Effects of large woody debris placement on stream channels and benthic macroinvertebrates

Robert H. Hilderbrand, A. Dennis Lemly, C. Andrew Dolloff, and Kelly L. Harpster

Abstract: Large woody debris (LWD) was added as an experimental stream restoration technique in two streams in southwest Virginia. Additions were designed to compare human judgement in log placements against a randomized design and an unmanipulated reach, and also to compare effectiveness in a low- and a high-gradient stream. Pool area increased 146% in the systematic placement and 32% in the random placement sections of the low-gradient stream, lending support to the notion that human judgement can be more effective than placing logs at random in low-gradient streams. Conversely, the high-gradient stream changed very little after LWD additions, suggesting that other hydraulic controls such as boulders and bedrock override LWD influences in high-gradient streams. Logs oriented as dams were responsible for all pools created by additions regardless of stream or method of placement. Multiple log combinations created only two pools, while the other seven pools were created by single LWD pieces. Total benthic macroinvertebrate abundance did not change as a result of LWD additions in either stream, but net abundances of Plecoptera, Coleoptera, Trichoptera, and Oligochaeta decreased, while Ephemeroptera increased significantly with the proportional increase in pool area in the low-gradient stream.

Résumé : De gros débris ligneux (GDL) ont été ajoutés dans deux cours d'eau dans le sud-ouest de la Virginie pour étudier une technique expérimentale de remise en état des cours d'eau. Ces débris ont été ajoutés pour comparer le jugement humain dans le placement des billes de bois par rapport à un placement aléatoire et à un tronçon non manipulé, et également pour comparer l'efficacité de ces méthodes dans un ruisseau à forte déclivité et dans un ruisseau à faible déclivité. La superficie de la nappe d'eau a augmenté de 146% dans le cas du placement systématique comparativement à 32% dans les tronçons à placement aléatoire du ruisseau à faible déclivité, ce qui sous-tend l'idée que le jugement humain peut être plus efficace que le hasard dans le placement des billes dans les ruisseaux à faible déclivité. Inversement, le ruisseau à forte déclivité a très peu changé après l'addition de GDL, ce qui donne à entendre que d'autres facteurs hydrauliques tels les rochers et le substratum rocheux, l'emportent sur les effets des GDL dans les ruisseaux à forte déclivité. Les billes orientées de manière à former des barrages ont été à l'origine de tous les bassins créés par addition quel que soit le ruisseau ou la méthode de placement. Les combinaisons de plusieurs billes n'ont créé que deux bassins, tandis que les sept autres bassins ont été le fait de GDL uniques. L'abondance totale des macroinvertébrés benthiques n'a pas changé par suite de l'addition de GDL dans l'un ou l'autre type de ruisseau, mais l'abondance nette de plécoptères, de coléoptères, de trichoptères et d'oligochètes a diminué alors que celle des éphéméroptères a augmenté de manière statistiquement significative en fonction de l'augmentation de la superficie de bassins dans le ruisseau à faible déclivité.
[Traduit par la Rédaction]

Introduction

The importance of large woody debris (LWD) is well documented in temperate stream ecosystems (Harmon et al. 1986). LWD influences geomorphic processes (Keller and Swanson 1979; Swanson et al. 1982), transport and storage of organic materials (Bilby and Likens 1980; Speaker et al. 1984; Smock et al. 1989; Trotter 1990), fish habitats (Bryant 1983; Dolloff 1986; Bisson et al. 1987), and aquatic invertebrate habitats (Anderson et al. 1978; Benke et al. 1984; O'Connor 1991). It also serves as an interface linking terrestrial and aquatic systems (Triska and Cromack 1980).

Most pools in old-growth streams are associated with LWD (Bilby 1984; Andrus et al. 1988; Carlson et al. 1990; Robison and Beschta 1990). Its presence is integral in maintaining stream channel complexity by creating and maintaining these pools (Swanson et al. 1976, 1984; Keller and Swanson 1979; Bisson et al. 1987; Maser et al. 1988; Fausch and Northcote 1992). Andrus et al. (1988) found that 70% of the pools in their streams were formed by LWD. Similarly, Carlson et al. (1990) reported that 50% of the debris within the bank full channel was contributing to pool formation. In contrast, streams in disturbed forests often have lower LWD loadings (Silsbee and Larson 1983; Sedell et al. 1988; Richmond 1994) and lower pool number and area (Ralph et al. 1994).

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Historically, managers viewed LWD as detrimental and cleared it from many stream channels (Sedell and Luchessa 1982; Dolloff 1994). Removal of LWD may destabilize the channel by causing erosional downcutting (Bilby 1984) or widening (Maser et al. 1988), increased bedload transport, redistribution of gravel bars, and shifting of thalwegs (Smith et al. 1993*a*, 1993*b*). This instability may significantly decrease pool frequency and area (Bilby 1984; Elliott 1986; Ralph et al. 1994), depth (Angermeier and Karr 1984), volume (Fausch and Northcote 1992), and ultimately channel heterogeneity and complexity (Swanson et al. 1984; Fausch and Northcote 1992) while increasing riffle area.

Stream habitat structures are constructed in an attempt to correct habitat "deficiencies" by altering stream channels to approximate pristine conditions, but anchoring structures may prevent the channel morphology from incrementally adjusting to alterations (Beschta and Platts 1986). This may result in damage or outright failure of the structure. Those least likely to fail make minimal modifications to the channel (Frissel and Nawa 1992), and are therefore of limited value. LWD may be a feasible alternative to fixed structures in deficient channels because pieces are free to shift and adjust to changing channel conditions.

Benthic macroinvertebrate abundances may be influenced by LWD through changes in pool and riffle availability. Reported abundances are greater in riffle than in pool habitats for most taxa except Chironomidae (Rabeni and Minshall 1977; Huryn and Wallace 1987; Brown and Brussock 1991). Changes in the proportional area of pools and riffles could trigger changes in the abundances of the benthic macroinvertebrates at larger scales and have consequences for detritus processing and food available to higher trophic levels.

