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Large wood in central Appalachian headwater streams: controls on and potential changes to wood loads from infestation of hemlock woolly adelgid

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ABSTRACT: Large wood (LW) is an important component of forested headwater streams. The character of LW loads reflects a balance between adjacent valley processes that deliver LW to the channel (herein recruitment processes) and stream channel processes that either retain or transport LW through the reach (herein retention processes). In the central Appalachian Mountains, USA, LW characteristics in headwater streams located in eastern hemlocks (*Tsuga candensis*) forests are expected to change because of infestation of hemlock woolly adelgid (*Adelges tsugae*, HWA), an exotic, invasive insect. We examined LW characteristics in 24 headwater streams ranging from un-infested to severe infestation, as determined by hemlock canopy health. The objectives of this work were to: (i) quantify wood loads; (ii) assess the relative importance of valley recruitment and in-stream retention mechanisms in controlling reach-scale wood loads; and (iii) assess if there was a detectable influence of HWA on LW loads. We hypothesized that LW loads would be similar to other forested streams in eastern USA and dominated by recruitment processes. In addition, higher LW loads would correspond with advanced HWA infestation. Mean wood frequency was 38 pieces/100 m ± 17 (standard deviation); mean wood volume was 3.69 m^3/100 m ± 2.76. In general, LW load characteristics were influenced by both recruitment and retention parameters; jam (accumulations ≥ 3 pieces) characteristics were dominated by retention parameters. Results suggest that adjacent stand basal area influences LW loads and once LW is recruited to the channel, streams lack sufficient hydraulic driving forces, despite having lower resistance structures, to transport LW out of the reach. Sites in moderate decline had higher proportions of short (1–2 m and 1–4 m) and very long (>10 m) LW with higher frequency of jams that were low in volume. We present a hypothesized conceptual model of expected changes to LW loads associated with HWA infestation and hemlock mortality. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS: wood loads; Appalachian mountains; hemlock woolly adelgid; large wood

Introduction

Extensive research has documented the important hydrologic, geomorphic, and ecologic functions of large wood (LW) in streams that range from steep, headwaters to gradual, lowland rivers (Gurnell *et al.*, 2002; Montgomery *et al.*, 2003; Daniels and Rhoads, 2004; Hassan *et al.*, 2005). The geomorphic influence of LW on streams largely depends upon the amount and arrangement of LW within the channel, collectively defined as the wood load (Gurnell *et al.*, 2002; Wohl and Jaeger, 2009), which reflects a balance between wood recruitment to the channel, retention within the channel, and in-channel processing (e.g. decomposition, breakage). Substantial effort has been put forward to characterize wood load characteristics (reviewed in Gurnell *et al.*, 2002), including abundance or volume (Fox and Bolton, 2007; Cadol *et al.*, 2009; Jones *et al.*, 2011) and spatial distribution (Comiti *et al.*, 2006; Magilligan *et al.*, 2008; Wohl and Jaeger, 2009; Morris *et al.*, 2010; Kraft *et al.*, 2011), and identify the environmental parameters that influence wood load (Hedman *et al.*, 1996; Morris *et al.*, 2007; Fremier *et al.*, 2010; King *et al.*, 2013).

In mountain systems, there appears to be some consensus of longitudinal trends in LW characteristics at river network scales ($10^{3–4}$ m), although substantial variation exists. In particular, wood loads tend to decrease in the downstream direction (Keller and Swanson, 1979; Magilligan *et al.*, 2008; Wohl and Jaeger, 2009; Fremier *et al.*, 2010) and individual pieces self-organize in non-random distributions that determine jam formation (accumulations ≥ 3 pieces) and spacing (Cadol *et al.*, 2009; Kraft *et al.*, 2011; Wohl and Cadol, 2011), which are strongly influenced by valley scale conditions (Morris *et al.*, 2010; Wohl and Beckman, 2011). However, in the headwater regions of these streams, reach scale (10^{1-2} m) controls on wood load appear less consistent across different hydroclimatic settings (Comiti *et al.*, 2006; Mao *et al.*, 2008; Cadol *et al.*, 2009; Wohl *et al.*, 2012a). In addition, natural and anthropogenic disturbances such as fire (Jones *et al.*, 2011; King *et al.*, 2013), storms (Kraft *et al.*, 2002; Wohl *et al.*, 2009), disease (Evans *et al.*, 2012; King *et al.*, 2013), debris flows (May and Gresswell, 2003a), and timber harvest (Gomi *et al.*, 2001; Hassan *et al.*, 2005; Magilligan *et al.*, 2008) play critical roles in LW characteristics at reach and network scales. LW characteristics at the headwater reach scale are important because they can strongly affect water, sediment, carbon, and nutrient transport processes to the downstream network (Harmon *et al.*, 1986; Warren *et al.*, 2007; Battin *et al.*, 2008) and critically influence instream habitat conditions for important freshwater fauna (Dolloff and Warren, 2003; Benke and Wallace, 2003).

Wood recruitment represents processes that transfer LW from the adjacent hillslope or riparian area to the channel and is a function of both forest stand and adjacent valley characteristics. Forest characteristics that influence wood recruitment include stand age, forest basal area, and natural or anthropogenic disturbance-related processes that includes tree mortality, treefall, blowdown, and management practices (Bragg, 2000; Gregory *et al.*, 2003; May and Gresswell, 2003b; Morris *et al.*, 2007; Wohl and Jaeger, 2009; Wohl and Cadol, 2011). Valley characteristics that influence wood recruitment includes drainage area, channel position within the network, hydrologic regime, valley confinement and gradient, presence of landslides and debris flows, and channel migration (Benda *et al.*, 2003; Swanson, 2003; Hassan *et al.*, 2005; Seo and Nakamura, 2009; Fremier *et al.*, 2010; Wohl and Cadol, 2011; Bertoldi *et al.*, 2013).

Retention of LW within the channel is a balance between resisting and driving forces; LW and channel characteristics can either increase hydraulic resistance that promotes LW retention or increase hydraulic driving forces that promote LW transport. LW characteristics that influence retention include piece size with respect to the stream channel, presence of rootwads, wood burial, branching complexity, orientation, and piece alteration through physical breakdown or decay (Gurnell *et al.*, 2002; Abbe *et al.*, 2003; Hassan *et al.*, 2005; Newbrey *et al.*, 2005; Merten *et al.*, 2010, 2011; Wohl *et al.*, 2012a). Channel characteristics that influence wood retention include streamflow velocity, flow depth, and roughness elements such as substrate, bedforms, mid-channel bars, meanders, secondary channels, and bank vegetation (Braudrick and Grant, 2001; Millington and Sear, 2007; Seo and Nakamura, 2009; Wohl and Cadol, 2011; Bertoldi *et al.*, 2013; Gurnell, 2013). The relative contribution of recruitment and retention controls and their interactions on LW loads of headwater streams remains unclear and varies across different hydroclimatic regimes (Fremier *et al.*, 2010).

Insect and disease outbreaks can be a severe natural disturbance to forests that have the potential to alter wood loadings and the relative influences of LW recruitment and retention processes (Bragg, 2000; King *et al.*, 2013). Eastern hemlock (*Tsuga canadensis*) is an evergreen canopy tree that functions as a foundational species across eastern North America (Ellison *et al.*, 2005). Forests dominated by eastern hemlock are undergoing a fundamental change in function and composition as a result of infestation of hemlock woolly adelgid (*Adelges tsugae*; HWA). HWA, an exotic, invasive pest insect, is causing widespread mortality in trees of all ages and sizes (Siderhurst *et al.*, 2010; Elliott and Vose, 2011) across a westward expanding portion of the range of eastern hemlock trees (see Figure 1). HWA causes loss of needles and buds that leads to the death of branches, and eventually whole tree mortality, which is estimated to occur from four to more than 20 years after infestation (McClure, 1990; Eschtruth *et al.*, 2013). It is quite likely that the amount of instream LW will increase substantially in the coming decades for those eastern hemlock forests affected by HWA (Ellison *et al.*, 2005; Evans *et al.*, 2012; Webster *et al.*, 2012). Eastern hemlocks are large trees with high tannin content (Harmon *et al.*, 1986) and wood is expected to last for 200 years within Appalachian streams (Hedman *et al.*, 1996) as a result of slow decay rates. The change in the composition of the riparian forests and inputs of potentially large volumes of slowly decaying LW could fundamentally alter stream hydrology and morphology and associated ecosystem dynamics. The impacts of natural forest disturbances attributable to insects on LW characteristics are only beginning to be recognized (Evans *et al.*, 2012; Webster *et al.*, 2012; King *et al.*, 2013).

Within the context of the large-scale disturbance associated with HWA infestation, this study provides baseline information on LW loads in eastern hemlock forest headwater streams in the central Appalachian Mountains, USA, an under-studied region (but see Evans *et al.*, 2012), across a gradient of HWA infestation from uninfested to those in severe decline. The objectives

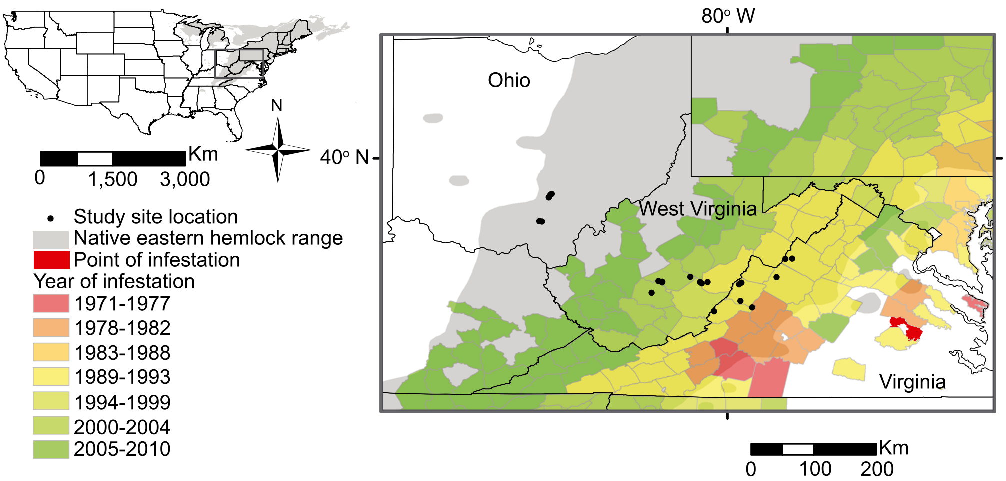

Figure 1. Location of study reaches in Ohio, West Virginia, and Virginia. The native eastern hemlock range is indicated in grey. The county of initial infestation of the hemlock woolly adelgid is indicated in red and the year counties were infested is indicated through 2010 and was provided by the US Forest Service North Research Station. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

of this work were to: (i) quantify LW loads in central Appalachian headwater streams; (ii) assess variables that predict reach-scale LW loads to determine the relative importance of recruitment and retention controls on LW load; and (iii) identify potential early impacts of HWA on LW characteristics in headwater streams of the central Appalachian Mountains. We hypothesize that (H_1) LW loads in the central Appalachian Mountains will be similar to other headwater eastern USA streams and (H_2) that LW loads will be dominated by recruitment processes as has been identified in other headwater eastern USA streams (Warren *et al.*, 2009). In addition, we hypothesize that (H_3) LW loads will be greatest in streams flowing through forests in severe decline associated with HWA infestation. Wood loads will be characterized by a larger contribution of smaller pieces that reflect limbs of dead trees that have not yet toppled. The third hypothesis builds on the conceptual model developed by Evans *et al.* (2012) that describes a coupled pattern between LW recruitment to streams and hemlock mortality associated with HWA infestation, although a time lag between infestation, tree mortality and LW loading results in LW recruitment peaking anywhere from 8 to 10 years (Orwig, 2014) to more than 30 years following the peak of hemlock decline. While we do not expect LW loads to have peaked, the purpose of this study is to test if hypothesized increased LW recruitment has begun in statistically detectable amounts in forests already in severe decline from HWA.

