.01$). However, both extents of habitat manipulation again had equivalent YOY and age 1+ brook trout densities by the end of the study (Fig. 6).

Brook trout size

The addition of LWD had little effect on the total length of age 1+ brook trout. Initial sizes in the within-stream experiment were equivalent between reaches to receive LWD additions and those that were to remain unmanipulated (Fall: $F_{1,3} = 0.01$, $p = 0.96$; Spring: $F_{1,3} = 0.0.69$, $p = 0.46$). Likewise, initial age 1+ brook trout total length was equivalent between streams to receive large vs. small extents of LWD additions (Fall: $F_{1,6} = 4.35$, $p = 0.08$; Spring: $F_{1,6} = 0.02$, $p = 0.88$). Mean age 1+ brook trout total length ranged from 137 to 145 mm over all streams/treatments. Age 1+ brook trout total length varied through time following the addition of LWD, but there were no effects of the treatment in either the within or among-stream experiments.

Discussion

LWD additions and effects on stream habitat

Because LWD levels varied greatly between streams prior to habitat manipulation, the proportional increase due to the additions ranged

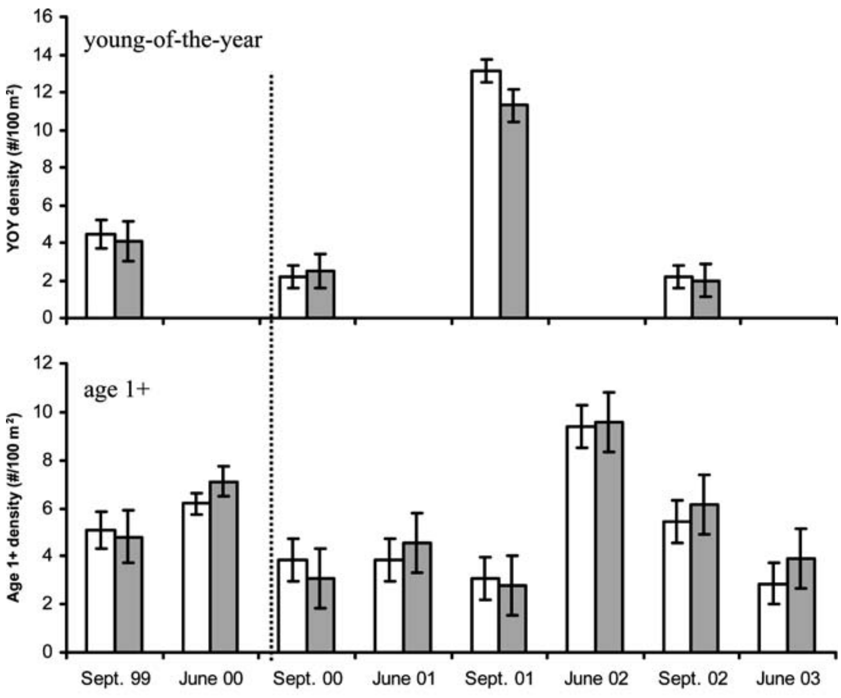

Figure 5. Mean brook trout density in the within-stream experiment. The dotted line corresponds to LWD additions. Open bars correspond to unmanipulated reaches and shaded bars correspond to reaches where LWD was added. Error bars correspond to standard errors.