We are not aware of existing guidelines or recommendations for using LWD as a stream restoration tool or its potential effects. The objectives of this study were to describe responses of two stream channels and benthic macroinvertebrates at the reach scale to additions of LWD in two Appalachian Mountain streams. Both had very low LWD loadings relative to undisturbed streams (Silsbee and Larson 1983; Sedell et al. 1988; Murphy and Koski 1989; Robison and Beschta 1990; Richmond 1994) and represent typical low- and high-gradient trout streams in Virginia. Our specific hypotheses were (*i*) unanchored LWD modifies channel features, (*ii*) LWD placement based on management experience is more effective than placing logs randomly, (*iii*) channel response to LWD additions is greater in the low-gradient stream than in the higher gradient stream, and (*iv*) total benthic macroinvertebrate abundance decreases as pool surface area increases proportionally to riffle areas.

Study areas

North Fork Stony Creek (hereafter referred to as Stony Creek) originates near the boundary between Monroe County, West Virginia, and the northern tip of Giles County, Virginia. It flows in a southwest direction and is a third-order tributary to the New River in Giles County, Virginia. In the study section, Stony Creek is first order, residing entirely on national forest lands within the Blacksburg Ranger District of the Jefferson National Forest and flows in a high mountain valley at approximately 900 m elevation. Average width in Stony Creek is approximately 5 m, but is variable. Width to depth ratio is 7.8, and average gradient approximately 1%. The stream channel is composed primarily of large and small gravels with some sand and cobble substrates, but boulders are rare. Within the study section, Stony Creek flows through a mature, second-growth forest of hemlock (*Tsuga canadensis*), white pine (*Pinus strobus*), yellow pine (*Pinus echinata*), and a few hardwoods such as black gum (*Nyssa sylvatica*). The entire watershed was extensively logged during the 1920s, and aerial photographs show logging all the way to the channel and complete removal of riparian vegetation. The current dense understory of rhododendron (*Rhododendron maximum*) and mountain laurel (*Kalmia latifolia*) covering the floodplain is a likely product of this practice.

North Prong Barbours Creek (hereafter referred to as Barbours Creek) originates near the boundary of Alleghany County and the northeast corner of Craig County, Virginia. It flows southwesterly and is a tributary to Craig Creek, which itself is a tributary to the James River. Barbours Creek is a first-order stream and flows through a mature, second-growth hardwood forest dominated by oaks (*Quercus* spp.) at approximately 900 m elevation. Average gradient is 3–6% and average width is about 5 m, although the stream is much narrower than its channel most of the year. Width to depth ratio is 7.3 and the dominant substrates are large and small gravels and cobble with numerous boulders.

Materials and methods

We divided the study reach of each stream into three treatment sections, each approximately 225 m long and separated by a 50-m buffer zone. The furthest downstream section was designated the random placement section and received LWD according to a randomized design to simulate natural log drop. The middle 225-m section was designated the systematic placement section and received LWD according to our judgement of how best to increase pool area. The upstream section served as an unmanipulated reference area.

We demarcated pool and riffle habitat units following descriptions by Bisson et al. (1982) and constructed an accurate stream map (ARC/INFO) for each study reach in May 1993. Runs were classed with riffles, glides were classed with pools, and the major pool-forming element (e.g., LWD, boulder) was recorded. Within each habitat unit, all preexisting LWD was recorded in one of four size-classes: (*i*) 10–50 cm in diameter and 1–5 m long, (*ii*) 10–50 cm in diameter and >5 m long, (*iii*) >50 cm in diameter and 1–5 m long, or (*iv*) >50 cm in diameter and >5 m long. Both streams were remapped in May 1994, 1 year after LWD additions.

Log orientations in the random placement section were determined according to a randomized design intended to simulate naturally recruited wood. The randomization process was based on four criteria: (*i*) distance from the downstream end of the section in 5-m intervals, (*ii*) side of the stream, (*iii*) orientation of the log axis to the stream bank in 45° intervals (upstream, perpendicular, and downstream; Fig. 1) excluding parallel to the stream bank, and (*iv*) orientation to the water surface (dam or ramp; Fig. 1). Placement positions of individual logs were then determined from computer-generated random numbers based on these criteria. Log positions in the systematic placement section followed the same basic orientations as the random placement section, but were subjectively determined by our judgements of how best to enhance stream habitats.

Prior to additions, we marked log positions for both sections and the length of log needed at a particular site was determined. Selected trees were felled at least 10 m from the stream bank, stripped of limbs, and cut to a minimum 4 m length and 25 cm top diameter. Limbs were

Fig. 1. Horizontal and vertical orientations used in positioning LWD with the butt end as the point of origin. Figure taken after Cherry and Beschta (1989).

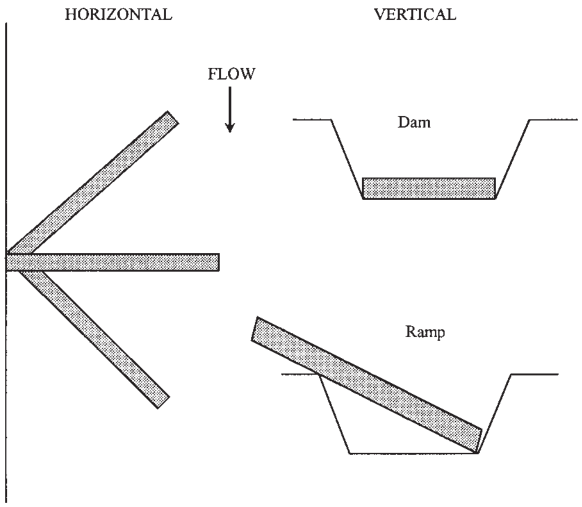
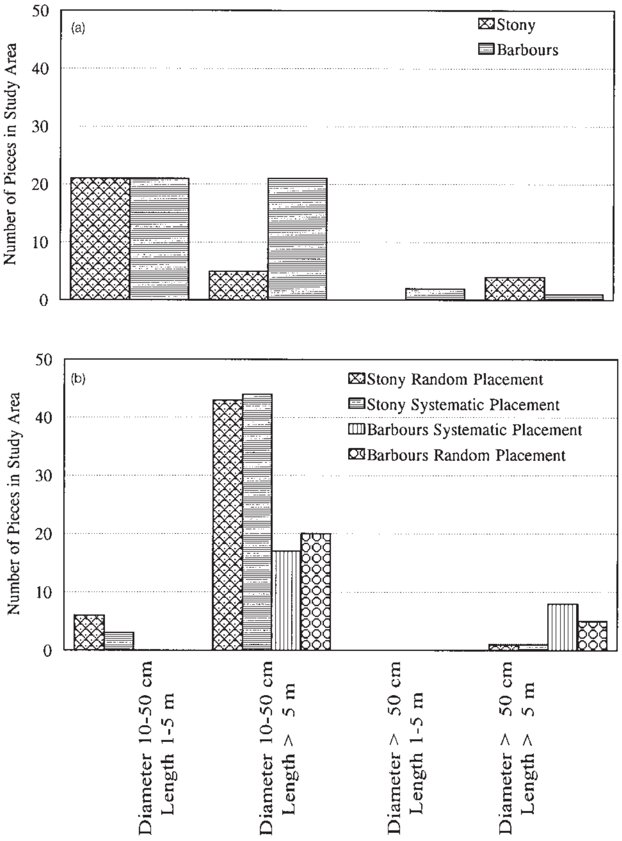