Study Sites

Study sites were small, mountain headwater streams with drainage area < 20 km^2 within the central Appalachian Mountains of the eastern USA. The sites are a subset of sites from previous work that evaluated HWA impacts through time on riparian forest conditions (Martin and Goebel, 2012, 2013), which had originally been selected to represent relatively undisturbed hemlock-dominated riparian forests. A total of 24 sites were sampled in Ohio, West Virginia, and Virginia, with each state having eight sites (Figure 1) located on lands managed by National Parks, National Forests, Ohio State Parks, and Ohio Department of Natural Resources. Study sites included the stream channel and the adjacent riparian and hillslope region extending approximately 35 m perpendicular from the channel (see Table I for full study site descriptions). Extensive logging occurred throughout the region until the early 1900s and all sites represent second- or third-growth forests, with the exception of a single old growth site (WV-CF1). Forest stand age was obtained from the jurisdictional land managers for each site and ranged from 83 to 137 years for a total mean age of 113 years (±47 years), excluding the single old growth site WV-CF1 at 325 years. The riparian areas of study sites were characterized by mixed hemlock/broadleaf stands and sites represented an even distribution of over-story hemlock decline from uninfested (eight sites), moderate (seven sites), to severe (eight sites). Hemlock decline was based on quantitative analysis of over-story hemlock basal area of individual trees located 10, 30, and 50 m from the stream channel conducted in 2009 and 2010 (Martin and Goebel, 2012, 2013, Jaeger personal communication, February 12, 2015). Sites were located away from roads except for infrequently used forest access roads on public lands that were generally anthropogenically undisturbed, but may be affected by low intensity recreational activities such as camping and hiking. Low-frequency, high-magnitude disturbance events such as debris flows, landslides, or blowdown can be quite significant in the study region (Eaton *et al.*, 2003) but there was no field evidence of recent disturbances of this nature at the study sites. The range of channel conditions during field data collection is illustrated in Figure 2.

The Ohio sites are located within the unglaciated Allegheny Plateau in the southeastern portion of the state. The unglaciated Allegheny Plateau is characterized by deep valleys and cliffs with sandstone, shale, and conglomerate bedrock that is overlain by Inceptisols, Alfisols, and Ultisols (Brockman, 1998; Boerner and Sutherland, 2003). The West Virginia sites are located within the Appalachian Plateau in the central eastern portion of the state. The Appalachian Plateau has a dissected topography with narrow, deep valleys with dendritic drainage networks; the predominately sandstone bedrock is overlain by Ultisol and Inceptisol soils (Buol, 1973; Fralish, 2003). The Virginia sites are within the Valley and Ridge province near the central western edge of the state. The Valley and Ridge province is characterized by folded topography with long, narrow steep ridges that are separated by level valley floors with trellis drainage networks (Fralish, 2003). Sandstone bedrock forms the ridges while shale and sandstone form the valley floors (Buol, 1973), which are overlain by Ultisol and Inceptisol soils (Fralish, 2003).

Climate is generally similar at all study sites. All sites experience cold winters (0 and 5°C) and warm, humid summers (17–23°C) (Kerr, 1983; Flegel, 2007; Cook and Slabaugh, 2006). Mean annual precipitation is approximately 1020 mm at the Ohio sites (Kerr, 1983; Lemaster and Gilmore, 1989) and 914–1270 mm at the Virginia sites (Cook and Slabaugh, 2006; Wolf and Thomas, 2006); West Virginia sites are slightly wetter receiving between ~1040 and 1480 mm of precipitation per year (Gorman and Espy, 1975; Carpenter, 1992). The Virginia sites have the highest amount of snowfall, with approximately 830 mm of snowfall on an annual basis. West Virginia receives approximately 725 mm of snowfall and Ohio 525 mm of snowfall on an annual basis (Kerr, 1983; Cook and Slabaugh, 2006).

The streams in each site are ungaged and a thorough classification of the flow regime is not feasible. Streamflow is generally highest in the spring, coinciding with snowmelt, and lowest in the summer, which is inferred from other US Geological Survey gages on similarly sized streams in the region. There were two ephemeral sites where the streambed was continuously dry through the reach, seven intermittent sites where flow was discontinuous or surface water presence was limited to isolated pools, and 15 perennial sites where flow was continuous at the time of field data collection (Table IB).

Methods

Data collection

Wood and stream data were collected for the study sites during Summer 2012/2013 low flow or dry streambed conditions. All reaches were approximately 90–190 m long (mean 130 m ± standard deviation 31 m), which generally represented 12–25 times the bankfull channel width. Reach length was constrained to consistent continuous channel and valley conditions. Therefore, significant changes in channel and/or valley characteristics resulted in variable reach lengths and 14 reaches that were less than 25 times the bankfull channel width; no reaches were less than 12 times the bankfull width. Four sites had reach lengths greater than 40 times the bankfull channel width. Reaches were surveyed to quantify channel and adjacent valley characteristics. A longitudinal profile and four cross-sectional profiles along each reach were surveyed using a laser theodolite and prism rod; an additional cross-section was included for those reaches greater than 120 m. Valley

Table I. Characteristics of study reaches (standard deviation of the mean) used in the principal component analysis (A) and additional site characteristics (B) that include elevation (E), valley width (W_v), valley side slope (S_v), forest stand age (Age), hemlock basal area, broadleaf basal area, total basal area (BA), relative unit stream power (ω), channel width (W_c), standard deviation in channel width (W_σ), hydraulic radius (R_h), channel slope (S_c), percentage bedrock (%BR), 84th percentile bed material size (D_{84}), and geometric standard deviation in bed material size (D_{sort}). Year of infestation and hemlock decline obtained from Martin and Goebel (2012). For hemlock decline, 0 denotes uninfested sites that are not in decline, 1–2 denotes sites in early decline, 3 denotes infested sites in moderate decline, and 4–5 denotes infested sites in severe decline. *Designates that variables were transformed for analysis. Untransformed values are shown in this table

(A)

	Recruitment characteristics							Retention characteristics							
Site	E (m)	*W_v (m)	S_v (m/m)	Age (yrs)	Hem BA (m^2/Ha)	Broad BA (m^2/Ha)	Total BA (m^2/Ha)	ω	W_c (m)	W_σ (m)	R_h	*S_c (m/m)	*%BR	*D_{84} (mm)	*D_{sort}
OH-BT	250	8	0.36	114	44	16	61	0.003	3.1	0.3	0.1	0.100	29	61	1.6
OH-HF1	247	8	0.64	114	29	29	58	0.005	3.3	1.3	0.3	0.061	14	48	1.5
OH-HF2	233	10	0.6	93	21	76	97	0.006	5.1	1.6	0.2	0.051	12	65	1.8
OH-HF3	225	31	0.78	83	15	94	109	0.003	6.3	0.6	0.5	0.017	19	78	2.0
OH-LK1	197	22	0.51	100	32	31	62	0.002	4.2	1.4	0.3	0.056	4	32	2.0
OH-LK2	226	4	0.78	100	31	26	57	0.004	2.8	0.2	0.2	0.099	57	129	2.9
OH-LK3	215	10	0.83	100	21	24	45	0.002	3.1	0.9	0.2	0.012	6	34	2.0
OH-SH	241	54	0.33	100	19	55	74	0.003	5.6	1.3	0.2	0.01	9	78	1.8
WV-BEAR	1024	116	0.25	110	12	25	36	0.018	7.2	1.4	0.3	0.015	0	117	2.1
WV-BIG	998	15	0.58	92	6	25	31	0.025	4.4	1.2	0.2	0.065	8	227	2.2
WV-BSR	696	31	0.58	88	0	57	57	0.070	6.2	2.1	0.4	0.087	0	168	1.7
WV-CF1	421	12	0.50	325	27	14	42	0.023	5.1	2.1	0.2	0.181	27	425	3.0
WV-CF2	472	9	0.60	114	16	28	44	0.003	2.4	0.8	0.3	0.025	2	236	3.3
WV-CW	1044	18	0.45	93	67	17	85	0.005	3.1	0.7	0.2	0.041	0	126	1.9
WV-MBR	351	25	0.78	100	20	19	40	0.134	5.5	1.0	0.3	0.166	39	145	2.9
WV-WC	528	64	0.48	103	32	23	56	0.060	5.3	1.5	0.4	0.053	2	760	3.8
VA-BC1	671	10	0.62	88	18	47	66	0.100	3.5	2.3	0.2	0.178	0	291	2.6
VA-BC2	609	17	0.6	137	18	41	59	0.024	4.1	0.4	0.2	0.043	3	238	2.1
VA-BP	598	143	0.5	93	66	36	102	0.009	7.2	0.3	0.4	0.019	21	146	1.8
VA-JR	634	51	0.46	102	55	29	84	0.018	14.1	1.5	0.6	0.013	9	186	1.9
VA-KR	575	144	0.25	125	38	50	87	0.030	8.5	2.0	0.4	0.030	1	287	1.9
VA-LPWC	591	62	0.49	103	11	50	61	0.033	9.0	1.2	0.3	0.030	0	220	1.8
VA-SC	533	61	0.45	127	36	23	59	0.027	7.9	1.4	0.5	0.021	1	239	2.2
VA-SF	746	112	0.32	113	49	9	58	0.022	11.8	3.2	0.5	0.023	1	202	1.3
Average	514	43	0.5	113	29	35	64	0.026	5.8	1.3	0.3	0.058	11	189	2.2
(standard deviation)	(265)	(44)	(0.2)	(47)	(18)	(20)	(21)	(0.033)	(2.9)	(0.7)	(0.1)	(0.052)	(15)	(155)	(0.6)

(B)

