



Wood abundance in urban and rural streams in northwestern South Carolina

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Abstract In streams and rivers, wood from riparian vegetation contributes to habitat complexity and substrates for stream biota, influences channel geomorphology, alters flow, retains sediment and organic matter, and enhances nutrient uptake. A few studies have shown that wood amounts in urban streams may be lower than in rural streams or that wood amounts in streams are inversely related to watershed impervious surface cover (ISC). To determine if these patterns occur more broadly, we compared wood amounts in urban and non-urban streams in the South Carolina Piedmont and Blue Ridge Provinces. We measured wood abundance in 20 streams draining urbanized (15–68% ISC) or non-urbanized ($\leq 2.5\%$ ISC) watersheds. Our results did not support the hypothesis that urban streams would have less wood than rural streams, and we found no relationship between wood amounts and watershed ISC. Indeed, one urban stream bordered by large riparian trees had the greatest wood volume of all streams in our study. Instead, large wood

amounts were best explained by tree canopy cover and length of unobstructed tree-lined channel upstream. These results suggest that the presence of numerous riparian trees influences wood amounts positively even in urban streams where wood amounts might be expected to be low.

Keywords Large wood debris · Headwater streams · Riparian · Land cover · Impervious cover

Introduction

The physical and ecological functions of wood from riparian trees have been well-studied in streams and rivers. For example, numerous studies have documented the importance of wood in providing habitat for fish (e.g., Fausch & Northcote, 1992; Flebbe, 1999; Bond & Lake, 2003; Clark et al., 2019). Wood also acts as an important surface for the development of stream biofilms (e.g., Hax & Golladay, 1993; Tank & Winterbourn, 1996; Vaz et al., 2014; Hellal et al., 2016), as an attachment site and refuge for macroinvertebrates (e.g., Benke & Wallace, 2003; Schneider & Winemiller, 2008; Molokwu et al., 2014; Dossi et al., 2020), and as an important component of habitat complexity for stream salamanders (e.g., Mackey et al., 2014; Rizzo et al., 2016). At the ecosystem level, wood is important to the retention of sediment

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(Nakamura & Swanson, 1993; Osei et al., 2015; Wohl & Scott, 2016; Schalko, 2020) and organic matter (Bilby & Likens, 1980; Osei et al., 2015) within stream channels. Wood can also influence channel morphology and dynamics, such as through pool formation (e.g., Bilby, 1984; Abbe & Montgomery, 2003). Wood may also enhance the downwelling of surface water (and thus dissolved oxygen, carbon, and nutrients) into hyporheic zones (Krause et al., 2014). Through such enhanced hyporheic exchange and the retention of fine sediments and particulate organic matter, wood dams can have important biogeochemical functions in streams and rivers, including serving as “hotspots” for processes such as ecosystem respiration (Blaen et al., 2018), denitrification (Groffman et al., 2005), and phosphate uptake (Valett et al., 2002). Although many of these physical and ecological functions of wood are associated with large wood (LW, diameter > 10 cm), smaller wood pieces (e.g., with diameters of 5–10 cm) may also influence channel morphology (e.g., creating step-pools in narrow channels; Galia et al., 2018) and contribute to habitat and resource availability for stream organisms (e.g., Hoffman & Hering, 2000; Bond & Lake, 2003; Schneider & Winemiller, 2008; Lester et al., 2009).

Given the important ecological functions of in-stream wood, it is important to understand the influences of human activity on the amount of wood in streams and rivers. Historically, wood was removed from larger rivers to improve navigability for boat traffic (Wohl, 2014). Changes in land use and land cover also may influence amount of wood in streams. For example, alteration of forest successional age from old-growth to second-growth forest as a result of forest harvesting or other forms of forest management can reduce amount of wood in streams (Bilby & Ward, 1991; Evans et al., 1993; Diez et al., 2001). Agricultural activities also may lead to reduced wood amount in streams due to clearing of riparian vegetation, channelization or dredging of stream channels, removal of wood from channels to reduce flooding, and overgrazing and trampling of riparian vegetation by livestock (Elosegi & Johnson, 2003; de Paula et al., 2013). However, relatively few studies have examined the impact of urbanization on the amount of wood in streams, even though the influence of urbanization on other aspects of stream ecology (e.g., effects of impervious surface runoff on stream hydrology,

nutrient and pollutant loading, and on the abundance and diversity of fish and macroinvertebrates) have been well-studied (e.g., Paul & Meyer, 2001; Walsh et al., 2005).

Human activity may influence the amount of wood in urban streams in a number of ways. For example, increased storm flow resulting from impervious surface cover (ISC) runoff in urban watersheds might flush wood downstream and increase the cross-sectional channel area through widening and incision, further facilitating the downstream movement of wood (Booth et al., 1997). Such inverse relationships between ISC and wood amounts in streams have been reported from the areas in and around the Puget Sound basin of Washington State (Horner et al., 1997); Vancouver, British Columbia (Finkenbine et al., 2000); Cleveland, Ohio (Blauch & Jefferson, 2019), and Melbourne, Australia (Vietz et al., 2014). Blauch & Jefferson (2019) also provide evidence that downstream mobility of LW is higher and stability of wood jams is lower in streams draining watersheds with greater ISC. On the other hand, bank erosion along some urban streams may cause bankside trees to collapse into stream channels (Roberts, 1989). Thus, it is possible that channel widening associated with increased runoff from impervious surfaces might increase rates of wood loading to urban streams.

In addition to the effects of impervious surfaces on runoff and channel dynamics, other factors may be important to the amount of wood in urban streams. For example, reduced wood amount may be associated with the lateral confinement of stream channels by the banks or valley sides (Segura & Booth, 2010; Blauch & Jefferson, 2019). In urban areas, especially, confinement due to the armoring of stream banks might minimize the input of wood from riparian vegetation and floodplains (Segura & Booth, 2010). Greater stream power in laterally confined reaches might also enhance the downstream transport of wood (Wyżga & Zawiejska, 2010). Also, wood accumulating against bridge supports and road culverts is often removed for safety reasons (Diehl, 1997; Lassetre & Kondolf, 2012). Wood removal from urban streams might be focused at road crossings, where there is concern over an increased flooding potential associated with wood accumulations (Lassetre & Kondolf, 2012). Furthermore, land owners and land managers might remove riparian vegetation and wood from urban streams for

Table 1 Watershed and land cover data for sample sites within the Blue Ridge and Piedmont provinces of northwestern South Carolina

Site	Category	Stream order ^a	Drainage area (km ²)	Site elevation (m)	Channel gradient (m/km)	% Forest	% Grass/pasture	% Developed (open/low) ^b	% Developed (medium/high) ^c	% ISC ^d
MC59	Forested	3	3.6	324	82	89.6	2.2	7.7	0.0	0.4
US32	Forested	2	6.6	380	127	92.2	0.5	7.2	0.0	0.2
US64	Forested	2	1.2	340	123	93.6	3.4	3.0	0.0	0.1
US65	Forested	2	1.8	340	140	92.8	0.8	6.2	0.0	0.1
VAC05A	Forested	1	2.5	395	177	99.2	0.0	0.7	0.0	0.0
ETR01	Rural	3	6.6	203	9	37.2	47.1	8.9	0.4	1.2
PRS01	Rural	2	2.7	230	10	46.0	32.2	14.6	0.4	1.7
RA04	Rural	2	2.9	179	21	37.0	40.8	15.2	0.7	2.5
TUC03	Rural	2	6.6	156	11	44.2	43.8	8.9	0.4	1.1
US72	Rural	1	4.4	303	16	67.8	23.3	7.7	0.5	1.0
BY33	Residential	2	2.2	278	14	10.7	2.8	80.7	5.8	20.8
CC02	Residential	2	3.6	264	15	10.4	5.3	78.5	5.6	18.1
GC24	Residential	2	2.2	231	17	15.2	13.4	57.1	13.4	22.4
RC15	Residential	1	0.8	296	15	17.3	1.5	80.6	0.2	15.3
UE16	Residential	2	1.3	303	22	14.3	4.4	74.2	7.1	14.9
CH02	Commercial	1	0.8	294	21	0.5	0.1	27.3	72.1	67.6
HC05	Commercial	2	3.9	263	11	1.5	5.6	40.3	52.3	49.8
LAC09	Commercial	1	1.4	291	30	3.6	0.4	43.0	53.0	51.8
RC10	Commercial	2	2.9	276	12	14.5	5.3	24.1	55.6	50.0
RC18	Commercial	2	2.0	293	13	4.1	1.6	37.3	56.8	52.0

^aStream order determined according to the Strahler order system

^bCombined “Developed, Open Space” and “Developed, Low Intensity” classification categories from 2011 National Land Cover Database (<https://www.mrlc.gov/data/legends/national-land-cover-database-2011-nlcd2011-legend> accessed May 2018)

^cCombined “Developed, Medium Intensity” and “Developed, High Intensity” classification categories from 2011 National Land Cover Database

^dPercent of watershed area covered by impervious surfaces

aesthetic reasons (Booth et al., 1997; Finkenbine et al., 2000; Elosemi & Johnson, 2003).