Fig. 2. Size-class distribution of naturally recruited (*a*) and experimentally added (*b*) LWD in Stony and Barbours creeks.



removed to maintain uniformity between logs. We used a front-end loader with a hydraulic winch to position logs in the stream. Logs were not keyed or otherwise pinned to the channel. Heavy equipment was operated in the riparian zone but did not enter the channel. Log volume was calculated by using the average diameter and assuming that the log was a cylinder (Lienkaemper and Swanson 1987) where volume = $3.1416 \times ((\text{butt diameter} + \text{top diameter})/4)^2 \times \text{length}$. Logs were added to both streams during summer 1993. Stony Creek received 100 pieces representing seven local tree species: 50 pieces in the random placement section and 50 pieces in the systematic placement section. Barbours Creek received 50 pieces representing six local tree species: 25 in the random placement section and 25 in the systematic placement section. Fewer pieces were added to Barbours Creek because rugged topography limited equipment access, but wood volume was equal to that added to Stony Creek.

Benthic macroinvertebrates were quantitatively sampled using a portable invertebrate box sampler (PIBS) with 350-µm mesh net. Total area sampled by one PIBS was 0.1 m^2. Both streams were sampled in late May 1993 (pretreatment) and late May 1994 (posttreatment). Both the reference and systematic placement sections were sampled in each stream. The random placement section was not sampled because of possible confounding effects from the systematic placement section located upstream, and it was assumed that responses should otherwise be similar for both treatment sections.

Five paired riffle samples and three paired pool samples were collected at randomly determined locations in each section. To minimize variability, both members of a pair were collected in similar local habitat conditions. However, to gain a representation of pools and riffles for the entire reach, samples were taken in differing habitat conditions within pools or riffles. In total, eight samples (five riffle, three pool) were collected for both the systematic placement and reference sections, yielding a total of 16 samples per stream per sampling period. Samples were preserved in 95% ethanol.

In the laboratory, organisms and leaf detritus were separated from mineral substrates by elutriation in a column of moving water and collected in a 500-µm sieve. Invertebrates were separated from the detritus by hand with the aid of a magnifying lens. Organisms were counted and identified to genus where practical. Most Diptera were identified to family. All invertebrates (except Chironomidae) in a given sample were retained, dried, and collectively weighed for biomass calculations.

Analysis of variance (ANOVA) was used to assess the patterns of variability in benthic macroinvertebrate samples. In an attempt to control variability and increase statistical power, the mean of each pair constituting a sample as described earlier was used for analysis rather than each individual member. (Treating samples in this way generally reduced the coefficient of variation (CV) by approximately 10%.) Benthic macroinvertebrates were analyzed by taxonomic order with three-way ANOVA using experimental section, year, and habitat type as factor levels. All results were considered significant at $P < 0.05$. All data were normalized using a $\log_{10}(Y + 1)$ transformation and passed the Kolmogorov–Smirnov one-sample goodness of fit test.

Results

Debris loadings

Prior to log additions, naturally recruited LWD in the study reach of Stony Creek averaged four pieces per 100 m. Pieces were distributed similarly between pools and riffles, averaging 0.74 piece per pool and 0.89 piece per riffle, with the size distribution heavily skewed to the smallest classes. Similarly, Barbours Creek contained 5.2 pieces per 100 m, averaging 1 piece per riffle and 0.45 piece per pool. Logs of the smallest diameter class dominated, but the distribution was split evenly among log lengths (Fig. 2).

After experimental log additions, LWD loadings equaled 20 pieces per 100 m in addition to preexisting logs for Stony Creek and 10 pieces per 100 m in addition to preexisting logs for Barbours Creek. Additions increased total number of logs, but the size frequency distribution changed little (Fig. 2). There were no significant differences (ANOVA) between

Table 1. Reach-level channel characteristics (SD in parentheses) in the random placement, systematic placement, and reference sections before (May 1993) and after (May 1994) LWD additions.

	Random placement		Systematic placement		Reference section	
	1993	1994	1993	1994	1993	1994
Stony Creek						
Number of pools	5	8	5	10	4	5
Mean pool length	11.8 (8.5)	10.4 (7.5)	10.6 (4.0)	14.1 (9.3)	16.6 (16.5)	13.0 (13.5)
Mean pool area	78 (52)	64 (43)	45 (16)	55 (38)	53 (60)	44 (36)
Total pool area	388	512	222	546	213	220
% change in area		32		146		3
Number of riffles	4	6	6	7	4	4
Mean riffle length	43.2 (72.6)	24.6 (21.3)	32.1 (29.5)	12.8 (6.9)	41.8 (30.3)	41.5 (30.6)
Mean riffle area	219 (357)	124 (101)	128 (120)	55 (22)	15 (136)	151 (137)
Total riffle area	926	796	768	443	623	615
% change in area		–16		–42		–1
Barbours Creek						
Number of pools	14	14	9	9	7	7
Mean pool length	8.3 (4.4)	9.1 (4.1)	8.4 (3.9)	8.4 (3.9)	9.4 (3.5)	9.4 (3.5)
Mean pool area	38 (19)	41 (18)	36 (14)	36 (14)	33 (14)	33 (14)
Total pool area	533	575	327	327	233	233
% change in area		8		0		0
Number of riffles	11	10	8	8	5	5
Mean riffle length	12.1 (6.5)	12.2 (5.0)	23.1 (23.6)	23.1 (23.6)	34.8 (28.0)	34.8 (28.0)
Mean riffle area	49 (23)	49 (23)	95 (110)	95 (110)	124 (91)	124 (91)
Total riffle area	534	492	759	759	622	622
% change in area		–8		0		0