	General site characteristics				
Site	Drainage area (km^2)	Reach length (m)	Year infested with HWA	Flow regime	Hemlock decline status
OH-BT	0.1	115	-	Intermittent	0
OH-HF1	0.3	112	-	Intermittent	0
OH-HF2	0.6	123	-	Intermittent	0
OH-HF3	1.1	127	-	Perennial	0
OH-LK1	0.2	186	-	Perennial	0
OH-LK2	0.1	142	-	Intermittent	0
OH-LK3	0.5	190	-	Perennial	0
OH-SH	1.6	142	-	Perennial	0
WV-BEAR	8.4	148	1998	Perennial	2
WV-BIG	1.7	99	1998	Perennial	3
WV-BSR	5	112	2002	Perennial	3
WV-CF1	0.6	86	2002	Intermittent	1
WV-CF2	0.3	97	2002	Intermittent	1
WV-CW	0.4	116	1993	Perennial	4
WV-MBR	4.4	109	2002	Perennial	3
WV-WC	6.1	116	2002	Ephemeral	3
VA-BC1	2	95	1993	Intermittent	5
VA-BC2	2.3	108	1993	Perennial	5
VA-BP	3.6	120	1991	Perennial	4
VA-JR	19.1	190	1991	Perennial	4
VA-KR	8.4	128	1991	Ephemeral	5
VA-LPWC	9.7	115	1993	Perennial	4
VA-SC	10.2	160	1991	Perennial	5
VA-SF	11.2	169	1991	Perennial	3
Average	4.9	130 (31)			

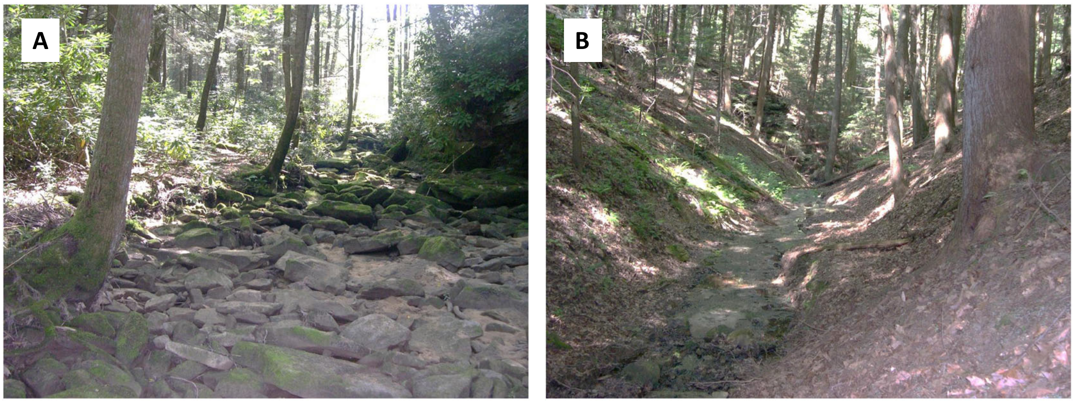

Figure 2. Views of (A) WV-WC with a drainage area of 6.1 km^2, D_{84} of 760 mm, and valley width of 64 m and (B) OH-LK2 with a drainage area of 0.1 km^2, D_{84} of 129 mm, and valley width of 4 m. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

width was field-measured in confined valleys (e.g. less than 25 m) or derived in a Geographical Information System (GIS; Esri ArcMap 10.0) for wider valleys using digital elevation models (DEMs) with resolution of at least 10 m, but typically 1–3 m. Right and left valley side slope was measured along distances of approximately 10 m from the toe of the valley using an inclinometer. Streambed substrate was characterized by measuring the intermediate-axis of 200 randomly selected clasts along each reach (Wolman, 1954; Kondolf, 1997). Drainage area and elevation were derived using GIS and a 10 m or finer DEM for all sites.

Systematic surveys of LW occurrence and characteristics were conducted in all study reaches following guidelines outlined by Wohl *et al*. (2010). A piece of wood was included in this study if it was greater than 1 m in length and 0.1 m in diameter or if its length was at least 2 m and 0.05 m in diameter (Cadol *et al*., 2009). All LW pieces that were at least partially within or suspended above the bankfull channel were included. Bankfull channel width (herein width) was defined by a marked scour line or break in slope or changes in vegetation from annual to mature perennials. The midpoint diameter, total length, and length within bankfull were recorded for all LW pieces. The presence of jams, three or more pieces of LW in contact with one another, was documented and the dimensions of all LW pieces associated with the jam accumulation that met the length and width criteria were recorded. The volume (V; m^3) of each LW piece and LW jam accumulation was approximated using the formula for the volume of a cylinder

$$V = \pi \left(\frac{d}{2}\right)^2 L$$

where d is the midpoint diameter and L is the length of the LW piece within the bankfull channel, which is a conservative estimate in order to evaluate the effective LW within the channel (Evans *et al*., 2012).

Each LW piece was classified as unattached/drift, bridge, collapsed bridge, ramp, pinned, or buried (see Table II for full definitions; Wohl *et al*., 2010). Pieces assigned as unattached/drift, pinned, or buried were classified as transported pieces. Collapsed bridges, bridges, and ramps were classified as *in situ* whereby they represented recruited pieces. This classification may misclassify some pieces; for example a piece may become pinned by another piece without previously being transported itself. Despite the possible limitations of this classification scheme, it provided a consistent means by which to coarsely identify transported and *in situ* pieces (Cadol *et al*., 2009). Wood load for each reach was calculated in common metrics of abundance and volume (Wohl *et al*., 2010; see Table III for definitions of wood load metrics). In addition, two wood

Table II. Definitions of large wood classifications

Classification	Definition
Unattached/drift	Entire piece within bankfull channel, no portion buried or pinned
Bridge	Both ends above bankfull channel, center suspended above channel
Collapsed bridge	Two ends above bankfull channel, broken some point along its length
Ramp	One end in above bankfull channel, one end in the channel
Pinned	All or a portion lodged beneath other pieces of wood
Buried	All or a portion buried in streambed

transportability ratios, length and draft ratios (Merten *et al*., 2010), for each piece of LW were calculated (Table III).

Forest cover was characterized with a modified version of the point-center-quarter method along three transects that extended 35 m perpendicularly from the stream channel (Cottam and Curtis, 1956). Transects were selected based on visual assessment of hillslope and forest stand conditions that were generally representative of the entire study reach. Each tree was classified as eastern hemlock, broadleaf, or rhododendron, which are the dominant vegetation types in this region. Although other conifer tree species occur within the region, none were specifically located along transects at any of the study sites. Diameter at breast height (DBH) was recorded for the closest tree in each quadrant at three randomly generated distances along each transect. A minimum of 5 m was required between each randomly generated point. Basal area was calculated for eastern hemlock, broadleaf, rhododendron, and all trees combined (total) for each site. Rhododendron basal areas were small (average 0.2 m^2/ha) and were only used in calculations of total basal areas.

Hemlock decline status for each study site was based on previous related research at the sites conducted between June 2009 and October 2010 (Martin and Goebel, 2012, 2013). Hemlock decline was quantified as a function of canopy foliage condition along parallel transects along the channel at distances of 10, 30, and 50 m from the channel (Martin and Goebel, 2012, 2013). Sites were partitioned into uninfested sites, sites in moderate decline, and sites in severe decline. Uninfested sites had no damage to foliage and no documented HWA infestation, sites in moderate decline had between 25 and 75% canopy foliage remaining, and sites in severe decline had less than 25% canopy foliage remaining following definitions outlined by Orwig and Foster (1998). Time of HWA infestation in moderate and severe decline sites was reported in

Table III. Large wood variables used to evaluate large wood characteristics in central Appalachian headwater streams

Variable	Equation	Units
LW frequency	$\frac{\text{\# LW encountered}}{\text{Reach length (m)}} \times 100$	(#/100 m)
In situ frequency	$\frac{\text{\# In situ LW encountered}}{\text{Reach length (m)}} \times 100$	(#/100 m)
Jam frequency	$\frac{\text{\# Jams encountered}}{\text{Reach length (m)}} \times 100$	(#/100 m)
LW density	$\frac{\text{\# LW encountered}}{\text{Channel area (m}^2\text{)}}$	(#/m^2)
LW volume per length	$\frac{\text{Total LW volume}\left(\text{m}^3\right)}{\text{Reach length (m)}} \times 100$	(m^3/100 m)
LW volume per area	$\frac{\text{Total LW volume}\left(\text{m}^3\right)}{\text{Channel area (m}^2\text{)}}$	(m^3/m^2)
Jam volume per length	$\frac{\text{Total jam volume}\left(\text{m}^3\right)}{\text{Reach length (m)}} \times 100$	(m^3/100 m)
Length ratio*	$\frac{\text{Total piece length (m)}}{\text{Channel width (m)}}$	(m/m)
Draft ratio	$\frac{\text{Midpoint piece diameter (m)}}{\text{Channel depth (m)}}$	(m/m)

*Total piece length includes LW length extending beyond the bankfull channel.

Martin and Goebel (2012, 2013), and had been obtained from the USA Forest Station's Northern Research Station and K. Costigan personal communication with R. Morin.

Data analysis

Stream channel, valley, and forest stand characteristics influence how LW is recruited and retained in a channel. In order to draw meaningful relationships between wood load and physical environmental parameters, the parameters were partitioned into two separate categories to reflect valley recruitment and instream retention processes of LW. Wood load response variables quantify the amount of LW at each site and included LW frequency per channel length, density per channel area, volume per channel length and channel area, proportion of LW (by number of pieces and volume) in jams, jam frequency per channel length, and jam volume per channel length (Table III). We included this comprehensive suite of wood load metrics, reasoning that this approach would reduce potential bias among statistical associations that may vary between predictor variables and individual wood load metrics and facilitate comparison between other studies.

A combination of principal component analysis (PCA) and step-wise multi-linear regression (MLR) models were used to identify the influences of LW recruitment and retention characteristics on LW loads. PC axes with eigenvalues > 0.1 (Kaiser-Guttman criteria) were retained (Jackson, 1993; Rencher, 1995). Correlations among variables were calculated using Pearson's coefficient and all included variables were less than a threshold correlation coefficient (r-value) of $\pm$ 0.8 to limit biased loadings within the PCs (Quinn and Keough, 2002). Variables were tested for normality using the Shapiro–Wilk test and visual inspection of distributions prior to the PCA; some variables were $\ln(x)$ transformed to meet test assumptions (Afifi *et al.*, 2003). The loadings on each PC was assessed for significance using a loading threshold of 0.50 (Afifi *et al.*, 2011) and 0.40 for moderately significant (Merriam *et al.*, 2011). PC loadings are correlation coefficients between the PC scores and the original variables that measure the relative importance of each variable in the PC. Characteristics used in this analysis may load positively or negatively along PCs that influence LW loads. The old-growth West Virginia site (WV-CF1) was a consistent outlier from visual inspection of the histograms, which heavily influenced the PCA loadings, and, therefore, was removed from all analyses including all graphical depictions.

The PCA was used to generate reduced sets of recruitment and retention variables to use in MLR. The final recruitment parameters were elevation, valley side slope, valley width, hemlock decline, stand age, basal area of hemlock and broadleaf, and total basal area. The final retention parameters were relative unit stream power (the quotient of the product of drainage area and bed slope by mean channel width), channel slope, channel width, standard deviation of channel widths, hydraulic radius (quotient of bankfull channel area and perimeter), percentage bedrock (% BR), D_{84} (84th percentile of substrate), and D_{sort} ((Folk, 1980) standard deviation of substrate sizes). Channel slope is used to determine relative unit stream power but the two variables were poorly correlated ($r = 0.62$) so both were incorporated in the final reduced set of PCA variables. As a categorical variable, flow regime classifications cannot be used in PCA, however, LW loads across the three flow classes were compared graphically.