In this study, our primary goal was to compare the amount of wood in low-order urban and rural streams in the Piedmont and Blue Ridge Physiographic Provinces of South Carolina, regions of especially rapid urban development within the United States (Terando et al., 2014). Given the variety of ways in which urban environments affect in-stream wood in other regions, we hypothesized that wood amounts would be lower in urban than rural streams. We also tested for relationships between wood amounts and both catchment-scale and reach-scale variables that are often associated with urban development. In terms of catchment-scale variables, because the relationship between peak stream flow and watershed ISC is strong

across the southeastern Piedmont (Koslofsky et al., 2016), we hypothesized that wood amount would be inversely related to watershed ISC. Because wood lost from a given reach might be replenished by wood transported from upstream reaches (Martin & Benda, 2001; Blauch & Jefferson, 2019), we also hypothesized that the amount of wood in a reach would be positively related to the length of upstream channel bordered by trees and lacking road crossings or other physical obstructions to wood transport. In terms of reach-scale variables, we hypothesized that the amount of wood would be positively related to the size and abundance of riparian trees but negatively related to channel incision, lateral confinement, and width. Another goal was to compare the physical functions of wood in rural and urban streams. A

previous study has demonstrated that wood mobility can be higher and stability of wood jams can be lower in more heavily urbanized watersheds (Blauch & Jefferson, 2019). Therefore, we hypothesized that we would find lower proportions of wood with visible physical functions (e.g., formation of pools and wood jams or sediment retention) in urban than rural streams in our region. Lastly, we hypothesized that we would find lower amounts of LW of sizes associated with lower mobility (Abbe & Montgomery, 2003; Blauch & Jefferson, 2019) in urban than rural streams.

Methods

Study Area and Site Selection

Our study was conducted in the Piedmont and Blue Ridge Physiographic Provinces of South Carolina. The climate of the region is warm temperate with annual precipitation varying with elevation. For example, normal annual precipitation varies from ~ 116 cm at Laurens (elevation 180 m) to ~ 178 cm at Caesars Head (elevation 975 m) (NOAA NCEI, 2020). Upland soils are predominantly ultisols that have developed on igneous and metamorphic rocks, although entisols or inceptisols may occur in floodplains (UCD CSRL, 2020).

We selected 20 headwater streams for study in the Saluda, Enoree, and Pacolet River basins during June–July 2012 (Table 1, Fig. 1). Streams were selected initially based on visual assessment of watershed land cover and accessibility from roads or trails using Google Earth imagery. Watershed areas upstream of sampling locations were obtained using WMS 9.0 (Aquaveo, Provo, Utah, USA). ISC from the 2011 National Land Cover Database was determined for each watershed using the U.S. Geological Survey's StreamStats v4.2.0 web application (<https://streamstats.usgs.gov/ss/> accessed May 2018). Other land cover data from the 2011 National Land Cover Database were accessed using the CropScape web application (<https://nassgeodata.gmu.edu/CropScape/> accessed May 2018). Land cover percentages within each watershed were determined using ArcMap 10.5 (Environmental Systems Research Institute, Redlands, California, USA).

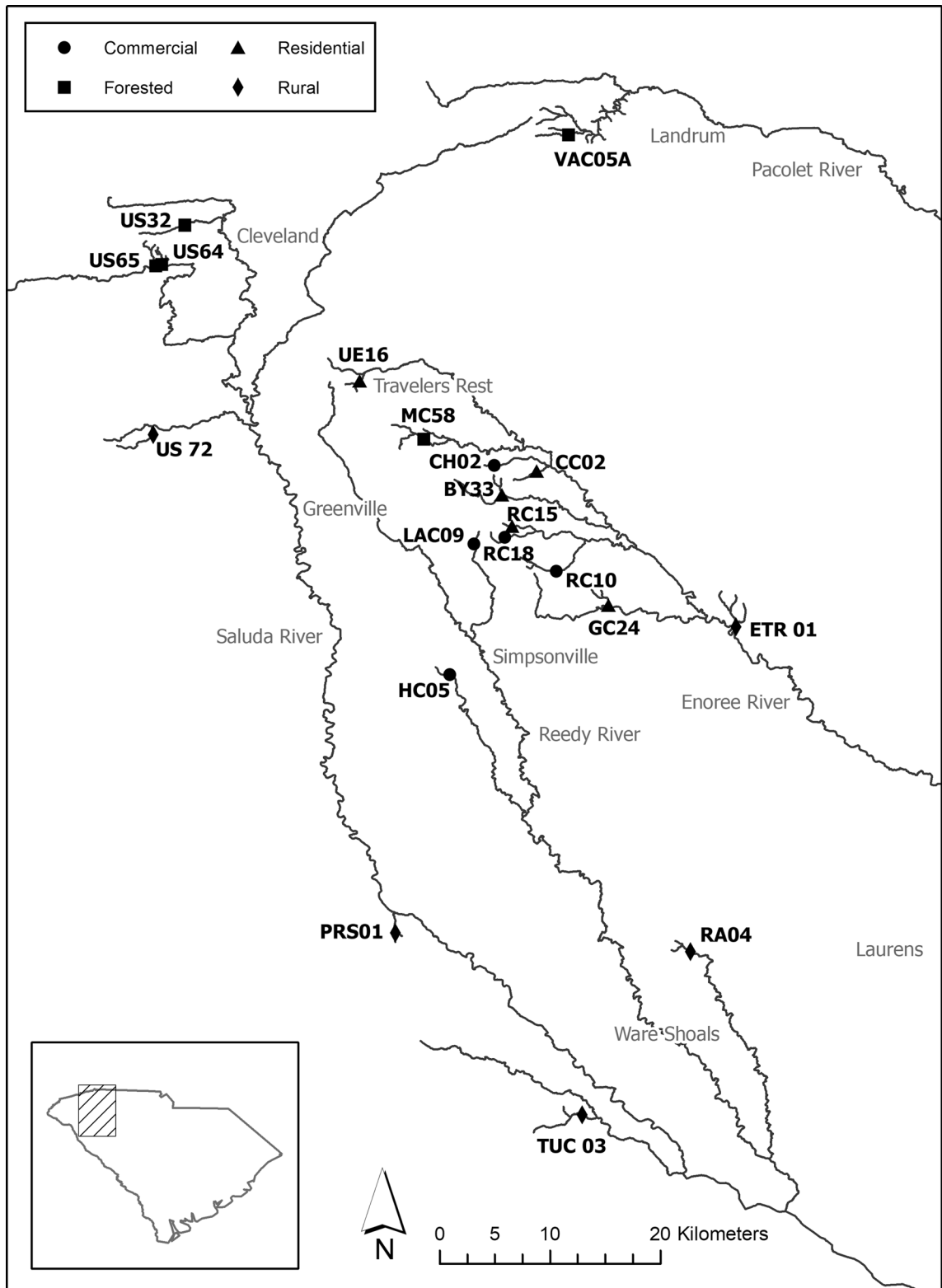
We sampled five streams in each of four watershed categories: forested, rural, residential, and

Fig. 1 Location of 20 sites at which wood was measured within streams in the Blue Ridge and Piedmont physiographic provinces of northwestern South Carolina

commercial/industrial (hereafter referred to as “commercial”; Table 1). These categories represent varying degrees of potential human influence on stream wood amounts in terms of watershed ISC and the likelihood of alteration or removal of riparian vegetation and/or stream wood.