treatment sections for log length ($\bar{x} = 6.3$ m Stony Creek; $\bar{x} = 7.7$ m Barbours Creek), diameter ($\bar{x} = 38$ cm; $\bar{x} = 49$ cm), or volume ($\bar{x} = 0.57$ m^3; $\bar{x} = 1.17$ m^3) for either stream. Between-stream differences were not tested because differing channel types warranted differing approaches. Despite the LWD density added to Stony Creek being double that of Barbours Creek, total volume of wood added was nearly identical between streams and sections, ranging from 29 to 31 m^3.

Habitat area

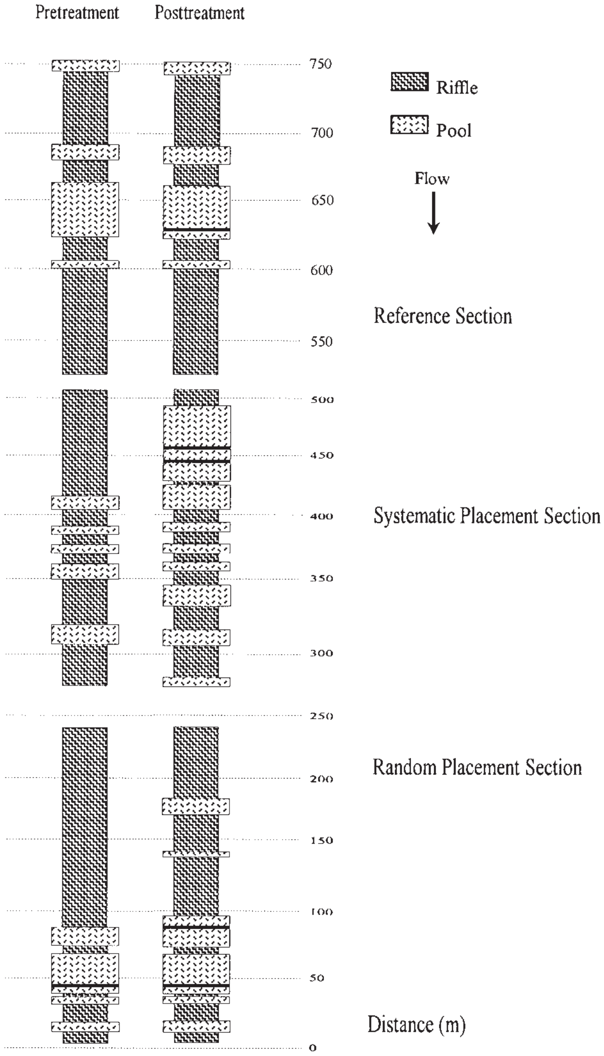
In Stony Creek, the low-gradient stream, channel features changed substantially in both treatment sections while remaining almost unchanged in the reference section. Of the 14 original pools in the study reach, 6 (43%) were formed by LWD. Debris-formed pools increased from 6 to 14 (61%) 1 year after our additions. Pool numbers nearly doubled in both treatment sections, increasing from 5 to 8 in the random placement and from 5 to 10 in the systematic placement section (Table 1). Pool number also increased in the reference section, but this was due to a shifting piece of preexisting LWD that split one pool into two occupying the same area. The created pools in the two treatment sections effectively broke up long stretches of riffle (Fig. 3) and substantially reduced the average riffle length and its standard deviation (Table 1). However, these differences were not significant in ANOVA because of high variability in riffle lengths. All new pools in the manipulated sections were caused by LWD addition, including one in the systematic placement section that was formed by scour around a detritus accumulation caused by LWD.

Logs oriented as dams in Stony Creek were responsible for all seven pools created by our additions, with all but one formed by single logs. Of these seven, four were formed by ponding water behind the dams, two were created as downstream plunge pools, while the last was formed by channel scour under a dam held in place by two ramps in the systematic placement section. Scour was observed around several ramps, but was localized around logs.

Total stream area occupied by pools in Stony Creek increased most dramatically in the systematic placement section. The random placement section also increased, while the reference section remained unchanged (Table 1). Percent stream area as pools increased from 30% pretreatment to 39% posttreatment in the random section and from 22 to 55% in the systematic placement section as riffle area decreased proportionately. This translated into a 32 and 146% relative increase in pool area in the random and systematic placement sections, respectively.

LWD additions in Barbours Creek, the high-gradient stream, produced minimal effects. No net change in the number of pools occurred in the random placement section (Table 1). Two pools were created by LWD additions, but two other pools reverted to riffles (Fig. 4). Both pools created in the random placement section were formed by scour underneath dams spanning the channel. The systematic placement section increased from nine to 10 pools, but shortly after the final mapping, portions of the dam maintaining the newly created pool eroded and reverted back to riffle. Thus, no net change occurred in the systematic placement section. Similarly, no net change occurred in the reference section, which remained at seven pools and seven riffles pre- and posttreatment. Changes in total pool and riffle area were not substantial (Table 1). Only 10% of the original pools in the study reach of Barbours Creek were associated with naturally recruited LWD, and none was formed by preexisting LWD in the random

Fig. 3. Pool–riffle sequencing before (May 1993) and after (May 1994) LWD additions in the random placement, systematic placement, and reference sections in Stony Creek (width is not to scale). The random placement section received LWD added according to a randomized design, while the systematic placement section received LWD placed according to our ideas of how best to manipulate habitats. The reference section received no LWD. Solid lines within pools demarcate separate pools divided by dams or small waterfalls.