Retained PCs were used in MLR to identify relationships between valley recruitment and in-stream retention potential with wood loading. Wood load response variables were also examined for normality with the Shapiro–Wilk test before the MLR and some variables were transformed to meet test assumptions. Bi-directional step-wise methods were used to identify significant models from the retained recruitment and retention PCs. Akaike's Information Criterion (Akaike, 1998) was used to select the best, most parsimonious model(s). Residual plots were examined for each best fit model to identify potential outliers and heteroscedasticity. Potential influence on wood loading from HWA infestation was assessed using simple linear regressions of the relative abundance of small pieces of LW (1–2 m and 1–4 m) and large pieces of LW (>10 m) against hemlock decline. All statistical analyses were performed in R (R Team, 2012) using the *stats* package.

Results

Channel characteristics of headwater central Appalachian streams

Channels in the central Appalachian Mountains were generally characterized as steep, narrow headwater channels (Table I(A) and I(B)). Most valleys were relatively confined (43 m (mean) ± 44 (standard deviation)) with steep valley side slopes (0.53 m/m ± 0.2) and streambed gradients (0.06 m/m ± 0.05). Mean channel width for all sites was 5.8 m, ranging from 0.5 to 15.5 m and increased with drainage area, which was generally larger in the Virginia sites. Substrate was generally coarse with a mean D_{84} of 189 mm (±155 mm). The mean proportion of bedrock was 11% across all sites. The Ohio sites had the highest proportion of bedrock (mean: 19%, range: 5–57%); the Virginia sites had the lowest proportion of bedrock (mean: 4%, range: 0–21%).

Large wood loads in headwater central Appalachian streams

In total, 1191 individual pieces of LW were measured across all study sites (Table IV). *In situ* pieces accounted for 23% of all pieces; the remaining 77% were classified as transported. There was a high frequency of short and narrow LW pieces (<3 m and 15 cm, respectively) with the two smallest size classes for piece length and diameter collectively accounting

Table IV. Average large wood (LW) loads and characteristics for each study reach and total mean (± standard deviation) for all reaches

Site	LW Characteristics					Wood load					Jam Characteristics			
	Total length (m)	Length ratio	Bankfull length (m)	Mean diameter (cm)	Draft ratio	Frequency (#/100m)	*In situ* frequency (#/100m)	Density (#/m^2)	Volume (m^3/100m)	Volume (m^3/m^2)	% LW in jams	% Volume in jams	Density (#/100m)	Jam volume (m^3/100m)
OH-BT	5.4	1.7	3.9	16	1.5	24	4	0.08	3.02	0.01	25	40	2	1.22
OH-HF1	3.1	0.9	2.4	18	0.5	62	8	0.19	4.36	0.013	65	57	3	2.49
OH-HF2	3.1	0.6	2.4	16	0.9	29	8	0.06	2.30	0.005	51	79	4	1.82
OH-HF3	4.1	0.7	3.0	14	0.2	30	8	0.05	2.14	0.003	40	46	2	0.98
OH-LK1	6.9	1.6	3.1	14	0.4	44	15	0.10	3.07	0.007	52	49	5	1.51
OH-LK2	5.2	1.9	2.8	16	0.7	29	5	0.11	2.25	0.008	45	55	2	1.23
OH-LK3	4.6	1.5	3.2	15	0.6	52	7	0.17	4.60	0.015	73	78	3	3.60
OH-SH	4.8	0.9	3.4	17	0.7	42	12	0.08	5.23	0.009	50	42	5	2.20
WV-BEAR	5.0	0.7	4.3	16	0.4	74	17	0.10	10.76	0.015	69	66	7	7.11
WV-BIG	3.9	0.9	2.9	12	0.5	47	15	0.10	2.18	0.005	28	19	3	0.42
WV-BSR	4.5	0.7	3.8	15	0.3	66	10	0.11	5.61	0.009	47	38	5	2.14
WV-CF1*	4.7	0.9	2.7	20	0.8	65	15	0.13	8.30	0.016	61	88	2	0.72
WV-CF2	3.4	1.4	2.0	13	0.4	53	20	0.22	2.07	0.008	43	61	5	1.25
WV-CW	4.3	1.4	2.7	13	0.8	36	14	0.12	2.04	0.007	24	23	3	0.47
WV-MBR	3.5	0.6	2.7	9	0.2	21	4	0.04	0.39	0.001	13	6	1	0.02
WV-WC	4.0	0.8	2.3	14	0.3	21	4	0.04	1.55	0.003	0	0	0	0.00
VA-BC1	4.1	1.2	3.0	9	0.5	23	5	0.07	0.35	0.001	0	0	0	0.00
VA-BC2	8.5	2.1	5.1	16	0.9	29	13	0.07	5.27	0.013	36	56	3	2.94
VA-BP	5.0	0.7	3.2	16	0.4	20	4	0.03	1.55	0.002	50	64	2	0.99
VA-JR	4.5	0.3	4.2	15	0.2	35	6	0.02	5.72	0.004	61	91	2	5.22
VA-KR	5.0	0.6	3.7	16	0.3	33	7	0.04	5.17	0.006	59	67	1	3.45
VA-LPWC	4.6	0.5	4.6	17	0.6	56	10	0.06	10.07	0.011	75	47	5	4.76
VA-SC	5.8	0.7	4.9	13	0.2	29	6	0.04	4.70	0.006	39	40	2	1.89
VA-SF	3.6	0.3	3.6	10	0.2	8	1	0.01	0.36	0.000	31	84	1	0.31
Average (standard deviation)	4.7 (1.2)	1.0 (0.5)	3.4 (0.9)	14 (3)	0.5 (0.3)	38 (17)	9 (5)	0.08 (0.05)	3.69 (2.76)	0.007 (0.004)	42 (21)	48 (26)	3 (2)	2.00 (1.83)

*Designates not included in averages.

for ~60% of the total wood load; LW pieces in individual size classes larger than 4 m or wider than 25 cm represented between 2 and 10% of the total wood load (Figure 3(A) and 3(B)). Median LW length within the bankfull channel was 2.6 m (range: 0.3–26.5 m) while the median total length of LW was 3.1 m (range: 0.05–32.8 m). Median length ratio was 0.7 (range: 0.3–2.1). Median LW diameter was 12 cm (range: 5–67 cm) and draft ratio was 0.4 (range: 0.2–1.7). Despite lower frequency, pieces in longer and wider size classes contributed to greater relative volume (Figure 3(C) and 3(D)). The largest length size class (>10 m) had substantially greater volume relative to smaller size classes (23% vs 4–12%) (Figure 3(C)). Pieces wider than 35 cm had disproportionately greater overall volume with the widest pieces contributing the most to relative volume (Figure 3(D)).

The average total wood frequency was 38 pieces/100 m while the total average *in situ* wood frequency was 9 pieces/100 m and the density of total wood was, on average, 0.08 pieces/m^2 (Table IV). The total wood volume in terms of channel length was 3.69 m^3/100 m and in terms of channel area was 0.007 m^3/m^2. The proportion of LW that formed jams, on average, accounted for 42% of the total LW abundance and 48% of the total wood volume. There was an average jam frequency of 3 jams/100 m and jam volume of 2.00 m^3/100 m.

Wood load values are compared with those reported in other studies of relatively small forested watersheds in the eastern USA region (Table V). In some cases in which drainage areas were not reported, small rivers were included in LW load averages. Two of the seven studies were specific to eastern hemlock forests with some degree of HWA infestation. Three studies, Silsbee and Larson (1983), Hedman *et al.* (1996), and Warren *et al.* (2009), included some remnant old-growth stands, although all studies had some degree of timber harvest history.

Recruitment and retention characteristics in headwater central Appalachian streams

The PCA for the recruitment parameters indicated that the first three axes explained 74.1% of the variance in LW loads (Figure 4(A); Table VI(A)). PC 1 represented general valley characteristics with moderate loadings in valley width and moderate negative loadings in elevation, valley side slope, and hemlock decline that collectively explained 35.4% of the variance. PC 2 represented forest structure characteristics with high loadings in broadleaf basal area and total basal area and explained 23.1% of the variance. PC 3 had high loadings of hemlock basal area and moderate negative loadings of elevation that explained 15.5% of the variance in the dataset.

The PCA for retention parameters indicated that the first three axes explained 79.4% of the variance in the LW loads (Figure 4(B); Table VI(B)). PC 1 represented a gradient of physical channel characteristics dominated by channel dimensions with moderate negative loadings of relative unit stream power, channel width, variation in channel width, and hydraulic radius that explained 37.8% of the variance in the dataset. PC 2 represented a gradient of channel roughness and hydraulic forces with high loadings in relative channel slope and moderate loadings in relative unit stream power and D_{sort} that explained 27.3% of the variance in the data. PC 3 had moderate loadings in standard deviation of channel widths and moderate negative loadings of percentage bedrock and high negative loadings of D_{sort} that explained 14.3% of the variance in the dataset.

Sites were overlaid on the recruitment and retention PCAs to identify potential patterns in recruitment and retention at the sites (Figure 4). With respect to recruitment parameters, the Ohio sites were characterized by steeper valley side slopes, confined valleys, younger forests with smaller hemlock basal