For forested streams, the drainage basins all had < 0.5% ISC (Table 1). Also, the streams all occurred within lands protected from development (e.g., state parks or privately-owned nature preserves). To our knowledge, riparian forests in those locations were left unmanaged, and we saw no evidence that wood was removed from stream channels. In contrast, for rural, residential, and commercial streams, riparian zones were subdivided among multiple land owners who may have had different levels of interest in modifying riparian vegetation and/or removing stream wood. In rural watersheds, ISC was slightly higher than in forested watersheds but still < 3%. Forest and grass/pasture together covered > 77% of the watershed areas. Generally, the riparian zones of these streams were forested, but at two sites (PRS01 and US72), pasture or other land cleared of forest occurred within about 20 m of the sampled stream channels. The drainage basins of streams in the residential category had higher ISC (15–22%) than did the basins of streams in the forested and rural categories. Also, single-family residences and their associated yards accounted for most of the developed land in residential watersheds. Across these sites, the distance of the residences (houses) closest to sampled stream channels ranged from about 20 to 50 m. Drainage basins of streams in the commercial category had the highest ISC (50–68%), and therefore greatest potential for hydrologic impacts of storm runoff on stream wood. The types of developed land within commercial watersheds was more variable than in residential watersheds and included commercial zones, apartment complexes, and (at sites HC05 and LAC09) municipal airstrips. At three sites (CH02, LAC09, RC15), commercial buildings and/or parking lots occurred < 10 m from the stream channels.

Forests in all watersheds were second-growth. Common riparian trees along the rural, residential,



and commercial streams (site elevations < 320 m) included oaks (*Quercus* spp.), red maple (*Acer rubrum* L.), tulip poplar (*Liriodendron tulipifera* L.), and sweetgum (*Liquidambar styraciflua* L.). Chinese privet (*Ligustrum sinense* Lour.), an exotic invasive shrub, also was abundant along Piedmont streams. Along the forested streams (site elevations > 320 m), common trees also included eastern hemlock (*Tsuga canadensis* L.), American beech (*Fagus grandifolia* Ehrh.), birch (*Betula* spp.), and sourwood (*Oxydendrum arboreum* (L.) DC.). Most hemlocks showed signs of crown thinning due to infestation by hemlock woolly adelgid (*Adelges tsugae* Annand.). Rosebay rhododendron (*Rhododendron maximum* L.), rather than Chinese privet, was the most common riparian shrub growing along Blue Ridge streams.

Elevation of stream sampling locations ranged from 156 to 395 m (Table 1). Stream channel gradients (from stream source to sampling location, estimated using 1:24,000 scale topographic maps) ranged from 9 to 30 m/km except for forested streams, for which the gradients ranged from 82 to 177 m/km. All streams occurred within the Piedmont Province except for four of the five forested streams (sites US32, US64, US65, and VAC05A; Fig. 1) which occurred in the Blue Ridge Province.

Quantifying wood

At each stream, we quantified dead wood along a 100-m reach under baseflow conditions. At all but one stream, the reach began 10 m upstream of the road or trail from which the stream was accessed. At one rural stream (TUC03), a broad right-of-way to the side of the road had been cleared of all woody vegetation (including canopy cover over the stream), so the reach was begun 10 m upstream of the right-of-way. At one stream in a commercial watershed (CH02), a road intersected the stream ~ 70 m upstream of the beginning of the reach. Sampling was resumed 10 m upstream of the intersecting road. At rural site PRS01, due to accessibility restrictions, the reach began 10 m downstream of the road (bridge) crossing the stream.

Our primary interest was in measuring LW as it is commonly defined (> 10 cm diameter and at least 1 m in length; e.g., Bilby & Ward, 1991; Abbe & Montgomery, 2003; Wohl & Scott, 2016). However,

preliminary observations suggested that smaller wood (SW, 5–10 cm diameter) was both abundant and functional in some streams. Also, several other studies also have included SW in measures of wood amounts in streams (e.g., Johnson et al., 2003; Lester et al., 2009; Galia et al., 2018; Vaz et al., 2021). Therefore, we measured all pieces of wood > 5 cm in diameter and > 1.0 m length within or resting directly above the bankfull channel (e.g., tree trunks or branches laying across the stream banks but which were not immersed in stream water). For each piece of wood, diameter was measured at the middle of the portion occurring within the bankfull channel. Branches from tree trunks were measured and calculated as separate wood volumes if they exceeded the minimum size requirements. Wood volume was calculated assuming that all wood pieces were cylindrical (as in Cordova et al., 2007).

The physical function (if any) of each piece of wood within each reach was recorded based on a classification scheme modified from Berg et al. (1998) and Cordova et al. (2007). One function was contribution to the formation of a debris dam which included two or more pieces of SW and/or LW as well as leaves and twigs. The remaining functions were exhibited by single pieces of SW or LW which (1) captured leaf litter and/or twigs, (2) formed a pool or stagnant area upstream, (3) visibly altered stream flow in some other manner, (4) stabilized the stream bank or stream bed, and/or (5) held sediment on the upstream side.

In conjunction with identifying wood functions, we also determined the abundance of larger wood pieces that might have greater stability (lower mobility) in stream channels. Specifically, we calculated the density of LW pieces in each stream reach that met the criteria for “key” wood, larger pieces that tend to resist downstream transport and which may accumulate other wood pieces (Nakamura & Swanson, 1993; Abbe & Montgomery, 2003; Blaich & Jefferson, 2019). As was done by Blaich & Jefferson (2019), we used the size criteria of Abbe & Montgomery (2003) for wood pieces in smaller (< 50 m wide) stream channels, in which key pieces have diameters greater than half the bankfull channel depth and lengths greater than half the bankfull channel width. We excluded pieces that met these size criteria but which

spanned the channel by resting upon the channel-full banks.

Measurements of stream channel morphology and riparian trees

We measured stream bankfull width at the beginning of each reach and every 10 m thereafter ($n = 11$ measurements per stream). Every 20 m along each reach, we measured the bankfull maximum depth, channel-full width, and channel-full maximum depth. As in Duncan et al. (2011) and Hardison et al. (2009), we used indicators such as low benches, the lowermost extent of herbaceous vegetation, tops of point bars, and scour lines to make bankfull width determinations. We used the lower of the benches or terraces above the bankfull channel on either side of the stream as an indicator of the channel-full width at each point, consistent with Riley et al. (2020). Bankfull channel area for each stream reach was calculated by multiplying the mean bankfull width of the reach by the reach length (100 m).

We calculated channel incision as the ratio of channel-full maximum depth to bankfull maximum depth (similar to Hardison et al., 2009). We calculated entrenchment as the ratio of channel-full width to bankfull width. Previous studies (Rosgen, 1994; Savery et al., 2001) have calculated entrenchment as the ratio of floodprone width to bankfull width, with floodprone width being determined as the channel width corresponding to a maximum depth of two times the bankfull maximum depth. However, in our study area, the total depth from the channel-full bank to the stream bed typically exceeded the bankfull maximum depth by more than two times in both rural and urban areas. Given that trees typically grew along the edges of the channel-full banks and had the potential to collapse into the bankfull channels, we used channel-full width rather than floodprone width to calculate entrenchment. We then calculated channel confinement as the inverse of the entrenchment ratio such that higher numerical values of confinement indicated more laterally constrained bankfull channels.

Canopy cover from riparian trees and sizes of riparian trees also were measured along each reach. A spherical densiometer was used at the beginning of the reach and every 10 m thereafter to estimate the percent canopy cover directly over the middle of the bankfull channel. Also, at each 10 m mark, the diameter at

breast height (DBH) of the nearest living tree stem (> 1 cm, if present) within a 5 m radius from each edge of the channel-full bank was measured. Total basal area of measured trees along both sides of each reach was calculated from tree diameters. For trees with multiple stems, basal area was calculated separately for each stem.

Lastly, we used Google Earth imagery and stream channel layers obtained from the USGS (2019) to estimate the length of stream channel upstream of each reach (or upstream from the access road in the case of site PRS01) that was bordered by trees and over which no obstruction to wood movement (either a road crossing or impoundment) occurred.