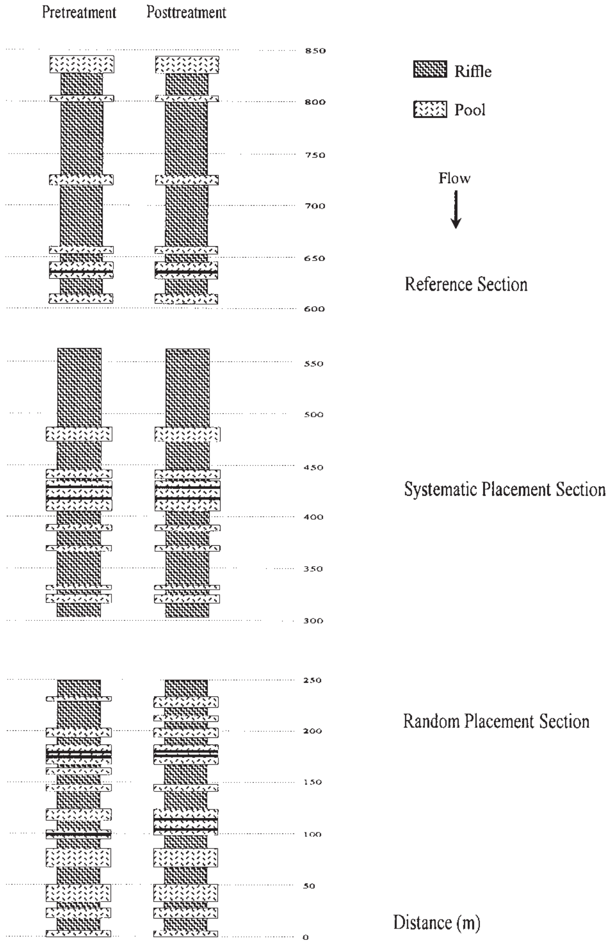


and systematic placement sections; three of the seven pools in the reference section were created or maintained by preexisting LWD.

Benthic macroinvertebrates

In low-gradient Stony Creek, Diptera were statistically most abundant (ANOVA) followed by Plecoptera, Coleoptera, Ephemeroptera, Trichoptera, Oligochaeta, and Decapoda, respectively (Table 2). Plecoptera, Coleoptera, Trichoptera, and Oligochaeta were all significantly more abundant (three-way ANOVA) in riffles than in pools, while Ephemeroptera were significantly more abundant in pools. The latter was mainly due to an almost total lack of riffle-dwelling Ephemeroptera. Diptera were not significantly different in abundance in pools and riffles ($P = 0.054$). Annual variation in total benthic macroinvertebrates in Stony Creek was highly significant (three-way ANOVA), with densities greater in 1994 than in 1993. However, when the treatment effect of annual variation was taken into account, no differences existed either between pools and riffles or between experimental sections. There was no treatment effect at any level on total biomass (minus Chironomidae) per sample, but even with the data transformed and approximately normal, variability in biomass was high (CV = 109%).

Fig. 4. Pool–riffle sequencing before (May 1993) and after (May 1994) LWD additions in the random placement, systematic placement, and reference sections in Barbours Creek (width is not to scale). The random placement section received LWD added according to a randomized design, while the systematic placement section received LWD placed according to our ideas of how best to manipulate habitats. The reference section received no LWD. Solid lines within pools demarcate separate pools divided by dams or small waterfalls.



In high-gradient Barbours Creek, Ephemeroptera were statistically most abundant followed by Coleoptera, Plecoptera, Diptera, Trichoptera, Oligochaeta, and Decapoda (Table 3). Coleoptera, Ephemeroptera, Plecoptera, and Trichoptera were significantly more abundant (three-way ANOVA) in riffles and Diptera in pools. Total benthic macroinvertebrates were significantly greater (three-way ANOVA) in 1994 than in 1993. Controlling for the effects of annual variation, total

Table 2. Mean number of benthic macroinvertebrates and dry weight biomass per 0.1 m^2 (SD in parentheses) by habitat unit type and year for the systematic placement and reference sections in Stony Creek.

	Pools				Riffles			
	Systematic placement		Reference		Systematic placement		Reference	
	1993	1994	1993	1994	1993	1994	1993	1994
Diptera *a**	100.5	308.7	109.2	343.2	78.3	167.9	55.4	312.2
	(4.6)	(157.4)	(43.8)	(204.6)	(40.6)	(145.2)	(23.7)	(203.8)
Plecoptera *a*†	82.3	57.3	59.3	65.7	251.6	139.1	119.1	277.2
	(38.6)	(58.8)	(37.5)	(19.5)	(94.8)	(46.3)	(46.8)	(159.2)
Coleoptera *b*†	26.2	31.2	23.0	20.5	70.1	72.9	66.2	73.6
	(8.7)	(27.9)	(5.8)	(2.3)	(24.7)	(46.8)	(37.9)	(25.5)
Ephemeroptera *c**†	21.2	18.0	8.2	49.0	6.9	6.4	5.5	30.3
	(6.9)	(5.2)	(0.8)	(25.2)	(3.7)	(1.7)	(2.6)	(14.3)
Trichoptera *c*†	11.8	5.8	5.7	6.5	23.4	15.0	7.1	14.7
	(4.0)	(0.8)	(1.0)	(5.8)	(9.1)	(7.3)	(0.7)	(9.3)
Oligochaeta *c*†	8.0	18.3	11.8	5.5	20.5	9.7	11.9	17.4
	(1.8)	(21.9)	(15.0)	(3.0)	(5.2)	(3.4)	(4.5)	(10.7)
Decapoda *c*†	1.8	1.5	1.0	5.0	0.8	0.7	0.5	1.0
	(1.5)	(1.3)	(0.5)	(4.4)	(0.9)	(0.6)	(0.4)	(0.6)
Biomass (g)	0.170	0.051	0.021	0.124	0.082	0.335	0.038	0.193
	(0.158)	(0.018)	(0.009)	(0.045)	(0.061)	(0.362)	(0.020)	(0.158)

Note: Letters following taxa denote homogeneous groups. Different letters distinguish significantly different ($P < 0.05$) groups on the basis of LSD multiple comparison. Significant differences were determined by ANOVA.

*Significant difference between years.

†Significant difference between pools and riffles.