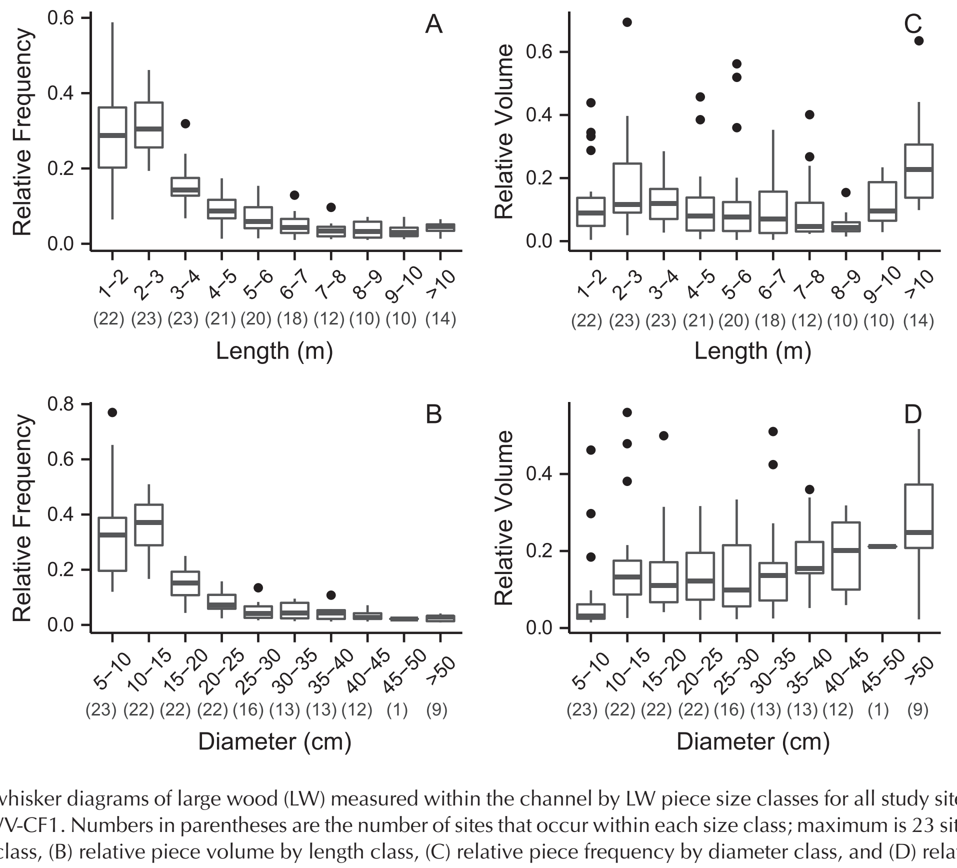

Figure 3. Box and whisker diagrams of large wood (LW) measured within the channel by LW piece size classes for all study sites with the exception the old growth site, WV-CF1. Numbers in parentheses are the number of sites that occur within each size class; maximum is 23 sites. (A) Relative piece frequency by length class, (B) relative piece volume by length class, (C) relative piece frequency by diameter class, and (D) relative piece volume by diameter class. The box represents the 25th and 75th percentiles of the distribution of LW frequency and volume, the thicker horizontal lines within the box represent the median, and the whiskers represent the 10th and 90th percentiles. Circles represent extreme values.

Table V. Large wood loads from forested watersheds in eastern USA region[a]

Location	n	A (km^2)	Frequency (#/100m)	Density (#/m^2)	Wood volume (m^3/100 m)	Wood volume (m^3/m^2)	Jams/100m	HWA present	Source
Central Appalachian Mountain Region	23	4.1	39	0.09	3.88	0.007	3	yes	This study
15 state region along eastern US extending from Alabama to Maine	47					0.004		yes	Evans *et al.*, 2012
Adirondack Mountains, New York	1	7.4	35				3.2		Warren and Kraft, 2008
White Mountains, New Hampshire and Adirondack Mountains, New York	28	0.05	29		3.35	0.007	2.9		Warren *et al.*, 2009
Connecticut	5	5.2	16		3.15		5.2		Costigan and Daniels, 2013
Tennessee, Southern Appalachian Mountain Region	2	2.4				0.008; 0.034			Silsbee and Larson, 1983
North Carolina, Southern Appalachian Mountain Region	11	4.3			14.85				Hedman *et al.*, 1996
Coweeta Hydrologic Laboratory, North Carolina, Southern Appalachian Mountain Region	8					0.016		yes	Webster *et al.*, 2012

[a]Values are averages over streams or rivers in each study (n). Values from Warren and Kraft (2008) are an average over a four-year monitoring period. Values from Costigan and Daniels (2013) are an average of the five of the seven streams in the study with drainage areas < 9 km^2. Values in Silsbee and Larson (1983) are for streams with logged and unlogged riparian areas, respectively. Values from Webster *et al.* (2012) are based on approximate LW estimates interpreted from a bar chart (Figure 5). Drainage area (A) of streams was not reported for Evans *et al.* (2012) nor Webster *et al.* (2012).

areas, and no hemlock decline as no sites in Ohio were infested with HWA at the time of this study. With respect to retention parameters, the Ohio sites had higher proportions of bedrock, low stream power, and smaller, well-sorted substrate. The West Virginia and Virginia sites were not well separated from each other. With respect to recruitment parameters, the West Virginia and Virginia sites were characterized by gradual valley side slopes, unconfined valleys, older forests with larger hemlock basal area, and moderate to severe hemlock decline. With respect to retention parameters the West Virginia and Virginia sites were characterized with lower proportions of bedrock, high stream power, and large, poorly-sorted substrate.

Predictors of LW loads

Results of the backward and mixed stepwise MLR produced identical models that included combinations of recruitment and retention PCs that influenced wood loads in these streams (Table VII; Table VIII). Retention PCs were particularly prevalent in predicting jam characteristics. A significant model was found for each wood response variable. The most significant final model for LW loads in terms of wood density (#/m^2) explained 49% of the variance and included all of the PCs; although, recruitment PC 2 was the only significant PC included in that model. The most significant final model for jam wood loads was in terms of percentage of the total volume of LW in jams, which explained 59% of the variance in the dataset, and only included retention PC 2 as a significant predictor. Recruitment PC 1 (valley characteristics) was present in several of the final models, but not at the 0.05 significance level. Recruitment PC 2 (forest structure) was present in all the final models and significant in three of the eight final models. Although Recruitment PC 3 (hemlock basal area and elevation) explained only ~15% of the LW variance, it was present in seven of the eight models and significant in five of the models at the 0.05 and 0.01 level. Retention PC 2 (channel roughness and hydraulics) appeared to be the most important factor as it was present in all models and significant in all but one of the final models. Retention PC 1 (channel dimension characteristics) was significant in three of the four models that it was included in.

The two ephemeral study streams generally had lower LW load characteristics with the exception of volume and jam volume (Appendix 1). However, no consistent trends in LW loads were identified between intermittent and perennial streams.

Impact of HWA on LW loads

Analyses between characteristics of LW load and hemlock decline status yielded weak relationships (Table IX; Figure 5). Differences in LW characteristics among decline classes were not statistically significant. Sites in moderate decline had the highest wood load with high total LW (Figure 5(A)), *in situ* LW (Figure 5(B)), and jam frequencies relative to uninfested and severely infested sites. Uninfested sites had higher LW frequencies than those in severe decline. LW density (# pieces/m^2) displayed a generally decreasing relationship as a function of hemlock decline (Figure 5(D)). LW total volume (m^3/100 m) and jam volume (m^3/100 m) were highest at the sites in severe decline and lowest at the sites in moderate decline (Figure 5(E) and 5(F), respectively). Sites in moderate decline had a higher proportion of small LW classes (i.e. <4 m; Figure 5(G) and 5 (H)) and large LW classes (i.e. >10 m; Figure 5(I)). Sites in severe decline generally had the lowest proportions of small LW.

Discussion

This study provides a detailed inventory of LW characteristics and controls on LW loads in central Appalachian streams and quantifies the impacts of HWA on LW loads in the region. Results of this study will be of particular interest to those who

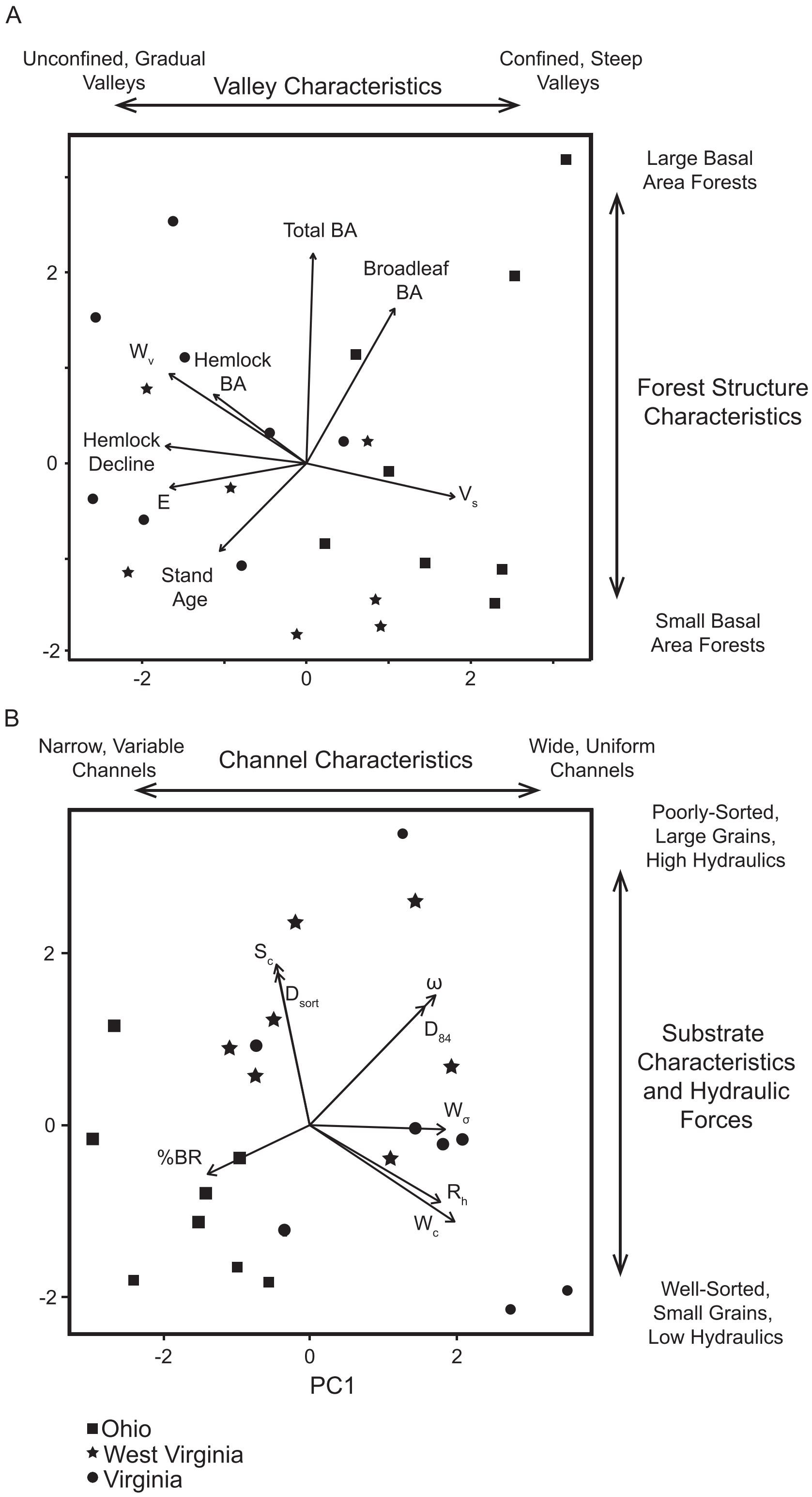

Figure 4. Biplots of the first two axes resulting from principal components analysis of (A) recruitment and (B) retention variables (n= 23 study reaches).

attempt to validate models of LW loads and develop long-term simulations of the impacts of disturbance. Results of this study are also useful to infer potential impacts to channel morphology and aquatic habitat in light of the expected hydrologic, geomorphic, and ecological changes expected as a result of HWA infestation.