Statistical analyses

We used R v4.0.3 (R Core Team, 2020) to conduct all statistical analyses at an alpha level of 0.05. To test for differences among the four land cover categories in wood amounts, measures of riparian tree size or abundance, and for channel characteristics, we used one-way analysis of variance (ANOVA), Welch's ANOVA, or Kruskal–Wallis tests. We tested for differences in amounts of LW and SW separately, and for each size class, we used separate tests for wood volume ($\text{m}^3/100 \text{ m}^2$ of bankfull channel) and wood density (number of wood pieces/ 100 m^2 of bankfull channel). For all comparisons, the Shapiro–Wilk W test was used to test for normality of residuals, and Bartlett's test was used to test for equality of variances. One-way ANOVA followed by Tukey HSD tests was used to test for differences in means among the four groups if assumptions of normality and equality of variance were met. In some cases, these assumptions were met following \log_{10} -transformation (incision ratio and median tree diameter) or Tukey's Ladder of Powers transformation (LW volume) using the *rcompanion* package (Mangiafico, 2020). If the assumption of normality of residuals was met but the assumption of equality of variances was not, Welch's ANOVA was used to test for differences among group means. If the assumption of normality of residuals was not met following transformation, the Kruskal–Wallis test was used to test for differences among group medians.

For ANOVA comparisons in which significant differences were found among land covers, we used omega squared (ω^2) as a measure of effect size using

the *effectsize* package (Ben-Shachar et al., 2020). We used ω^2 rather than the commonly used eta squared given that eta squared is more subject to bias associated with small sample sizes (Olejnik & Algina, 2003).

Beta regression was used to compare mean percent canopy cover (as proportions of complete canopy cover) across the four land cover categories using the *betareg* (Cribari-Neto & Zeileis, 2010) and *emmeans* (Lenth, 2021) packages. To compare the proportions of wood pieces displaying physical functions across land cover categories, we combined LW and SW pieces at each reach because no LW was found at one stream reach (LaC09), preventing the calculation of the proportion of LW displaying function at that reach. The proportions of total wood pieces displaying functions were then used in a weighted logistic regression. Specifically, we used a binomial *glm* function with *logit* links, weighted by the total number of wood pieces in each stream reach. The *Anova* function in the *car* package (Fox & Weisburg, 2019) was then used to conduct a Wald Chi square test to test for differences in proportions among the four land cover categories.

To determine which watershed-scale and/or reach-scale variables were most strongly related to in-stream wood amounts (LW volume, LW density, SW volume, and SW density), we used an approach similar to that used by de Paula et al. (2013). Specifically, we used Akaike's Information Criterion adjusted for small sample size (AIC_c; Anderson, 2008) to evaluate the relative fit of linear regression models using the following eight explanatory variables: watershed impervious cover, channel incision ratio, channel confinement, channel-full width, mean canopy cover over the channel, median DBH of riparian trees, basal area of riparian trees, and length of the unobstructed wooded riparian zone upstream of the reach. We chose channel-full width over bankfull width as an explanatory variable because we hypothesized that trees growing at the edge of the channel-full banks could contribute wood to the stream by collapsing into the channel as the banks eroded. Also, given that forest streams had channel gradients up to 20 times higher than streams in the other four categories (Table 1), we included channel gradient as an additional explanatory variable.

To meet the assumptions of single and multiple linear regression analyses, the following data

transformations were used: \log_{10} -transformation for SW volume, incision ratio and length of upstream tree-lined channel; square root transformation for LW density; Tukey's Ladder of Powers transformation for LW volume, SW density, and channel gradient; and logit transformation for watershed impervious cover and percent canopy cover. Following transformations, variance inflation factor (VIF) analysis was used to test for collinearity among the explanatory variables using the *vif* function in the *car* package (Fox & Weisburg, 2019). Based on global models including all nine explanatory variables, all VIF values were < 4.5. Therefore, we assumed that the collinearity among these variables was sufficiently low to retain the variables in the model selection process (James et al., 2013). All models were tested for homoscedasticity of residuals with the Bruesch-Pagan test using the *lmtest* package (Zeileis & Hothorn, 2002). Residuals of the models were tested for normality using Shapiro–Wilk tests.

We used the *AICcmodavg* package (Mazerolle, 2020) to calculate AIC_c scores for all models. In the first iteration of model selection, we compared AIC_c scores of nine single-predictor variable models with a null (intercept-only) model. Models with AIC_c scores higher than the null model were then eliminated before conducting the second iteration of model selection. In the second iteration of models, for each response variable, we used the predictor variables from the models that passed the first iteration. Linear models with either one or two predictor variables were used. As in de Paula et al. (2013), we did not attempt to construct models with more than two predictor variables due to our relatively small sample size (20 streams). Best-supported models were identified as those with $\Delta\text{AIC}_c < 2$ and in which the 85% confidence intervals for the coefficients did not include zero (Arnold, 2010).

Results

Comparisons of wood amounts, channel characteristics, and riparian tree abundance among land cover categories

Overall, we found few of the differences between urban and rural streams we expected in wood amounts, wood function, channel morphology, or riparian

Table 2 Amounts of in-stream wood, percentages of wood pieces with visible physical functions, and density of key wood pieces within watersheds dominated by different land covers in the Blue Ridge and Piedmont physiographic provinces of northwestern South Carolina

Watershed category	LW density (pieces/100 m ²)	SW density (pieces/100 m ²)	LW volume (m ³ /100 m ²)	SW volume (m ³ /100 m ²)	Functional pieces (%)	Key pieces density (pieces/100 m ²)
Forested	2.3 (0.3)	2.1 (0.4)	0.16 (0.12–0.53)	0.02 (0.01–0.04)	69.9 (4.0)	0.5 (0–0.9)
Rural	2.3 (0.9)	3.2 (0.6)	0.23 (0.004–0.60)	0.02 (0.01–0.04)	69.9 (3.0)	1.9 (0–2.5)
Residential	1.5 (0.3)	2.3 (0.6)	0.16 (0.02–0.25)	0.01 (0.01–0.05)	71.2 (4.4)	0.3 (0–1.2)
Commercial	2.0 (1.0)	1.7 (0.4)	0.06 (0–1.64)	0.02 (0.01–0.03)	73.6 (7.5)	0 (0–2.3)

LW = large wood (> 10 cm diameter) and SW = small wood (5–10 cm diameter). “Functional pieces” is expressed as a percentage of the sum of LW and SW pieces with visually identifiable physical functions. Key pieces had diameters greater than half the bankfull channel depth and lengths greater than half the bankfull channel width. Values are means (with SE), except for LW volume, SW volume, and key pieces density, which are medians (with ranges). Measurements were made along a 100-m reach at each stream

$N = 5$ streams per category

LW density: Kruskal–Wallis test, $\chi^2 = 2.34$, $P = 0.51$

SW density: ANOVA, $F = 1.44$, $P = 0.27$

LW volume: ANOVA following $x^{0.3}$ transformation, $F = 0.71$, $P = 0.12$

SW volume: ANOVA, $F = 0.21$, $P = 0.89$

Functional pieces (%): Wald test, $\chi^2 = 0.15$, $P = 0.98$

Key pieces density: Kruskal–Wallis test, $\chi^2 = 1.34$, $P = 0.72$

vegetation. Even though the watersheds of urban streams had higher ISC (Table 1), we found no significant differences in either the volume or density of either LW or SW among the four categories of watersheds (Table 2). For LW volume, commercial streams had the highest range, with one stream (LaC09) having no LW and another (RC10) having the highest LW volume of any of the 20 streams sampled. Both the density and volume of LW also were highly variable among rural streams (Table 2).

The percentage of total wood pieces (LW + SW) exhibiting physical functions within the streams also did not differ significantly among the land cover categories, although the lowest percentages were found in rural and residential streams (Table 2). Among all 20 streams, 21% of pieces contributed to the formation of debris dams, 22% retained leaf litter and/or fine twigs outside of debris dams, 11% contributed to bank or streambed stabilization, and 8% held sediment upstream. Only two single pieces formed a pool or created an upstream stagnant area, and only 6% altered flow in other visible ways. Also, the density of wood pieces meeting the key wood criteria did not differ significantly among the four land cover categories (Table 2).

Urban streams were not more incised or confined than forested streams, nor did their bankfull widths or channel-full widths differ significantly from forested

streams (Table 3). Instead, streams in the rural category had the most incised but least confined channels (Table 3). The median incision ratio of rural streams was 1.9 to 2.6 times greater than the median ratios of the other stream categories, and the mean confinement of rural streams was 0.7 to 0.8 times the means of streams in the other categories. However, there were large uncertainties around the effect sizes of land cover on both incision ratios and confinement. Based on the 95% confidence intervals for ω^2 , the estimated proportion of the variation in both variables explained by land cover ranging from 0 to ~ 60% (Table 3).