Table 3. Mean number of benthic macroinvertebrates and dry weight biomass per 0.1 m^2 (SD in parentheses) by habitat unit type and year for the systematic placement and reference sections in Barbours Creek.

	Pools				Riffles			
	Systematic placement		Reference		Systematic placement		Reference	
	1993	1994	1993	1994	1993	1994	1993	1994
Ephemeroptera *a**†	58.5	108.8	51.7	84.0	126.0	202.7	130.7	168.8
	(25.4)	(28.1)	(18.4)	(52.5)	(37.9)	(79.2)	(73.9)	(24.1)
Plecoptera *a*†	53.5	79.7	40.2	81.7	170.7	134.3	112.0	175.2
	(6.9)	(58.3)	(19.8)	(94.6)	(153.2)	(27.5)	(44.4)	(94.0)
Coleoptera *ab**†	37.0	99.5	39.2	150.5	113.5	131.2	98.7	142.9
	(8.4)	(57.7)	(7.3)	(161.5)	(67.3)	(64.8)	(21.9)	(22.4)
Diptera *b*†	96.5	123.0	115.8	147.2	72.5	67.3	66.7	70.0
	(27.7)	(41.4)	(38.3)	(38.8)	(39.6)	(47.6)	(10.6)	(8.1)
Trichoptera *c*†	1.7	1.8	7.5	4.0	17.0	22.8	17.5	14.9
	(0.3)	(1.5)	(5.7)	(2.8)	(7.3)	(23.8)	(5.7)	(7.3)
Oligochaeta *c**	3.5	12.3	1.8	3.5	7.5	5.6	2.2	8.7
	(2.8)	(17.5)	(1.8)	(2.2)	(6.6)	(2.9)	(2.3)	(5.7)
Decapoda *c*	1.7	1.2	1.5	0.7	1.4	1.1	1.8	0.9
	(1.8)	(1.3)	(1.3)	(0.8)	(0.7)	(0.4)	(1.1)	(0.2)
Biomass (g)	na	0.136	na	0.302	0.268	0.466	0.103	0.254
		(0.088)		(0.410)	(0.235)	(0.482)	(0.032)	(0.191)

Note: Letters following taxa denote homogeneous groups. Different letters distinguish significantly different ($P < 0.05$) groups on the basis of LSD multiple comparison. Significant differences were determined by ANOVA.

*Significant difference between years.

†Significant difference between pools and riffles.

abundance was significantly greater in riffles than in pools, but there was no difference between experimental sections. Biomass (minus Chironomidae) was no different between pools and riffles or between years. Similar to Stony Creek, biomass was highly variable (CV = 94%). Samples for 1993 pools were destroyed prior to weighing and were not available for analysis.

Discussion

The ability of LWD to alter channel morphology is widely known, but its effectiveness and feasibility as a stream restoration tool under differing conditions are not well described. Additions of LWD substantially increased both the number and total surface area of pools in both treatment sections of low-gradient Stony Creek. In contrast, channel changes in high-gradient Barbours Creek were minimal: the systematic placement section remained unchanged, and the two pool creations in the random placement section were countered by the reversion of two preexisting pools to riffles, making no net change in pool frequency and minimal changes in area.

Gradient ranged between 3 and 6% in the treatment sections of Barbours Creek compared with approximately 1% in Stony Creek. Ralph et al. (1994) found that while pool frequency decreased in low-gradient streams subjected to intensive logging, high-gradient streams were largely unaffected. They attributed this to factors other than LWD serving as hydraulic controls in the high-gradient streams. Barbours Creek would not constitute high gradient by Ralph et al. (1994), but was sufficiently steep that hydraulic effects of boulder and bedrock probably overrode those of LWD, while the gravel-dominated bed of the low-gradient stream was more easily altered per unit stream power.

Steep banks in Barbours Creek created equipment access problems, so the treatment sections received half the number of pieces added to Stony Creek. Doubling the debris frequency in the high-gradient stream might produce greater channel responses, but pool area and LWD volume are significantly related (Bisson et al. 1987; Bilby and Ward 1989; but see Andrus et al. 1988), and total volume of LWD added was not different between sections or streams. Increasing the number of logs might also increase channel response through synergistic effects. In coastal Oregon streams, an average of three pieces of wood were associated with the formation of each pool in streams with similar gradient (Carlson et al. 1990). However, of the 27 cases of LWD additions where two or more logs were placed together on Stony Creek and 17 on Barbours Creek, only two of these aggregates created pools; single logs created all others. Prior to our additions, most pools formed by naturally recruited LWD in the study sections were also associated with only one piece. The findings of others may be a historical artefact of surveying streams with naturally high debris loadings rather than tracking channel responses to additions.

Professional judgement in log placement was more effective than random placement in creating pool habitat in low-gradient Stony Creek. Log additions created pools in both manipulated sections, but more pools were created by systematic placement, and the proportional area occupied by pools increased more substantially. The differences between methods of LWD placement were subtle. A log can be positioned in an almost infinite number of orientations, but without physical anchoring, most logs are unstable. Therefore, log orientations in the systematic placement were much the same as in the random placement section. The major difference was that in the systematic placement section, we used the same orientations to divert or exaggerate flow in areas where the channel could be altered. An example was placing a dam in such a way as to create a scour jet in midchannel.

All LWD additions forming pools in each stream were oriented as dams. Modes of pool formation were through scour by flow constriction between the log and stream bed ($n = 3$), downstream plunge pool ($n = 2$), and ponding water ($n = 4$). Although no ramp orientations were directly responsible for pool creation, areas of scour were observed around numerous logs. It is probable that some of these scours will lengthen through time and form pools as bedload is transported downstream.

Straight, clean boles were added to minimize variability among pieces and orientations owing to root wads or branches. Almost half of the LWD added to Stony Creek moved after bank full discharge. A detailed analysis of which characteristics caused instability is in progress, but our additions had a greater than typical chance of movement compared with pieces with root wads or branches intact.

Benthic macroinvertebrates

We reject the hypothesis of decreasing benthic macroinvertebrate abundance with increasing pool surface area for Stony Creek, as there was no difference in total abundance between pools and riffles. In contrast, numerous investigators (Rabeni and Minshall 1977; Huryn and Wallace 1987; Brown and Brussock 1991) have reported higher numerical abundance in riffles. This also occurred in high-gradient Barbours Creek, but pool area did not increase substantially, again causing us to reject the hypothesis.