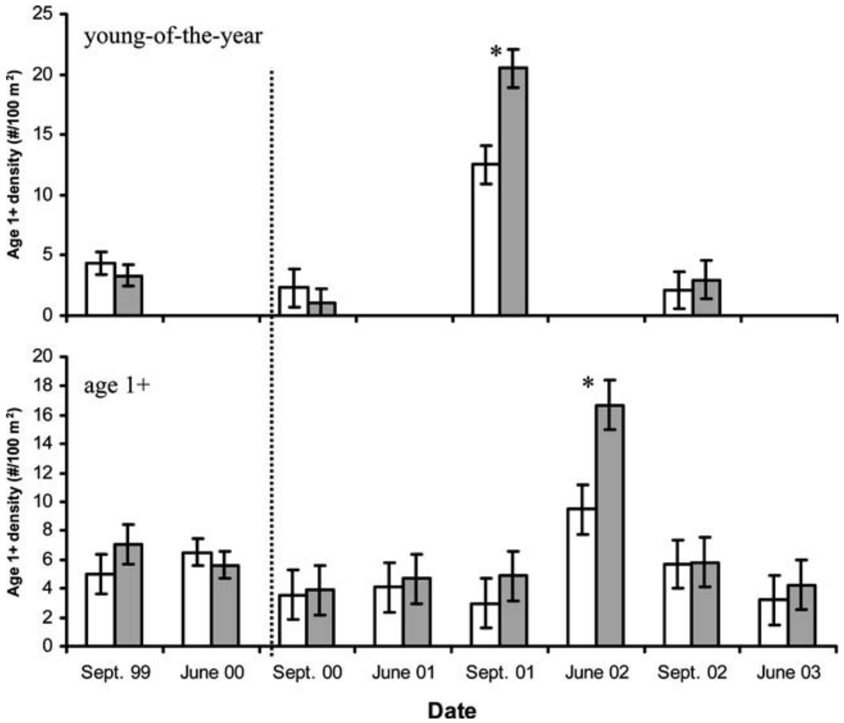

Figure 6. Mean brook trout density in the among-stream experiment. The dotted line corresponds to when LWD additions occurred. Open bars correspond to streams where LWD was added to one 300 m reach and shaded bars correspond to streams where LWD was added to three 300 m reaches. Significant differences between extents of LWD additions are denoted by (*) Error bars correspond to standard errors.

from 20 to 109% by number and 20–293% by volume. This disparity may be viewed as confounded treatment applications. However, if we would have added LWD to each stream in proportion to pre-manipulation levels, a 25% increase for example, we would have added as little as 4 trees per 100 m or as much as 29 trees per 100 m, depending on the stream. With as little as 4 trees per 100 m added, essentially no treatment would have been applied, whereas the addition of 29 trees per 100 m would also add a confounding effect of increased sunlight penetration and increased water temperatures. There is no ideal design for such manipulative studies because pre-manipulation habitat can vary widely among streams even within a small geographical region. Therefore, we chose an application that would add large pieces of LWD that could potentially form pool habitat without risking a significant opening of the canopy. In terms of large size classes of LWD which are most likely to form pools, all manipulated areas had significantly higher levels of LWD following the additions.

The addition of LWD had minimal effects on stream channel morphology in the eight streams of this study. Added pieces of LWD did create new pools in all of the streams except TFR, but there was no net increase in pool area following habitat manipulation. Channel structure in these headwater streams was dynamic, and as new pools were created by the LWD_A, other pools were lost. Also, some of the pools created by the LWD_A were only temporary; formed one particular year post-treatment and filling by the following year.

The lack of an effect on stream channel morphology may in part be due to stream gradient. We found a marginally significant negative correlation between stream gradient and the number of pools created per 300 m stream reach. In a similar study involving LWD additions to Appalachian streams, Hilderbrand et al. (1997) found pool area increased significantly in a low gradient (approximately 1%) stream while it did not change in a high gradient (3–6%) stream. They also noted that in the high gradient stream, some of the pools created by their LWD additions quickly reverted back to riffle habitat. Warren & Kraft (2003) also found that removal of LWD from high gradient streams of the Adirondack Mountains, NY, had no effect on brook trout populations and suggested that boulders are the main factor contributing to habitat complexity in high gradient systems. The average gradient in six of the eight streams in this study exceeded 3%. The stream where LWD formed the most pools (Schoolcraft Run) was also the stream with the lowest gradient.