The median lengths of tree-lined stream channel unobstructed by roads or impoundments upstream of the reaches were 2.3 to 4.0 times higher for forested and rural streams than for residential or commercial streams (Table 4). However, the uncertainty around the effect size of land cover on unobstructed channel lengths was large, with the estimated proportion of variation in channel length ranging from 0 to 53% based on the 95% confidence interval for ω^2 (Table 4).

The size and abundance of riparian trees were not significantly lower along the urban than forested or rural reaches (Table 4). For example, the median diameter of riparian trees did not differ significantly among the four watershed categories (Table 4). Canopy cover over the stream channels also did not differ significantly among the four land cover

Table 3 Channel characteristics of streams in watersheds dominated by different land covers in the Blue Ridge and Piedmont physiographic provinces of northwestern South Carolina

Watershed category	Incision ratio	Confinement	Bankfull width (m)	Channel-full width (m)
Forested	2.1 (2.1, 2.9) ^a	0.69 (0.03) ^a	3.9 (3.6, 4.5)	6.1 (1.0)
Rural	5.4 (5.2, 6.9) ^b	0.49 (0.07) ^b	2.8 (2.6, 3.1)	5.4 (0.9)
Residential	2.8 (2.8, 3.3) ^{ab}	0.62 (0.05) ^{ab}	3.4 (2.7, 3.5)	5.0 (0.8)
Commercial	2.6 (2.3, 3.2) ^{ab}	0.72 (0.03) ^a	3.5 (3.2, 4.0)	4.6 (0.6)

Channel measurements were made along a 100-m reach at each stream. Values for confinement and channel-full width are means (with SE). The other value are medians (with interquartile ranges). For each variable, groups with different letters differed significantly ($P < 0.05$) based on Tukey HSD tests

$N = 5$ streams per category

Incision ratio: ANOVA with \log_{10} -transformed data, $F = 5.43$, $P = 0.009$, $\omega^2 = 0.40$ (95% CI 0.00, 0.63)

Confinement (inverse of entrenchment ratio): ANOVA, $F = 4.42$, $P = 0.019$, $\omega^2 = 0.34$ (95% CI 0.00, 0.59)

Bankfull width: ANOVA, $F = 2.57$, $P = 0.09$

Channel-full width: ANOVA, $F = 0.61$, $P = 0.62$

Table 4 Characteristics of riparian vegetation and extent of upstream wooded riparian zones along streams in watersheds dominated by different land covers in the Blue Ridge and Piedmont physiographic provinces of northwestern South Carolina

Watershed category	Median tree diameter (cm)	Total basal area (m ²)	Mean canopy cover over channel (%)	Tree frequency (% maximum)	Distance to obstruction (km)
Forested	18.4 (3.8)	1.36 (0.28) ^{ab}	91.5 (0.5)	86.4 (2.5)	1.6 (1.4, 3.1)
Rural	10.3 (8.7)	0.80 (0.46) ^a	87.4 (2.1)	70.9 (6.8)	1.4 (0.8, 1.5)
Residential	13.9 (9.7)	0.97 (0.44) ^{ab}	84.8 (2.7)	72.7 (14.3)	0.6 (0.2, 0.7)
Commercial	14.4 (4.9)	1.65 (0.60) ^b	80.4 (7.1)	81.8 (7.6)	0.4 (0.3, 0.4)

Measurements of diameters of bankside trees were made at 10-m intervals along a 100-m reach at each stream. “Tree frequency” is expressed as a percentage of the maximum number of tree stems (diameter at breast height > 1 cm) that could have been measured at 10-m intervals on both banks (maximum of 22 trees possible per stream). “Distance to obstruction” represents the length of channel upstream of the reaches that was bordered by trees and over which no road crossings or impoundments occurred. Values are means (with SE), except for distance to obstruction, which are medians (with interquartile ranges). For each variable, groups with different letters differed significantly ($P < 0.05$) based on Tukey HSD tests

$N = 5$ streams per category

Median tree diameter: ANOVA with \log_{10} -transformed data, $F = 1.81$, $P = 0.19$

Total basal area: ANOVA: $F = 3.49$, $P = 0.041$, $\omega^2 = 0.27$ (95% CI 0.00, 0.53)

Mean canopy cover: Beta regression, $F = 1.14$, $P = 0.33$

Tree frequency: Welch’s ANOVA, $F = 1.49$, $P = 0.29$

Distance to obstruction: ANOVA, $F = 3.55$, $P = 0.038$, $\omega^2 = 0.28$ (95% CI 0.00, 0.53); no differences detected by Tukey HSD at $P < 0.05$

categories (Table 4). However, canopy cover was consistently high ($> 90\%$) over forested streams and varied most over commercial streams. Similarly, the percentages of bankside sampling locations occupied by trees did not differ significantly among watershed categories but were less variable (consistently $> 80\%$) along forested streams (Table 4). Total basal area of

riparian trees did not differ significantly among the categories with the exception of riparian trees in commercial streams having significantly (2.1 times) higher mean total basal area than riparian trees found in rural streams. However, the uncertainty around the overall effect size of land cover on basal area was high, with 0 to 53% of variation in basal area explained by

Table 5 Top single and multiple linear regression models for large wood (LW, > 10 cm diameter) and small wood (SW, 5–10 cm diameter) amounts in 20 urban and rural streams in the Blue Ridge and Piedmont physiographic provinces of northwestern South Carolina

Dependent variable	Model	$\Delta AICc$	w_i	Adjusted R^2
LW volume ^a	CAN + LUC	0.00	0.87	0.44
	LUC	4.96	0.07	0.20
	CAN	5.38	0.06	0.18
LW density ^b	CAN + LUC	0.00	0.52	0.35
	CAN	2.63	0.14	0.18
	DBH + LUC	3.44	0.09	0.23
	DBH	3.69	0.08	0.13
	CAN + DBH	3.72	0.08	0.22
	LUC	3.87	0.08	0.13
SW volume ^c	BAS	0.00	0.42	0.12
	CON	0.26	0.37	0.11
	BAS + CON	1.47	0.20	0.14
SW density ^d	CON	0.00	0.44	0.27
	BAS + CON	0.26	0.39	0.33
	BAS	1.89	0.17	0.20

Best-supported models ($\Delta AICc < 2.00$ and with 85% confidence intervals of coefficients not including zero) are indicated with bold font

$\Delta AICc$ Akaike Information Criterion adjusted for small sample size

w_i = model weight

^aLW volume ($m^3/100 m^2$ bankfull channel area), $x^{0.3}$ -transformed

^bLW density (# pieces/100 m^2 bankfull channel area), square root-transformed

^cSW volume ($m^3/100 m^2$ bankfull channel area), \log_{10} -transformed

^dSW density (# pieces/100 m^2 bankfull channel area), $x^{0.4}$ -transformed

BAS = riparian tree basal area (m^2), *CAN* = % canopy cover over channel, logit-transformed, *CON* = channel confinement (inverse of entrenchment ratio), *DBH* = mean DBH of bankside trees (cm), *LUC* = length of unobstructed tree-lined channel upstream of sampling reach (km), \log_{10} -transformed

land cover based on the 95% confidence interval for ω^2 (Table 4).

Relationships between wood amounts and predictor variables

Contrary to our expectations, watershed ISC was not a predictor in any of the regression models which passed the first round of model selection for either LW or SW amounts (Online Resource 1). Likewise, for LW amounts, no models with measures of channel morphology were among the best-supported models. Instead, for both volume and density of LW, the best-supported models included both canopy cover and length of unobstructed tree-lined channel

upstream as predictors (Table 5). These models explained 44% and 35% of the variation in LW volume and LW density, respectively. Volume and density of LW were positively related to both canopy cover (Fig. 2) and length of tree-lined channel upstream (Fig. 3). By contrast, for volume and density of SW, the best-supported models included riparian tree total basal area and channel confinement, but even these models explained $\leq 33\%$ of the variation in SW amounts (Table 5). Small wood amounts were inversely related to both total basal area (Fig. 4) and channel confinement (Fig. 5).

Discussion

Importance of riparian vegetation vs. watershed impervious cover

In contrast to previous studies (e.g., Horner et al., 1997; Finkenbine et al., 2000; Stewart et al., 2012; Vietz et al., 2014; Blaich & Jefferson, 2019), we found no differences in wood amounts between urban and rural streams. Instead, our results suggest that riparian vegetation was more important than watershed ISC in explaining variation in wood amounts. For example, the stream with the greatest wood volume ($\sim 1.6 \text{ m}^3/100 \text{ m}^2$ of bankfull channel) of all 20 sites was a commercial site (RC10). In spite of extensive ISC in the RC10 watershed, this reach had a forested riparian zone, well-developed canopy cover ($\sim 94\%$), and a relatively long ($\sim 1.5 \text{ km}$) unobstructed upstream channel bordered by trees.