LW characteristics and loads

LW dimensions in this study were consistent with dimensions reported elsewhere although the majority of the wood could be considered intermediate to small size (Hassan *et al.*, 2005). In particular, the overall length and draft ratios were low, indicating that the LW had a high mobilization potential (Gurnell *et al.*, 2002; Hassan *et al.*, 2005; Warren and Kraft, 2008; Wohl and Goode, 2008). Distribution of LW diameters appeared to be similar to Evans *et al.* (2012) where HWA-infested sites located throughout the eastern USA hemlock range tended to have higher proportions of large diameter LW; lengths were not reported in their study. Relative volume by diameter size class was fairly uniform for small to intermediate size classes (e.g. < 35 cm) but increased substantially with the largest class sizes, as documented elsewhere (Comiti *et al.*,

Table VI. Principal component loadings and explained variance for the first three components for the reduced set of (A) recruitment and (B) retention variables. Variables loading significantly (>0.5) on a PC axis are shown in bold. Values between 0.4 and 0.5 are considered moderate loading and are shown in italics

(A) *Recruitment*	PC 1	PC 2	PC 3
E	*−0.42*	0.00	*−0.45*
S_v	*−0.43*	0.30	−0.16
W_v	*0.46*	−0.11	0.00
Hemlock decline	*−0.44*	0.00	−0.31
Age	−0.27	−0.29	0.29
Hem BA	−0.29	0.23	**0.64**
Broad BA	0.27	**0.52**	−0.36
Total BA	0.00	**0.70**	0.21
Standard deviation	1.7	1.4	1.1
Proportion of variance (%)	35.4	23.1	15.5
Total variance explained (%)	35.4	58.6	74.1
(B) *Retention*	PC 1	PC 2	PC 3
ω	*−0.40*	*0.41*	0.00
W_c	*−0.46*	−0.31	−0.17
W_σ	*−0.43*	0.00	*0.44*
R_h	*−0.42*	−0.25	−0.39
S_c	0.11	**0.52**	0.29
% BR	0.33	−0.16	*−0.41*
D_{84}	−0.37	0.38	−0.34
D_{sort}	0.10	*0.49*	**−0.51**
Standard deviation	1.7	1.5	1.1
Proportion of variance (%)	37.8	27.3	14.3
Total variance explained (%)	37.8	65.1	79.4

2006; Cadol *et al.*, 2009). Relative volume by length class was also generally uniform except for lengths greater than 10 m.

Wood loads in this study are slightly higher in frequency but generally comparable in volume and jam frequency relative to those reported in other streams in eastern US forested watersheds with similar disturbance history (Table V), thus supporting our first hypothesis. One exception, Webster *et al.* (2012), reported more than twice the overall wood volume in eight streams in the Southern Appalachian Region of North Carolina, although their study included smaller piece sizes of > 0.005 m diameter versus 0.01 m in this study. Within the same region Hedman *et al.* (1996) reported substantially higher (14.85 m^3/100m) wood volumes, which included only pieces >1.5 m versus 1 m. Webster *et al.* (2012) report, generally, lower wood volumes for eastern hemlock streams not yet affected by HWA than what was documented in the uninfested Ohio sites of this study. Evans *et al.* (2012) quantifies LW loads throughout the native range of the eastern hemlock extending from Maine to Alabama, representing a broad range of hydroclimatic regions compared to the Central Appalachian region, which may account for LW loads that are approximately 50% lower than those found in this study. However Evans *et al.* (2012) report LW loads that were approximately 40% higher for those sites infested by HWA relative to this study; although, time since infestation was not reported so it is difficult to draw inferences for the variation in their reported wood loads and those found in this analysis.

Relative influences on wood load

Our results demonstrate that LW loads in headwater streams in the Central Appalachian region can be predicted by combinations of recruitment and retention characteristics and that in particular, retention characteristics dominate LW jam characteristics. Regression analyses indicated that combined recruitment and retention PCs explained 40–49% of the variation (one model explained 25%) in LW abundance and volume with highly significant best-fit models

Table VII. Best fit models from multiple linear regressions for large wood (LW) loads with derived principal components (PC). Parameters significant to the 0.05 level are bold and to the 0.10 level are italicized. The Ndf and Ddf are the numbers of degrees of freedom in the numerator and denominator, respectively, for calculating the *F* statistic

Response variable	Predictor variable	Coefficient	*P*-value	Ndf, Ddf	*F*	R^2	*P*-value
LW frequency (#/100 m)	**Intercept**	**37.522**	**<0.000**	**4, 18**	**4.972**	**0.42**	**0.007**
	Recruitment PC 2	**−5.096**	**0.03**				
	Recruitment PC 3	**−10.827**	**0.001**				
	Retention PC 1	**3.006**	**0.01**				
	Retention PC 2	**−6.378**	**0.008**				
LW density (#/m^2)	**Intercept**	**0.083**	**<0.000**	**6, 16**	**3.321**	**0.49**	**0.026**
	Recruitment PC 1	0.004	0.59				
	Recruitment PC 2	**−0.018**	**0.03**				
	Recruitment PC 3	−0.009	0.40				
	Retention PC 1	0.014	0.11				
	Retention PC 2	−0.007	0.34				
	Retention PC 3	0.006	0.49				
LW volume (m^3/100 m)	**Intercept**	3.685	**<0.000**	**3, 19**	**3.386**	**0.25**	**0.040**
	Recruitment PC 2	−0.557	0.17				
	Recruitment PC 3	**−1.238**	**0.01**				
	Retention PC 2	**−1.087**	**0.12**				
LW volume (m^3/m^2)	**Intercept**	**0.007**	**<0.000**	**5, 17**	**4.109**	**0.41**	**0.013**
	Recruitment PC 1	−0.008	0.21				
	Recruitment PC 2	**−0.001**	**0.03**				
	Recruitment PC 3	**−0.002**	**0.04**				
	Retention PC 1	**0.002**	**0.02**				
	Retention PC 2	**−0.002**	**0.01**				

Table VIII. Best fit models from multiple linear regressions for LW jam loads with derived principal components (PC). Parameters significant to the 0.05 level are bold and to the 0.10 level are italicized. The Ndf and Ddf are the numbers of degrees of freedom in the numerator and denominator, respectively, for calculating the *F* statistic

Response variable	Predictor variable	Coefficient	*P*-value	Ndf, Ddf	*F*	R^2	*P*-value
Jam frequency (#/100 m)	**Intercept**	**2.87**	**<0.000**	**6, 16**	**2.944**	**0.35**	**0.039**
	Recruitment PC 1	−0.275	0.32				
	Recruitment PC 2	−0.275	0.31				
	Recruitment PC 3	**−1.154**	**0.006**				
	Retention PC 1	**0.628**	**0.05**				
	Retention PC 2	**−0.763**	**0.007**				
	Retention PC 3	**0.225**	**0.45**				
Percentage of pieces in jam	**Intercept**	**42.439**	**<0.000**	**3, 19**	**8.349**	**0.50**	**<0.000**
	Recruitment PC 2	−3.294	0.20				
	Recruitment PC 3	−4.912	0.12				
	Retention PC 2	**−12.147**	**<0.000**				
Percentage of volume in jam	**Intercept**	**48.222**	**<0.000**	**1, 21**	**32.970**	**0.59**	**<0.000**
	Retention PC 2	**−13.232**	**<0.000**				
Jam volume (m^3/100 m)	**Intercept**	**2.001**	**<0.000**	**3, 19**	**3.497**	**0.25**	**0.040**
	Recruitment PC 2	−0.360	0.19				
	Recruitment PC 3	*−0.644*	*0.06*				
	Retention PC 2	**−0.823**	**0.005**				

Table IX. Parameter estimates for simple linear regression relationship between large wood (LW) load characteristics and severity of hemlock decline. Bolded values are significant to the 0.1 level. Here a and b are parameters in the relation y = a + bx. SE_b is the standard error of the coefficient b; R^2 is the coefficent of determination; *F* is the value of the *F* distribution; *p*-value is the significance probability

	a	b	SE_b	R^2	*F*	*p*-value
LW frequency (#/100m)	40.709	−3.188	4.231	0.03	0.568	0.46
In situ frequency (#/100m)	8.951	−0.125	1.260	0.00	0.010	0.92
Jam frequency (#/100m)	3.370	−0.500	0.452	0.06	1.224	0.28
LW density (pieces/m^2)	**0.107**	**−0.024**	**0.013**	**0.15**	**3.698**	**0.07**
LW volume (m^3/100m)	3.192	0.494	0.693	0.02	0.508	0.48
Jam volume ($m^{3/}$100m)	1.709	0.292	0.464	0.02	0.400	0.54
1–2 m (proportion)	29.190	−2.638	2.552	0.05	1.068	0.31
1–4 m (proportion)	70.854	−3.819	3.262	0.06	1.371	0.26
>10 m (proportion)	9.817	2.344	3.465	0.02	0.458	0.51

(Table VII). Regression analyses for LW jam characteristics explained 25–59% of the variation and were dominated by retention PCs, particularly retention PC 2 (channel roughness and hydraulics) (Table VIII).

Higher values in LW load characteristics that do not include jam characteristics (e.g. frequency, density, and volume) were generally associated with smaller width, lower gradients, smaller, well-sorted grains, and lower relative unit stream power, reflecting generally low hydraulic driving forces. Negative coefficients for recruitment PC 2 and PC 3 indicated that higher loads were associated with forests characterized by larger basal area (total, hemlock, and broadleaf) demonstrating that recruitment process stand conditions played an important role in LW loads. However, the absence of recruitment PC 1 suggested that, at least for these headwater study sites, physical valley conditions such as elevation, valley confinement, and hillslope steepness were not useful predictors of LW load. Hemlock decline status was also included in this recruitment PC and therefore was also not a significant predictor of LW load.

Jam characteristics were primarily controlled by retention parameters, particularly retention PC 2 (channel roughness and hydraulics). Regression analyses identified that retention PC 2 explained 59% of the variation in percentage of LW volume in jams and was a significant predictor in all four models for jam characteristics (Table VIII). We interpret the significant prevalence of PC 2 to suggest that LW jams form where both in-channel hydraulic driving forces and substrate resisting characteristics are lower (e.g. well-sorted, smaller grains). However, the presence of recruitment characteristics of forest stand structure in LW jam models, though not significant, suggests at least some influence on jam characteristics.