In other studies, addition of LWD increased pool area (Binns, 1994; Riley & Fausch, 1995; Cederholm et al., 1997). However, in these studies the added structures were imbedded in the streambank or cabled to remaining tree stumps. Although engineered structures are very successful in the modification of stream channel morphology, these practices are labor-intensive techniques necessitating the use of heavy equipment, and the associated costs limit the scale of habitat manipulation. The methodology used in the habitat manipulations here was quite simple in comparison. A total of 4800 m of stream were manipulated in two days by two loggers.

The majority of the added pieces remained within the study areas on the streams. Only 18 out of the total 355 added pieces were unaccounted for by 2003. Relatively few of the added pieces ($<5\%$) were unstable, traveling more than 5 m between years. Stability was most closely governed by total length of the piece. In another study in Appalachian streams, Hilderbrand et al. (1998) also found LWD stability to be governed by length.

The high retention of LWD_A gives an indication of the number and volume of LWD that was once in Appalachian streams. Flebbe & Doloff (1995) report numbers of pieces of LWD in streams of old growth forests in Virginia ranging from 111 to 206 pieces per km. These numbers equate to 33–62 pieces per 300 m. The average number of pieces of LWD found per 300 m in our study falls within this range. However, the abundance of large pieces (>5 m length and >50 cm diameter) was lower than that reported by Flebbe & Dolloff (1995) for old growth streams. Also, the riparian areas of Appalachian streams once had a greater abundance of coniferous species such as red spruce (*Picea rubens*) and eastern hemlock (*Tsuga canadensis*) which decompose more slowly than hardwood species (Bilby et al., 1999). The high retention of LWD in our study coupled with the greater size of LWD in old growth systems, and differences between present and past species composition, suggest accumulations of LWD were much greater in the past than what is typically seen today even in areas where secondary growth of the riparian vegetation has matured.

Although the LWD additions did not significantly increase the pool area in these streams, the amount of LWD_A serving some sort of function was similar to LWD_N under summer baseflow conditions. By 2003, approximately 33% of the LWD_A was not serving any sort of function which was comparable to the 31% of LWD_N that was not serving any apparent function. However, the proportion of LWD_A that became involved in the formation of pools was higher than the proportion of LWD_N involved in pool formation. The LWD_A pieces were significantly larger than the standing stock of naturally occurring pieces in these central Appalachian streams, and the potential for pool creation increases with LWD size (Richmond & Fausch, 1995). Although the methodology used to add LWD in this study failed to increase pool area significantly, the full potential of the added LWD to enhance stream channel morphology may not be realized for many more years.

Brook trout populations

Brook trout abundance in small streams generally increases with the amount of pool area (Gowan & Fausch, 1996a; Neuman & Wildman, 2002) and pool area is influenced by the abundance of LWD (Richmond & Fausch, 1995; Berg et al., 1998). It was presumed that increasing the abundance of LWD would increase the area of pool habitat thereby potentially increasing brook trout abundance. However, pool area remained unchanged with the addition of LWD and it may be argued that a treatment was not applied to the streams. Nevertheless, LWD also supplies other benefits to stream habitat in addition to the creation of pool habitat, such as increased organic matter retention with potential increases in invertebrate production, and increases in overhead cover and refugia. Our results showed that the number of pieces of LWD involved in providing overhead over increased slightly in the within-stream experiment and increased significantly in the among-stream experiment. These habitat components could increase brook trout abundance through attraction of immigrant fish and higher retention of resident fish (Gowan & Fausch, 1996a, Harvey, 1998). However, Sweka (2003) conducted a study of brook trout movement on the streams used in this study, but found no significant influence of the LWD additions on immigration or retention rates of brook trout.