The lack of an inverse relationship between wood amounts and watershed ISC in our study contrasts with previous studies. For example, Blaich & Jefferson (2019) found an inverse relationship between LW abundance and watershed ISC and a positive relationship between wood mobility (over several months) and watershed ISC in streams in northeastern Ohio. However, the lower abundance and greater mobility of wood in urban streams in their study did not appear to be related to runoff from ISC because the relationship between streamflow and watershed ISC in their region was weak. Instead, the lower abundance of in-stream wood in more urbanized watersheds appeared to be more closely related to lower proportions of forested riparian zone along upstream reaches and thus fewer sources of wood to the reaches they studied. Blaich & Jefferson (2019) further suggest that channel characteristics of the streams in more urbanized watersheds also played a role in increased wood mobility, with more urbanized streams having wider, more incised, or more confined channels that facilitated the mobility of the relatively small wood pieces found in streams in their region. However, in our study, urban stream channels were not more incised, wider, or more confined than rural streams, and all the streams studied were bordered by trees of sufficient size to provide LW.

The positive relationship between canopy cover over the stream channels and LW amounts within the channels presumably reflects the influence of larger

riparian trees capable of providing LW. In contrast to LW, SW amounts were not explained by canopy cover but instead were inversely related to total basal area of bankside trees (Fig. 4). Based on studies of wood loads in forests (e.g., Manning et al., 2020), one might expect in-stream SW abundance to be positively related to basal area of riparian trees. However, not all tree species release as many small branches as others even with equivalent basal areas (Manning et al., 2020), so the relationship between SW and basal area may be complicated by the species composition of the riparian tree community. Also, SW pieces are likely to be more mobile and decompose faster (through both physical and biological processes) than LW pieces in stream channels (e.g., Merten et al., 2013; Galia et al., 2018; Blaich & Jefferson, 2019). As a result, SW mobility and susceptibility to decomposition may weaken the relationship between SW amounts and the abundance of riparian vegetation along a given reach.

Wood functions

Although several of the urban streams in our study had low amounts of wood, much of the wood present was functional, with a mean of about 71% of wood pieces modifying stream habitat or flow in some way across residential and commercial streams collectively. Similarly, the densities of key wood pieces were not significantly lower in urban than rural streams in our study. However, whether the function of these wood pieces is sustained or short-lived may depend upon the mobility of wood in these streams. For urban streams in our study, even with shorter distances to upstream obstructions to wood movement compared to forested and rural streams, the rate of supply of wood from riparian trees may have been sufficient to offset losses due to elevated storm flow. It would be useful for future studies in both the southeastern Piedmont and other regions to use budgeting (mass balance) approaches (e.g., as in Benda et al., 2003) to compare the residence times of wood in urban and rural streams.

In contrast to studies of LW in streams in some other regions, such as the Pacific Northwest of the United States (e.g., Montgomery et al., 1995; Beechie & Sibley, 1997), virtually no pools were formed by single pieces of wood in our study reaches. The only two pieces of LW across all 20 reaches that formed

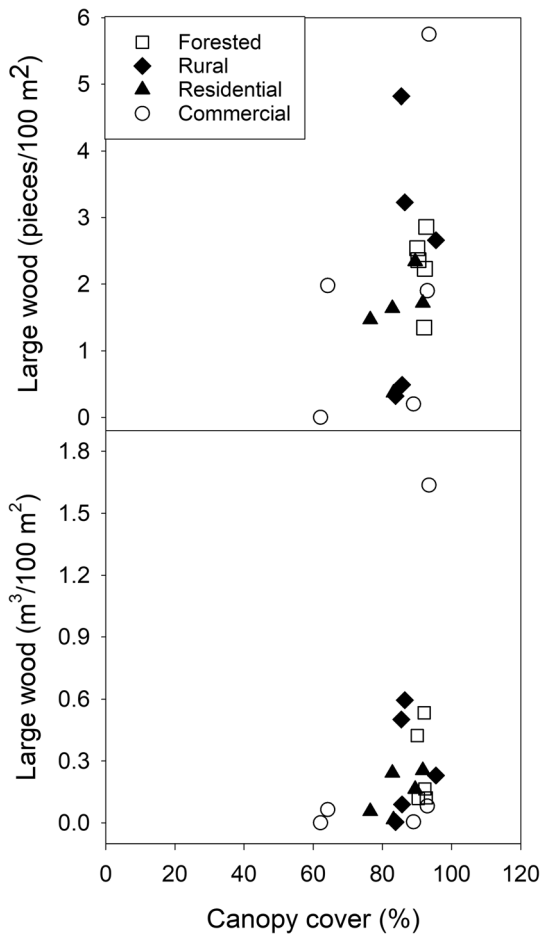


Fig. 2 Relationships between density (upper panel) and volume (lower panel) of large wood (> 10 cm diameter) within the bankfull channels of first to third-order streams ($n = 5$ per category) and percent canopy cover over the stream channels. All streams occurred in the Blue Ridge and Piedmont physiographic provinces of northwestern South Carolina

pools as single pieces (not as part of debris dams) had diameters ≥ 30 cm (including one piece at commercial reach RC10). The relatively small size of most of the riparian trees in our study area may have limited the supply of wood of sufficient size to form pools on their own in the stream channels. For example, across all 20 reaches, only 24% of bankside tree stems had $DBH \geq 30$ cm. Some tree species may exert a greater influence on the supply of LW to streams, as well. For example, along the RC10 reach, the largest pieces of LW were trunks of fallen tulip poplars (maximum diameter of ~ 50 cm) that formed stable key pieces of wood that retained large amounts of sand and other sediment within the channel.

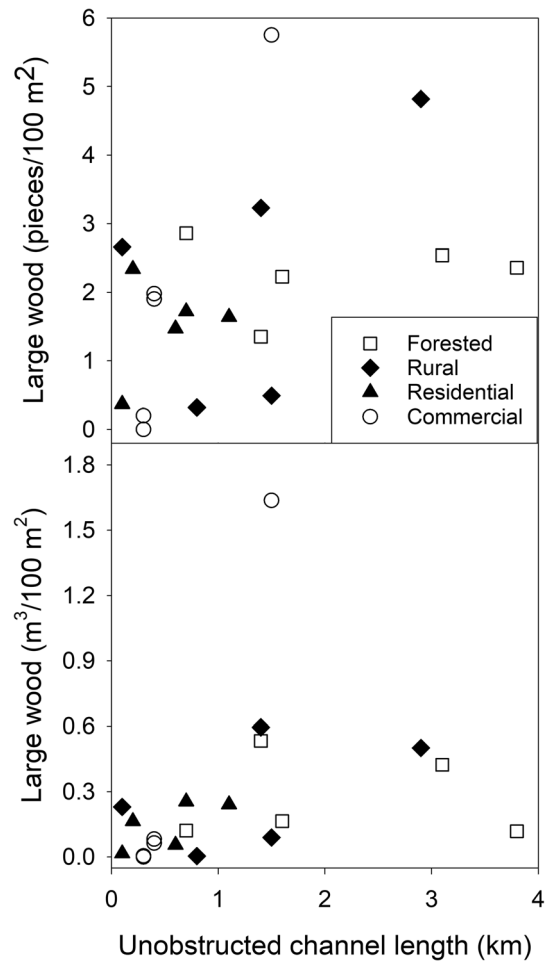


Fig. 3 Relationships between density (upper panel) and volume (lower panel) of large wood (> 10 cm diameter) within the bankfull channels of first to third-order streams ($n = 5$ per category) and length of unobstructed tree-lined channel upstream of 100-m long sampling reaches. All streams occurred in the Blue Ridge and Piedmont physiographic provinces of northwestern South Carolina

Although the contribution of LW to pool formation in these small streams appears to be minimal, LW may nonetheless be important as a source of cover for fishes, providing protection from both terrestrial and aquatic predators (Dolloff & Warren, 2003). Also, the retention of leaf litter by debris dams may be especially important to macroinvertebrates in urban streams, in which elevated stormflow and nutrient concentrations may lead to reduced leaf retention or faster decomposition compared to forested streams (Paul et al., 2006; Sterling et al., 2016). Additional studies are needed to determine the extent to which