These findings generally do not support our second hypothesis that recruitment processes would better predict wood loads. In particular, we hypothesized that the recruitment characteristics of stand conditions, specifically stand age, would be the strongest predictor in wood loads. This finding was reported for forested streams in northeastern USA with similar timber harvest history to the sites in our study (Warren *et al.*, 2009). Stand age did not load significantly on any of the PCs and did not have a role in predicting wood loads. This finding is contrary to Warren *et al.* (2009) in which wood loads increased with stand age. Our study did not include as broad a range of stand age (35–315 years), but focused on mature second growth forests (83–127 years), which may account for why stand age was not a predictor of wood load for our sites. Instead, our results suggest that other recruitment parameters, notably tree basal area in the adjacent riparian forest influence LW loads. In addition, once LW is recruited to the channel, streams lack sufficient hydraulic driving forces, notably they were characterized by low relative unit stream power and gradual streambed gradient despite lower

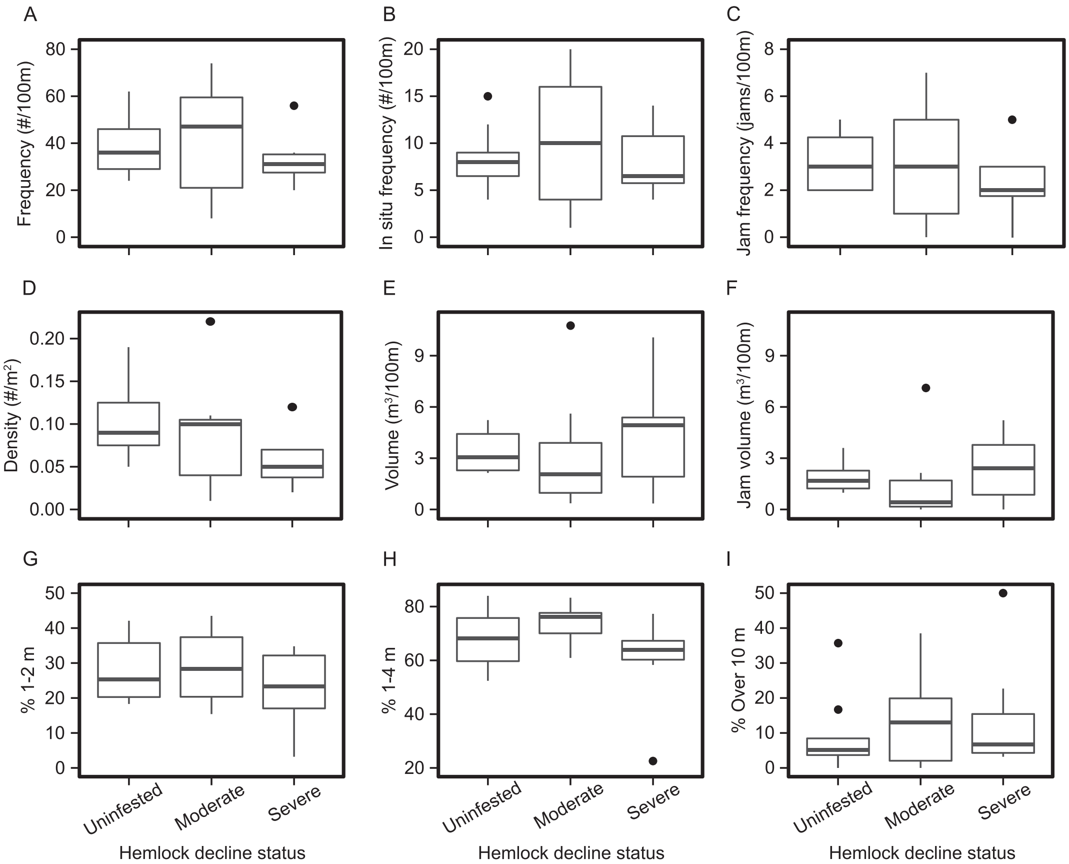

Figure 5. Box and whisker diagrams of the distribution of large wood (LW) characteristics in terms of (A) total LW frequency, (B) *in situ* LW frequency, (C) jam frequency, (D) LW density, (E) LW volume, (F) jam volume, (G) proportion of LW 1–2 m in length, (H) proportion of LW 1–4 m in length, and (I) proportion of LW >10 m as a function of hemlock decline status obtained from Martin and Goebel (2012). The box represents the 25th and 75th percentiles of the distribution of LW characteristics, the thicker horizontal lines within the box represent the median, and the whiskers represent the 10th and 90th percentiles. Circles represent extreme values.

resistance structures of well-sorted small grains to transport LW out of the reach.

Retention processes may control LW residency in these streams. Many pieces had low draft and length ratios indicating that they are easily mobilized and the majority (77%) of LW was identified as being transported. As a consequence of low hydraulic driving forces in predicted high wood loads, most pieces are likely mobilized during episodic high flow events that may exceed bankfull (Bilby and Ward, 1989; Swanson, 2003; Wohl and Goode, 2008). However, distance traveled by each piece may be limited by the strength of in-stream retention characteristics. Several studies have documented that a variety of processes may influence piece residence time and distance transported including piece size (Braudrick and Grant, 2001; Wohl and Goode, 2008), debris dams (Martin and Benda, 2001, Warren and Kraft, 2008), and flow regimes (Cadol and Wohl, 2010). In the streams of this study, the strength of retention processes (channel dimensions and substrate size) may limit long travel distances by pieces, which results in higher wood loads that are generally composed of small pieces that have been transported short distances within the reach.

It is difficult to quantify the effect of variation of flow regime on large wood loads or the relative contributions from recruitment and retention processes as a result of the general scarcity of research of LW in ephemeral systems (Dunkerley, 2014). The residence time, distribution, and accumulation of LW in sites with long durations of dry periods likely varies from sites with more continuous flows (Dunkerley, 2014). Dunkerley (2014) found that ephemeral streams in a dryland environment have low abundances of LW jams and low rates of accumulation when compared with perennial humid environments. The study sites of this analysis are in a humid region and the intermittent and ephemeral streams likely support streamflow for either large portions of or multiple times throughout the year, only experiencing long duration low or no flow periods in the summer months. The majority of the LW encountered had been transported so it is possible that flows are sufficient enough to rearrange LW and potentially to form jams; the two study streams classified as ephemeral had slightly higher jam frequency relative to intermittent and perennial streams (Appendix 1). Additional hydrologic research is necessary to rigorously evaluate the role of flow intermittency on LW characteristics.

Impact of HWA on LW loads

At present a detectable signal of HWA impact on LW loads was weak and may be limited by the small sample size of infested sites evaluated. We had hypothesized that the highest wood loads, characterized by small LW pieces, would correspond to sites in severe decline (H_3). We reasoned that hemlock mortality in severely declining sites would be sufficiently advanced to result in breakage of limbs but not tree toppling. Our results generally did not support the hypothesis. Study reaches in more severe decline had neither more LW pieces nor higher amounts of small LW pieces. In addition, sites in severe decline did not have significantly higher wood volume relative to moderate or uninfested sites. However, jams were generally less frequent but of larger volume in sites with severe hemlock decline, which provides partial support for H_3.

Based on our findings, we present a preliminary conceptual model that describes the mechanism by which HWA may change LW loads in streams through time (Figure 6). This conceptual model is hypothetical and may serve as a framework for future studies to test that include a more comprehensive range of hemlock decline across hydroclimatic regimes. Upon infestation, HWA first causes death of buds and leaves that leads to death of branches within a four to sometimes >20 year time period depending on climate and geographical region (McClure, 1990; Lewis *et al.*, 2008; Ford *et al.*, 2012; Martin and Goebel, 2012; Orwig *et al.*, 2012; Eschtruth *et al.*, 2013). Branches are easily recruited to and transported within streams because of their small size, promoting frequent jam formation. As time progresses, HWA will cause mortailty and eventual toppling (McClure, 1990) of the whole tree, although dead hemlock trees will remain standing while other tree species establish. The lag period between tree mortality and toppling can extend for eight to ten years (Orwig, 2014), which can be shortened under high windstorm conditions. Toppled tree trunks, which can be of large diameter and length, eventually will be recruited into the channel and serve as key pieces for jam formation. Key member jam pieces are typically larger than the average LW size of a particular reach (Costigan and Daniels, 2013) and serve as stable pieces in the channel that catch mobile wood, facilitating large volume jam formation. An additional lag period between toppling and recruitment may exist if tree trunks topple as bridges well above the channel and thus are not geomorphically effective. Toppled trees potentially may persist as bridges for several decades as a result of slow wood decay rates.

As hemlock decline advances, jam frequency will be a function of large branch breakage and tree toppling density and their subsequent recruitment into the channel. Relatively low jam frequency in severely declining sites in this study could be a function of limited branch breakage and tree toppling, which may escalate as age of infestion advances beyond 20 years. However, overall wood volume may remain limited in very severely declining sites if smaller pieces have been processed through the reach prior to the recruitment by these key pieces. Forests will convert to a different tree-dominated species, which depends on the location where the infestation occurs. Based on the time periods of decline, mortality, breakage, toppling, and recruitment, potential elevated LW loads associated with HWA may occur as quickly as 12 years following initial infestation or may extend to 30 years or for several more decades if hemlock decline is slow and trees are recruited to the channel as collapsed bridges. These ideas presented in this conceptual diagram are generally consistent with the conceptual model presented by Evans *et al.* (2012) that proposes a lagged coupling of increased wood load with forest basal area decline. HWA-associated forest disturbance has not yet peaked at the sites in this study and therefore neither have LW loads to streams, either as individual pieces or jam accumulations, suggesting that these sites may be following at least a 30-year trajectory for potential elevated LW loads to channels. Further research is needed to rigorously test and refine the conceptual model we propose here, particularly with regard to the interaction between whole tree toppling, jam formation, and small LW piece availability for jam recruitment.

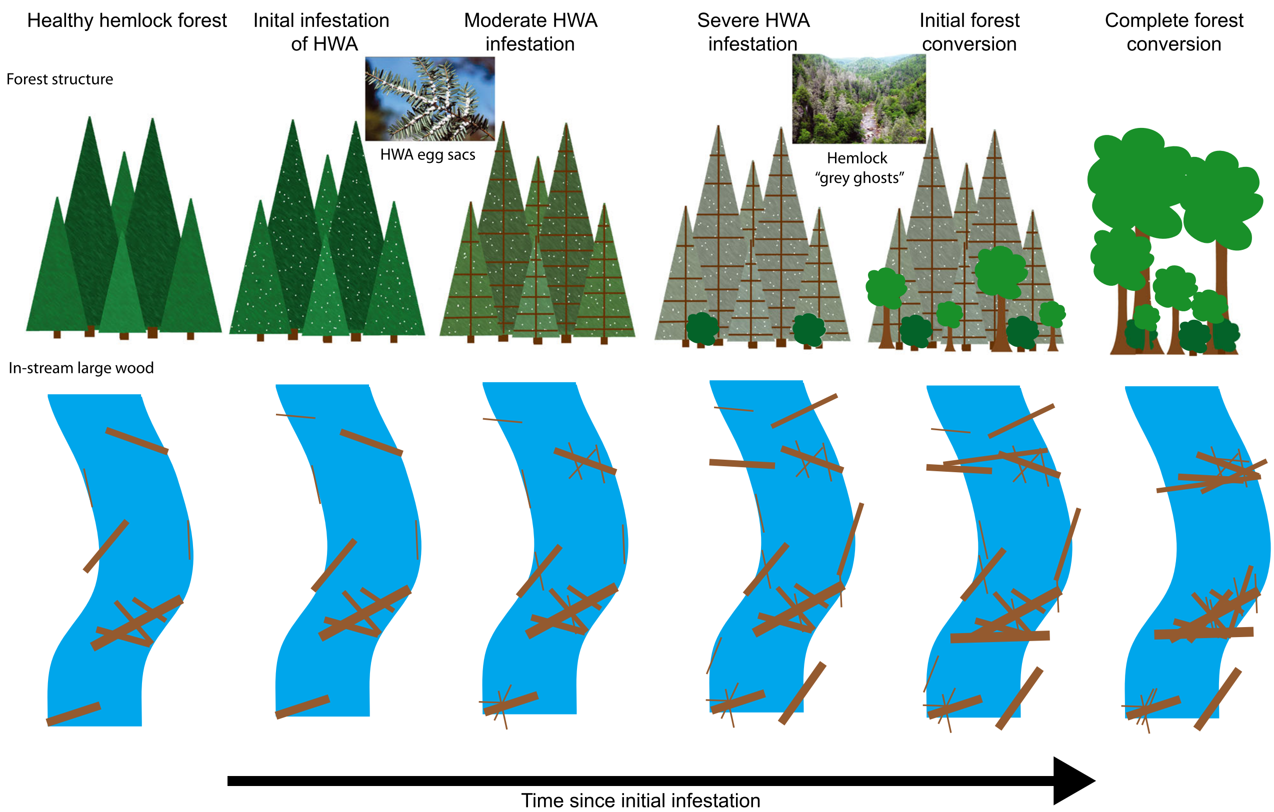

Figure 6. Conceptual model of large wood (LW) characteristics with hemlock woolly adelgid-associated hemlock decline. Total LW volume, jam frequency, and jam size will change as a function of hemlock decline, which advances from left to right. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Management implications