Strong associations between taxa and habitat types were present in both streams and resulted in proportional shifts in the abundance of benthic macroinvertebrate taxa for Stony Creek. At the reach scale, Ephemeroptera increased in total abundance through increased pool area, while Plecoptera, Coloeptera, Trichoptera, and Oligochaeta all decreased. We speculate that this shift may reduce the food supply available to the resident brook trout (*Salvelinus fontinalis*) population on the basis of information from other investigators (Allan 1978; Morgan and Robinette 1978; LaRoche 1979; Hubert and Rhodes 1989), but diet information is lacking. Similar habitat associations existed in Barbours Creek, but no reach level shifts in abundance occurred. Biomass did not differ between pools and riffles, between sections, or between years in either stream. The high variation in biomass reduced the statistical power to detect differences, but is a natural component of lotic systems.

Only mineral substrates of pools and riffles were sampled in this study; leaf packs and wood were not. Benke et al. (1984) reported that most of the invertebrate production in blackwater streams with shifting sand bottoms was associated with wood. However, most of the LWD additions in this study were dewatered in both streams during base flow conditions, and leaf packs comprised a very small fraction of available area and were temporally transient. We recognize that part of the invertebrate community was excluded from our samples, but felt that the numerically most important components affected by the LWD additions were sampled.

Conclusions

Adding LWD can be an effective technique for increasing pool area and numbers in low-gradient channels with mobile substrates. Rosgen and Fittante (1986) recommended against most types of fish habitat improvement structures in this type of channel generally because of channel instability and the resulting ineffectiveness. LWD additions in these channels, however, may be feasible because the pieces can move and adjust to local channel conditions, unlike permanent habitat improvement structures. We strongly recommend adding logs with branches or root wads attached because straight, clean boles are much more likely to move during elevated flows. Alternatively, logs could be cabled to stationary objects with enough slack to allow pieces to shift as the channel changes, yet remain fixed in the general vicinity. We also recommend adding decay-resistant species from outside the streamside zone to maximize piece longevity and minimize impact to the stream and future LWD supply.

A few well-placed logs can modify channel morphology more effectively than randomly heaving logs into low-gradient stream channels. Regardless of stream or placement method, pieces creating pools were all oriented as dams, and single pieces appeared more effective than multiple log combinations. This suggests that managers can produce desired channel alterations with minimal effort by using intuition to select placement sites.

Many high-gradient channel types are not recommended for receiving fish habitat improvement structures because habitat is usually not limiting (Rosgen and Fittante 1986). Considering the overall lack of channel response to LWD additions in our high-gradient stream and the expense of personnel and heavy equipment involved, the cost would most likely outweigh any benefits. Stream habitat restoration ultimately depends on protection of the riparian zone, but in low-gradient streams like Stony Creek, LWD additions may maintain stream channel complexity until there is sufficient debris recruitment from the riparian zone.

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References

Allan, J.D. 1978. Diet of brook trout (*Salvelinus fontinalis* Mitchill) and brown trout (*Salmo trutta* L.) in an alpine stream. Verh. Int. Ver. Theor. Angew. Limnol. **20**: 2045–2050.

Anderson, N.H., Sedell, J.R., and Triska, F.J. 1978. The role of aquatic invertebrates in processing of wood in coniferous forest streams. Am. Midl. Nat. **100**: 64–82.

Andrus, C.W., Long, B.A., and Froehlich, H.A. 1988. Woody debris and its contribution to pool formation in a coastal stream 50 years after logging. Can. J. Fish. Aquat. Sci. **45**: 2080–2086.

Angermeier, P.L., and Karr, J.R. 1984. Relationships between woody debris and fish habitat in a small warmwater stream. Trans. Am. Fish. Soc. **113**: 716–726.

Benke, A.C., Van Arsdall, T.C., Jr., Gillespie, D.M., and Parish, F.K. 1984. Invertebrate productivity in a subtropical blackwater river; the importance of habitat and life history. Ecol. Monogr. **54**: 25–63.

Beschta, R.L., and Platts, W.S. 1986. Morphological features of small streams: significance and function. Water Resour. Bull. **22**: 369–379.

Bilby, R.E. 1984. Removal of woody debris may affect stream channel stability. J. For. **82**: 609–613.

Bilby, R.E., and Likens, G.E. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology, **61**: 1107–1113.

Bilby, R.E., and Ward, J.W. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Trans. Am. Fish. Soc. **118**: 368–378.

Bisson, P.A., Nielsen, J.L., Palmason, R.A., and Grove, L.E. 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow. *In* Acquisition and utilization of aquatic habitat inventory information. *Edited by* N.B. Armantrout. Western Division, American Fisheries Society, Portland, Ore. pp. 62–73.

Bisson, P.A., Bilby, R.E., Bryant, M.D., Dolloff, C.A., Grette, G.B., House, R.A., Murphy, M.L., Koski, K.V., and Sedell, J.R. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. *In* Proceedings of a Symposium on Streamside Management: Forestry and Fishery Interactions. *Edited by* E.O. Salo and T.W. Cundy. Institute of Forest Resources, University of Washington, Seattle, Wash. pp. 143–190.

Brown, A.V., and Brussock, P.P. 1991. Comparisons of benthic invertebrates between riffles and pools. Hydrobiologia, **220**: 99–108.

Bryant, M.D. 1983. The role and management of woody debris in west coast salmonid nursery streams. N. Am. J. Fish. Manage. **3**: 322–330.

Carlson, J.Y., Andrus, C.W., and Froehlich, H.A. 1990. Woody debris, channel features, and macroinvertebrates of streams with logged and undisturbed riparian timber in northeastern Oregon, U.S.A. Can. J. Fish. Aquat. Sci. **47**: 1103–1111.

Cherry, J., and Beschta, R.L. 1989. Coarse woody debris and channel morphology: a flume study. Water Resour. Bull. **25**: 1031–1036.

Dolloff, C.A. 1986. Effects of stream cleaning on juvenile coho salmon and Dolly Varden in southeast Alaska. Trans. Am. Fish. Soc. **115**: 743–755.