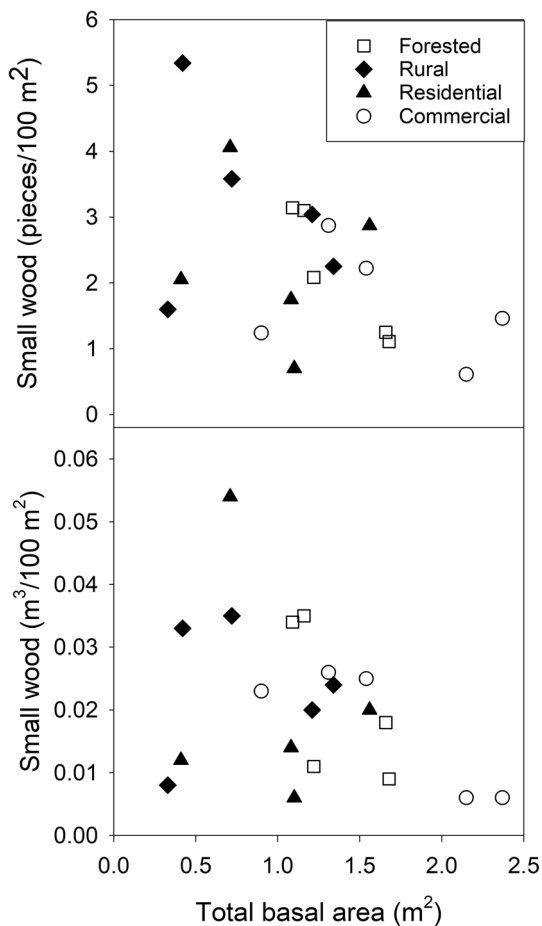


Fig. 4 Relationships between density (upper panel) and volume (lower panel) of small wood (5–10 cm diameter) within the bankfull channels of first to third-order streams ($n = 5$ per category) and total basal area of trees growing on or adjacent to the channel-full banks. All streams occurred in the Blue Ridge and Piedmont physiographic provinces of northwestern South Carolina

fish, macroinvertebrates, and other stream biota utilize wood in urban streams and whether the increased habitat complexity and retention of organic matter resources (such as leaf litter) provided by wood can offset negative influences of urban land cover, such as elevated stormflow or pollutants in water and sediments (e.g., Violin et al., 2011; Sterling et al., 2016; Reid & Tippler, 2019).

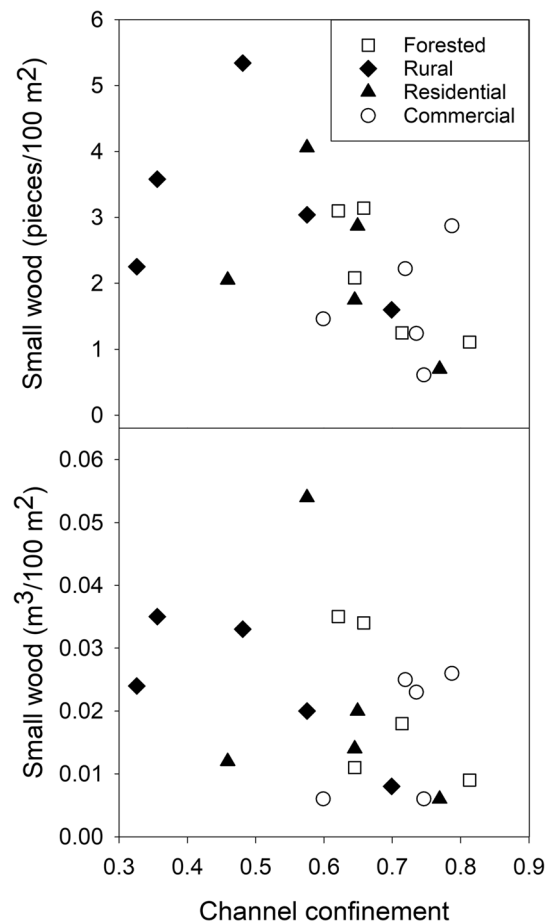


Fig. 5 Relationships between density (upper panel) and volume (lower panel) of small wood (5–10 cm diameter) within the bankfull channels of first to third-order streams ($n = 5$ per category) and mean channel confinement as measured along 100-m reaches. Confinement is bankfull width/channel-full width

Limited relationships between wood and channel characteristics

Contrary to our expectations from previous studies (e.g., Booth et al., 1997; Segura & Booth, 2010; Blaich & Jefferson, 2019), we found little evidence that channel morphology in urban watersheds differed from that in rural watersheds or that amount of wood was related to measures of channel morphology. The only relationship we observed was an inverse relationship between the density of SW and channel confinement (Fig. 5), a result that is consistent with an inverse relationship between wood amounts and channel confinement in montane streams in the Czech

Republic (Galia et al., 2018). The reason for this relationship is uncertain and merits future research. However, one possible explanation for the lower SW amounts in more constrained channels is that stream water has greater power to transport SW pieces from such channels, especially under storm flow conditions. A similar phenomenon has been reported for total wood storage in the Czarny Dunajec River, a fifth-order river in southern Poland (Wyżga & Zawiejska, 2010), in which wood storage was lower in narrower channelized sections of the river (with higher river power) than in wider un-channelized sections (with lower power).

Other predicted relationships between channel morphology and the amount of wood in the streams were not supported by our results. For example, we saw evidence for recent channel widening due to bank sloughing or collapse only along one residential reach (BY33). At commercial reach RC10, the channel was incised, but the banks did not appear to be undergoing active erosion or collapse. Even for urban streams, channel incision in the southeastern Piedmont region may be limited by depth to bedrock (Johnson & Royall, 2019), which is predominantly gneisses and granites (Horton & McConnell, 1991) that are relatively resistant to weathering. The greater incision of rural sites in our study (Table 3) may reflect their occurrence at lower elevations in the Piedmont (Table 1), where depth to bedrock may be greater (e.g., Zimmer & Gannon, 2018). Incision at rural sites also may be greater due to downcutting of stream channels through sediments that had been eroded from uplands affected by agricultural activity prior to the 1930s (Trimble, 2008).

In some regions, bank armoring or other artificial bank reinforcement is used to reduce channel erosion along urban streams (e.g., Segura & Booth, 2010; Blauch & Jefferson, 2019). These bank reinforcements, while reducing erosion, may reduce the abundance of riparian vegetation as well as the interaction of the stream with its floodplain (Segura & Booth, 2010). Segura & Booth (2010) provide evidence from urbanized streams near Seattle, Washington, that the amount of LW is inversely related to the extent of bank armoring. Although we observed bank armoring (with riprap) only at one commercial reach (LAC09), this was the only reach in our study lacking LW.

Other anthropogenic influences on wood abundance and riparian vegetation

Although LW amounts did not differ among the four land cover categories, of the seven reaches with the lowest LW volumes, four were commercial reaches (CH02, HC05, LAC09, and RC18) and two were residential reaches (BY 33 and RC15). Aside from the bank armoring and associated lack of riparian vegetation along part of the LAC09 reach, we observed several examples of other ways in which roads or alteration of riparian zone vegetation either affected in-stream wood directly or had the potential to influence wood amounts. For example, at one commercial reach (CH02), we observed that wood had accumulated on the upstream side of the culvert of a road that crossed our sampling reach. Thus, the culvert restricted the downstream movement of wood into the lower end of the reach. Along a portion of another commercial reach (RC18), understory trees and shrubs had been removed, presumably to improve visibility of nearby office buildings. Lastly, sewer line rights-of-way may also reduce density of woody riparian vegetation, as we observed along one bank of a residential reach (RC15).

Although human influences on wood abundance and riparian vegetation was most commonly observed at or near urban reaches, we also saw evidence of such influences at some rural reaches. For example, bridge supports and culverts under roads upstream of some rural reaches may have reduced downstream transport of wood into those reaches. Also, proximity of pasture or other cleared land to stream banks resulted in reduced abundance of riparian trees along two rural reaches (ETR01 and US72). Unfortunately, we have no specific information about either riparian forest management or wood removal in our study area. Also, public policies and regulations may have varied from one local government (e.g., city/town or county) to the next, as well as over time (i.e., regulations limiting the removal of riparian trees in place at the time of our study may not have been in place in previous decades when the residential or commercial areas we studied were first developed). Additional studies are needed to determine the extent to which riparian trees and stream wood are managed along both rural and urban stream reaches in our region.