Both age 1+ and YOY brook trout density varied over the course of this study in all streams. A large year class of YOY occurred in all streams in 2001, but fall densities of YOY were significantly higher in the streams receiving LWD additions over a larger extent of stream. The overall greater amount of LWD in these streams appeared to provide additional areas of overhead cover and refuge for YOY brook trout, thereby increasing survival from spring to fall. Addition of LWD also created sites where leaf pack and fine woody debris accumulated. Culp et al. (1996) found the addition of fine woody debris increased the density of YOY rainbow trout (*Oncorhynchus mykis*) in a Canadian stream. Also, Nislow et al. (1999) showed early season age-0 Atlantic salmon (*Salmo salar*) preferred slower current velocities associated with areas where LWD and boulders were added in Connecticut River tributaries (VT, U.S.A.). Our addition of LWD increased overhead cover and likely increased preferred habitat for YOY brook trout. This pattern carried over to the spring 2002, where age 1+ brook trout density was also highest in the streams receiving large scale additions of LWD. These observations seemed to be confined to the among-stream experiment because at no time during the course of the study did the reaches where LWD was added have significantly higher YOY or age 1+ brook densities than unmanipulated reaches in the within-stream experiment. This indicates that the effect of habitat manipulations upon brook trout populations requires application and assessment at a relatively large spatial scale to be observed, possibly due to high variability in habitat quality and fish abundance at smaller spatial scales. Higher density in the streams manipulated over a larger extent was short-lived, and densities were equivalent between the small and large extents of habitat manipulation by the fall 2002. This suggests that density-dependent factors may have been realized as seen in other salmonids (Dunham & Vinyard, 1997) when the large 2001 cohort matured.

Age 1+ brook trout size was unaffected by LWD additions. LWD increases the storage of leaf matter (Raikow et al., 1995) which provides substrate and food resources for aquatic macroinvertebrates, thereby increasing the potential for production at higher trophic levels (Grunell et al., 1995). Thus, size may be expected to be greatest in areas with abundant LWD, but no such effect was found here. Others have also failed to show a relationship between LWD abundance and growth. Riley & Fausch (1995) and Gowan & Fausch (1996a) did not show any influence of additions of LWD to brook trout growth in Colorado streams and Harvey (1998) did not find any difference in growth rates of cutthroat trout (*Oncorhynchus clarki clarki*) occupying pools with abundant LWD and pools without LWD. The potential of LWD to increase food availability to stream fish, may be offset by decreased foraging efficiency in habitats with a high degree of instream overhead cover (Wilzbach & Cummins, 1986). Stream dwelling salmonids prefer areas with abundant LWD and its associated cover (Young, 1995, 1996; Neuman & Wildman, 2002) and preference for areas with abundant cover and decreased risks of predation may be greater than preference for areas where energy acquisition is maximized.

Management implications

Although this technique of habitat manipulation may not be as effective as anchoring pieces of LWD or embedding them into the streambank (e.g. Binns 1994; Riley & Fausch 1995) the cost is low. A total of 4800 m of stream were manipulated in 2 days by a crew of two loggers using nothing more than chainsaws. Thus, long stream reaches can be manipulated in a short amount of time. The number of pools created per tree felled could likely be increased with a small amount of prior planning. In this study approximately 15 trees per 300 m reach were felled so that the amount of added LWD was equivalent among all manipulated stream reaches for experimental design purposes. Future endeavors would make more efficient use of each felled tree if areas of steep gradient are avoided and only the largest diameter and longest trees are used, thereby increasing stability and the probability of forming a pool.

Brook trout populations failed to increase following habitat manipulations. This could most easily be attributed to the lack of influence of the LWD additions on stream habitat, but Hunt (1976, 1988) suggests the response of trout populations to habitat manipulations may take at least five years post-manipulation. The streams of this study were monitored for 3 years post-manipulation. Future evaluations may show brook trout populations to increase, with the increase being greatest in those streams where LWD was added to a larger spatial scale.

Managers should use habitat manipulations in addition to, not in place of wise land-use. Riparian areas should continue to be protected; for these are the source of vital stream habitat components and energy sources. Managers should also recognize that stream fish population dynamics are complex and responses to stream habitat should be evaluated over long periods of time.

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