Natural disturbance regimes vary geographically as a function of climate, topography, vegetation, and their interactions (Moore and Richardson, 2012) and the impacts of disturbance on LW loads are only beginning to be documented (Evans *et al.*, 2012; Webster *et al.*, 2012; King *et al.*, 2013). Fire and insect outbreaks are among the more severe natural disturbances that can alter LW loads through large pulses of LW input to streams (Wohl and Cadol, 2011; King *et al.*, 2013), which have associated ecological consequences (Bragg, 2000; Hassan *et al.*, 2005). Given the importance of LW on other physical, biological, and ecological processes (Gurnell *et al.*, 2002), it is necessary to understand the potential impacts of large-scale forest disturbances on LW in order to effectively mitigate impacts on aquatic ecosystems (King *et al.*, 2013).

As a result of HWA infestation, hemlocks will likely disappear from eastern forests in the near future and re-establishment is not expected (Ellison *et al.*, 2005). Within these forested central Appalachian streams, LW loads currently reflect a mixture of recruitment and retention processes with a predominance of retention processes on jam formation. However, dramatic HWA-associated changes to stand conditions, specifically widespread tree mortality, may alter the relative influence of these processes. Results of others (Evans *et al.*, 2012; Webster *et al.*, 2012) have indicated higher wood loads in streams impacted by HWA. As time progresses and HWA-infested trees begin to topple, more and larger pieces of wood are expected to be recruited to the channel. Increased LW loading, jam formation, and jam size may become quite pronounced in these streams. Field observations indicated that large hemlocks (DBH $>$ 50 cm) are within close proximity to the channel (P.J. Soltesz, personal observation) and their recruitment to the channel is quite likely.

Projected increased LW loading and potential increased jam formation may result in significant ecological impacts, particularly transient storage processes and downstream flux of materials including carbon. LW jams are extremely efficient in trapping materials, principally sediment and other LW (May and Gresswell, 2003a), to the extent that can force bedrock channels to maintain an alluvial morphology (Massong and Montgomery, 2000). Therefore, increased wood loads associated with HWA mortality can substantially increase retention of wood, sediment, and nutrients (Ellison *et al.*, 2005; Northington *et al.*, 2013) that previously would be transported downstream during high flows.

Changes in the hydrologic regime are expected as forests transition from eastern hemlock to a different dominant species (Ford and Vose, 2007). Eastern hemlocks are evergreen trees that maintain year-round transpiration rates, with particularly high transpiration rates in the spring. With the loss of this species, persistent increases in soil moisture and streamflow, decreases in the diurnal fluctations of streamflow, and increase in the width of the variable source area are predicted (Ford and Vose, 2007). Research is needed to assess how changes in the hydrologic regime, particularly changes in hydraulic driving forces, may influence LW characteristics in these streams. In addition, changes to the hydrologic regime could have implications for those species that have adapted to the flow regime characteristics of streams draining eastern hemlock forests (Ross *et al.*, 2003) as well as terrestrial communities (Adkins and Rieske, 2013).

Large wood itself serves as a significant carbon storage element accounting for the bulk of riverine carbon in conifer forests (Beckman and Wohl, 2014). Under the assumption that LW is 50% carbon (Lamlom and Savidge, 2003) with a conversion ratio of 450 kg/m^3, mean carbon storage ranges between 1274 kg/100 m (3.1 kg/m^2) in streams draining uninfested forests to 1420 kg/100 m (2.9 km/m^2) in moderate forest decline class streams to 1310 kg/100 m (2.0 kg/m^2) in severe forest decline class streams. These estimates are a conservative first-order approximation because fine and coarse particulate matter are not included (Beckman and Wohl, 2014). Expected increases in LW loading to streams as a consequence of HWA mortality will augment transient carbon storage in these systems. There is also the potential to sequester riverine carbon over longer periods as a consequence of long residence times (>40 years) for very large LW pieces or LW jams (Hedman *et al.*, 1996). Therefore, even in these confined valley systems, the potential magnitude of materials stored behind HWA-associated LW jams will not only affect sediment, carbon, and nutrient flux at the reach scale (Wohl *et al.*, 2012b), but may have downstream consequences to reaches adapted to reliable delivery of materials (Hassan *et al.*, 2005). However, these effects may take some time (e.g. 10–40 years) to become fully realized, considering the low hydraulic forces of these streams that are incapable of mobilizing LW into jam accumulations and the lag period between tree mortality, tree toppling, and recruitment to the channel.

Conclusions

This study is part of an ongoing investigation of HWA impacts on terrestrial and aquatic ecosystem processes. LW loads were influenced by both recruitment and retention parameters; though, retention parameters explained more variation overall in jam characteristics. The majority of pieces were small relative to the stream channel indicating most pieces have high transport potential and potentially low residence times. Higher LW loads were associated with larger forest basal areas and low hydraulic driving forces within the channel. Early signs of HWA impact on LW loads were weak; sites in more moderate decline had higher proportions of small LW (<4 m) and larger LW (>10 m), but sites in severe decline had larger, but fewer jams. A conceptual model that describes mechanisms of HWA impact on LW results provides a framework for future research to test and further refine. It will be important for land managers to continue monitoring wood loads in central Appalachian streams for effective watershed management to maintain ecosystem health.

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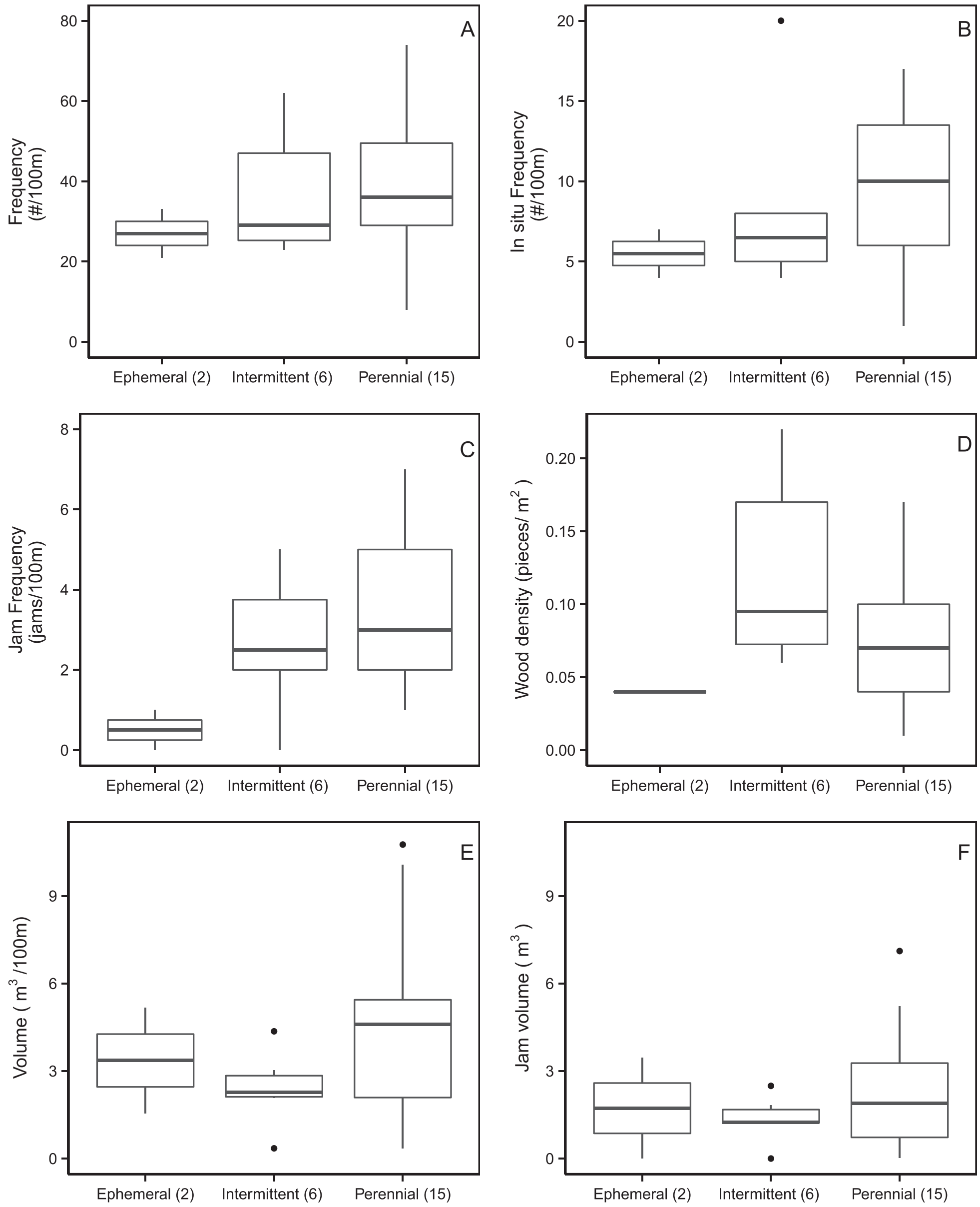

Appendix 1. Box and whisker diagrams of the distribution of large wood (LW) characteristics in terms of (A) total LW frequency, (B) *in situ* LW frequency, (C) jam frequency, (D) LW density, (E) LW volume, (F) jam volume, (G) proportion of LW 1–2 m in length, (H) proportion of LW 1–4 m in length, and (I) proportion of LW >10 m across flow classes of Ephemeral, Intermittent, and Perennial. Numbers in parentheses indicate number of study streams for each box and whisker plot. The box represents the 25th and 75th percentiles of the distribution of LW characteristics, the thicker horizontal lines within the box represent the median, and the whiskers represent the 10th and 90th percentiles. Circles represent extreme values.

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