Table 6 Wood loads in low-order streams in temperate regions of eastern and central North America

Region	Basin or riparian land cover	Strahler stream order	Bankfull width (m)	Wood load (m ³ /ha)	Sources
<i>Southeastern US</i>					
Blue Ridge and Piedmont Provinces (South Carolina)	Urban (commercial and residential)	1–2	1.7–4.9	Mean = 27 (1–166) ^a	This study
	“Rural” (forest/pasture)	1–3	2.1–3.1	Mean = 31 (1–63) ^a	
	Forest (second-growth)	1–3	3.6–7.2	Mean = 29 (13–57) ^a	
Piedmont Province (North Carolina)	Urban	NR (< 4)	9.8–11.3	Mean = 5 (3–7) ^b	Owusu-Adjei (2007)
Blue Ridge Mountains (Georgia, North Carolina, South Carolina)	Forest (mid-successional to old-growth)	1–4	4.8–10.9	Mean = 198 (92–339) ^c	Hedman et al. (1996)
Great Smoky Mountains (North Carolina, Tennessee)	Forest (second-growth)	2	NR	Mean = 85 ^a	Silsbee & Larson (1983)
	Forest (old-growth)	2	NR	Mean = 339 ^a	
Upper Atlantic Coastal Plain (South Carolina)	Floodplain forest (old-growth)	NR	8–14	Mean = 50 (1–178) ^c	Wohl et al. (2017)
<i>Northeastern US</i>					
Piedmont Province (Pennsylvania)	Meadow	2	Mean = 1.66	Mean = 5 (SE = 5) ^d	Sweeney (1993)
	Forest (second-growth)	2	Mean = 2.83	Mean = 76 (SE = 62) ^d	
Allegheny High Plateau (Pennsylvania)	Forest (second-growth)	2	NR	Mean = 90 (SE = 27) ^c	Williams & Cook (2010)
	Forest (old-growth)	2	NR	Mean = 326 (SE = 83) ^c	
White Mountains (New Hampshire) and Adirondacks (New York)	Forest (second-growth to old-growth)	NR	1.4–15.1	Mean = 71 (6–237) ^c	Warren et al. (2009)
<i>North Central US</i>					
Southeastern Minnesota	Mostly agricultural	2–3	Mean = 5.4	Mean = 17 (0–117) ^a	Johnson et al. (2003)
Till and Lake Plains (central Michigan)	Mostly row crop, some forest	1–4	2–10	Mean = 23 (0–312) ^a	Johnson et al. (2003)
Upper Peninsula of Michigan	Forest (second-growth)	NR	1.9–12.0	Mean = 77 (SE = 15) ^c	Cordova et al. (2007)

Wood load values are means with standard error (SE) or ranges

NR not reported

^aWood pieces > 5 cm

^bWood pieces > 3 cm

^cWood pieces > 10 cm

^d“Large wood” (minimum diameter not given)

Comparisons with wood loads in other regions

To our knowledge, our study is one of the first to report wood loads in streams of the Piedmont region of the United States. Wood loads in urban streams in our

study were as high or higher than those of four reaches of North Buffalo Creek, an urban stream in the North Carolina Piedmont (Owusu-Adjei, 2007; Table 6). Riparian zones along North Buffalo Creek ranged from forested to devoid of riparian trees (Owusu-

Adjei, 2007). Aside from lack of riparian trees along some reaches, the greater channel widths of North Buffalo Creek relative to streams in our study may have contributed to lower wood retention and loads (e.g., Blauch & Jefferson, 2019). Similarly, wood loads in our study tended to be higher than those in meadow-bordered reaches of a small stream in the Piedmont of southeastern Pennsylvania (Sweeney, 1993; Table 6). One other study conducted in South Carolina (Riley et al., 2020) reported LW volumes for streams draining minimally developed Piedmont watersheds. The range of wood loads in their study was approximately 1 to 18 m³/100 m of stream channel, compared to a range of only 0.01 to 2.4 m³/100 m for LW in forested and rural streams in our study. However, Riley et al. (2020) do not report channel widths, so it is not possible to compare wood loads on a per-channel area basis between their study and ours. Also, the size of watersheds in their study ranged to as high as 26 km², whereas all watersheds in our study were < 7 km². Thus, the sizes of some streams in their study were probably larger than in our study, making direct comparisons of wood loads difficult.

Wood loads in forest streams vary among bioclimatic regions (Wohl et al. 2017). Compared to low-order streams in similar bioclimatic regions of North America (i.e., wet temperate regions with deciduous or mixed coniferous-deciduous forests), the wood loads of forested streams in our study tend to be relatively low (Table 6). In particular, the highest wood load of a stream in our forested category was only about 60% as high as the lowest wood load among forested streams elsewhere in the southern Blue Ridge Province studied by Hedman et al. (1996). In fact, wood loads in forested streams in our study are closer to mean wood loads from streams in agricultural regions of the north-central United States (Table 6). It is possible that the riparian forests along the forested streams in our study are at an earlier successional stage than those studied by Hedman et al. (1996) and thus contribute smaller volumes of wood to the streams. However, we do not have data on the ages of riparian trees in our study, nor do we have sufficient information on past human influences on those riparian zones. In the future, for forested streams in the South Carolina Blue Ridge Province, death of eastern hemlock due to hemlock woolly adelgid infestation may increase wood loads to streams, as has been documented in other areas of the

central and southern Appalachian Mountains (Costigan et al., 2015; McDade et al., 2020).

In contrast to the forested streams in our study, the wood load of commercial reach RC10 (166 m³/ha) was higher than loads in many streams flowing through second-growth forests in both the southern Blue Ridge Province and even some streams in old-growth floodplain forest in the South Carolina coastal plain (Table 6). Thus, it may be possible for wood loads to reach relatively high levels in urban streams in this region if riparian trees are numerous enough and are given the opportunity to reach larger sizes. Tulip poplar, as a fast-growing but potentially long-lived species that can reach large sizes (Beck, 1990), may be especially important in this regard. The species was a common large riparian tree in all four land cover categories, accounting for 17 of 31 stems with DBH \geq 50 cm across all 20 stream reaches.

Lastly, we acknowledge that longer reaches may have provided more accurate estimates of wood amounts in the streams we studied. However, the 100-m reach lengths we used are consistent with lengths used for quantifying wood loads in small headwater streams in other regions. For example, Elozegi et al. (1999) used reach lengths of about 70 m for two first-order streams with channel widths (of about 3–4 m) similar to those in our study. Also, several previous studies that quantified in-stream wood loads used reach lengths that were 15–20 times channel bankfull width (Cordova et al., 2007; Segura & Booth, 2010; Blauch & Jefferson, 2019). Similarly, Costigan et al. (2015) used reach lengths that were 12–25 times bankfull width for low-order streams in the central Appalachian Mountains. For 19 of the 20 streams we studied, the 100-m reach length was 20 to almost 60 times mean bankfull width. For the widest stream reach in our study (US32), 100 m was 14 times the mean bankfull width.

Future Directions

Our results suggest that amounts of stream wood, especially LW, are more closely associated with the abundance of riparian trees than with land cover (including ISC) at the whole watershed scale. However, additional studies are needed to examine more fully the relative influence of ISC and riparian vegetation on wood in urban streams. Additional

studies of wood mobility in urban streams would be especially helpful. To our knowledge, Blauch & Jefferson (2019) is the only study published thus far in which the mobility of stream wood has been measured in watersheds of varying degrees of urbanization. Additional studies are needed which examine the relationship between wood mobility and stream discharge patterns (including high discharge following storm events) in urban watersheds. Mobility of both LW and SW should be studied, as our results and those of Galia et al. (2018) suggest that the loads and mobility of SW and LW are influenced by different factors (e.g., channel morphology or types and characteristics of riparian trees). In conjunction with measurements of wood mobility, more detailed studies of the relative importance of riparian tree abundance within and upstream of a reach on wood loads would also be useful, as would more information on wood removal by land owners and the influence of bridges and road culverts on wood mobility.

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Data availability The data generated during this study are available from the corresponding author on reasonable request.

Code availability Standard statistical methods were conducted using publicly available software.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication All authors agree with the content of the manuscript and have given their consent to submit.

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