Dolloff, C.A. 1994. Large woody debris: the common denominator for integrated environmental management of forest streams. *In* Implementing integrated environmental management. *Edited by* J. Cairns Jr., T.V. Crawford, and H. Salwasser. Center for Environmental Management and Hazardous Materials Studies, Virginia Polytechnic Institute and State University, Blacksburg, Va. pp. 93–108.

Elliott, S.T. 1986. Reduction of a Dolly Varden population and macrobenthos after removal of logging debris. Trans. Am. Fish. Soc. **115**: 392–400.

Fausch, K.D., and Northcote, T.G. 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. Can. J. Fish. Aquat. Sci. **49**: 682–693.

Frissel, C.A., and Nawa, R.K. 1992. Incidence and causes of physical failure of artificial structures in streams of western Oregon and Washington. N. Am. J. Fish. Manage. **12**: 182–197.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., Jr., and Cummins, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. **15**: 133–302.

Hubert, W.A., and Rhodes, H.A. 1989. Food selection by brook trout in a subalpine stream. Hydrobiologia, **178**: 225–231.

Huryn, A.D., and Wallace, J.B. 1987. Local geomorphology as a determinant of macrofaunal production in a mountain stream. Ecology, **68**: 1932–1942.

Keller, E.A., and Swanson, F.J. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surf. Proc. Land. **4**: 361–380.

LaRoche, A.L., III. 1979. The impacts of stocking hatchery reared trout on the native brook trout populations of two streams in central Virginia. M.S. thesis, Virginia Polytechnic Institute and State University, Blacksburg, Va.

Lienkaemper, G.W., and Swanson, F.J. 1987. Dynamics of large woody debris in streams in old-growth Douglas fir forests. Can. J. For. Res. **17**: 150–156.

Maser, C., Tarrant, R.F., and Franklin, J.F. 1988. From the forest to the sea: a story of fallen trees. U.S. For. Serv. Gen. Tech. Rep. No. PNW-229.

Morgan, E.L., and Robinette, J.R. 1978. Life history study of brook trout *Salvelinus fontinalis* (Mitchill), Great Smoky Mountains National Park. USDI National Park Service report to Southeast Regional Office, Atlanta, Ga.

Murphy, M.L., and Koski, K.V. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. N. Am. J. Fish. Manage. **9**: 427–436.

O'Connor, N.A. 1991. The effects of habitat complexity on the macroinvertebrates colonising wood substrates in a lowland stream. Oecologia, **85**: 504–512.

Rabeni, C.F., and Minshall, G.W. 1977. Factors affecting microdistribution of stream benthic insects. Oikos, **29**: 33–43.

Ralph, S.C., Poole, G.C., Conquest, L.L., and Naiman, R.J. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Can. J. Fish. Aquat. Sci. **51**: 37–51.

Richmond, A.D. 1994. Characteristics and function of large woody debris in mountain streams of northern Colorado. M.S. thesis, Colorado State University, Fort Collins, Co.

Robison, E.G., and Beschta, R.L. 1990. Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, U.S.A. Earth Surf. Proc. Land. **15**: 149–156.

Rosgen, D., and Fittante, B.L. 1986. Fish habitat structures: a selection guide using stream classification. *In* Proceedings of the 5th Trout Stream Habitat Improvement Workshop. *Edited by* J.G. Miller, J.A. Arway, and R.F. Carline. Pennsylvania Fish Commission, Harrisburg, Pa. pp. 163–179.

Sedell, J.R., and Luchessa, K.J. 1982. Using the historical record as an aid to salmonid habitat enhancement. *In* Acquisition and utilization of aquatic habitat inventory information. *Edited by* N.B. Armantrout. Western Division, American Fisheries Society, Portland, Ore. pp. 210–223.

Sedell, J.R., Bisson, P.A., Swanson, F.J., and Gregory, S.V. 1988. What we know about large trees that fall into streams and rivers. *In* From the forest to the sea: a story of fallen trees. *Edited by* C. Maser, R.F. Tarrant, and J.F. Franklin. U.S. For. Serv. Gen. Tech. Rep. No. PNW-229. pp. 47–81.

Silsbee, D.G., and Larson, G.L. 1983. A comparison of streams in logged and unlogged areas of Great Smoky Mountains National Park. Hydrobiologia, **102**: 99–111.

Smith, R.D., Sidle, R.C., and Porter, P.E. 1993*a*. Effects on bedload transport of experimental removal of woody debris from a forest gravel-bed stream. Earth Surf. Proc. Land. **18**: 455–468.

Smith, R.D., Sidle, R.C., Porter, P.E., and Noel, J.R. 1993*b*. Effects of experimental removal of woody debris on the channel morphology of a forest, gravel-bed stream. J. Hydrol. **152**: 153–178.

Smock, L.A., Metzler, G.M., and Gladden, J.E. 1989. Role of debris dams in the structure and functioning of low-gradient headwater streams. Ecology, **70**: 764–775.

Speaker, R., Moore, K., and Gregory, S. 1984. Analysis of the process of retention of organic matter in stream ecosystems. Verh. Int. Ver. Theor. Angew. Limnol. **22**: 1835–1841.

Swanson, F.J., Lienkaemper, G.W., and Sedell, J.R. 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. U.S. For. Serv. Gen. Tech. Rep. No. PNW-56.

Swanson, F.J., Janda, R.J., Dunne, T., and Swanston, D.N. 1982. Sediment budgets and routing in forested drainage basins. U.S. For. Serv. Gen. Tech. Rep. No. PNW-141.

Swanson, F.J., Bryant, M.D., Lienkaemper, G.W., and Sedell, J.R. 1984. Organic debris in small streams, Prince of Wales Island, southeast Alaska. U.S. For. Serv. Gen. Tech. Rep. No. PNW-166.

Triska, F.J., and Cromack, K. 1980. The role of wood debris in forests and streams. *In* Forests: fresh perspectives from ecosystem analysis. *Edited by* R.H. Waring. Oregon State University, Corvallis, Ore. pp. 171–190.

Trotter, E.H. 1990. Woody debris, forest-stream succession, and catchment geomorphology. J. N. Am. Benthol. Soc. **9**: 141–156.