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HERBACEOUS VERSUS FORESTED RIPARIAN VEGETATION: NARROW AND SIMPLE VERSUS WIDE, WOODY AND DIVERSE STREAM HABITAT

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ABSTRACT

We investigated interactions of riparian vegetative conditions upon a suite of channel morphological variables: active channel width, variability of width within a reach, large wood frequency, mesoscale habitat distributions, mesoscale habitat diversity, median particle size and per cent fines. We surveyed 49 wadeable streams, 45 with low levels of development, throughout the Upper Little Tennessee River Basin in the Southern Appalachians. Conversion of riparian forest to grass has reduced aquatic habitat area (quantified by active channel width), channel width variability, wood frequency, mesoscale habitat diversity and obstruction habitat (wood and rock jams), and such conversion has increased the fraction of run and glide habitat. Channels with grassy riparian zones were only one-third to three-fifths of the width of channels with forested riparian zones, and channels with grassy or narrow forested riparian zones were nearly devoid of wood. Particle size metrics were strongly affected by stream power and agricultural cover in the basin, but the data suggest that elimination of riparian forest reduces median bed particle size. Results indicate that even modest increases in the extent and width of forested riparian buffers would improve stream habitat conditions. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: geomorphology; riparian ecology; nonpoint source pollution; rivers/streams

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INTRODUCTION

Riparian vegetation is known to affect channel width, shade, recruitment of wood and organic matter, and, indirectly, stream metabolism. While it is well established that riparian forest conversion to grass on channels less than 20 m wide results in reduced wood inputs, less shade and narrower channels (e.g. Anderson *et al*., 2004, Sweeney *et al*., 2004, Faustini *et al*., 2009), many relevant habitat questions remain about how such conversion affects other stream habitat characteristics. Most studies of geomorphic response to riparian condition have focused on channel dimensions as the response variables and have not evaluated how riparian vegetation relates to other important ecological or morphological characteristics. Exceptions include studies by Sweeney *et al*. (2004) and Bott *et al*. (2006), which found not only that riparian deforestation caused channel narrowing but also that the wider forested reaches featured higher numbers of macroinvertebrates and higher metabolic rates including gross primary productivity, organic matter processing and nitrogen uptake.

In this investigation, we used cross-landscape comparisons to assess the effect of riparian condition (and associated landowner actions) on a suite of physical habitat characteristics including aquatic habitat area (measured by active channel width, also known as bed width (e.g. Leigh, 2010), within-reach variability in active channel width, wood frequency, the diversity and distributions of mesoscale habitat types, and bed particle size distributions. We also evaluated the relationship between the frequency of wood and the frequency of obstruction habitat, and we calculated physical habitat diversity using the Shannon–Weiner index applied to the number and proportion of habitat types found in each reach. We randomly selected 49 wadeable stream segments within constraints of landowner permissions. Some stream segments were nested, and all were within 21 separately named basins that are tributaries to the Upper Little Tennessee River (Figure 1) in the Southern Appalachians. Three types of riparian conditions were common in the study area, full forest (greater than 10 m of forest on either side of the channel), one-tree buffers (1 to 3 m of trees on either side of the channel) and no forest (lawn or pasture growing to the streambank). There were also a few streams (six in our data set) with intermediate vegetative conditions between full and one-tree buffers (between 3 and 10 m of forest). Forest in this case signified unmanaged

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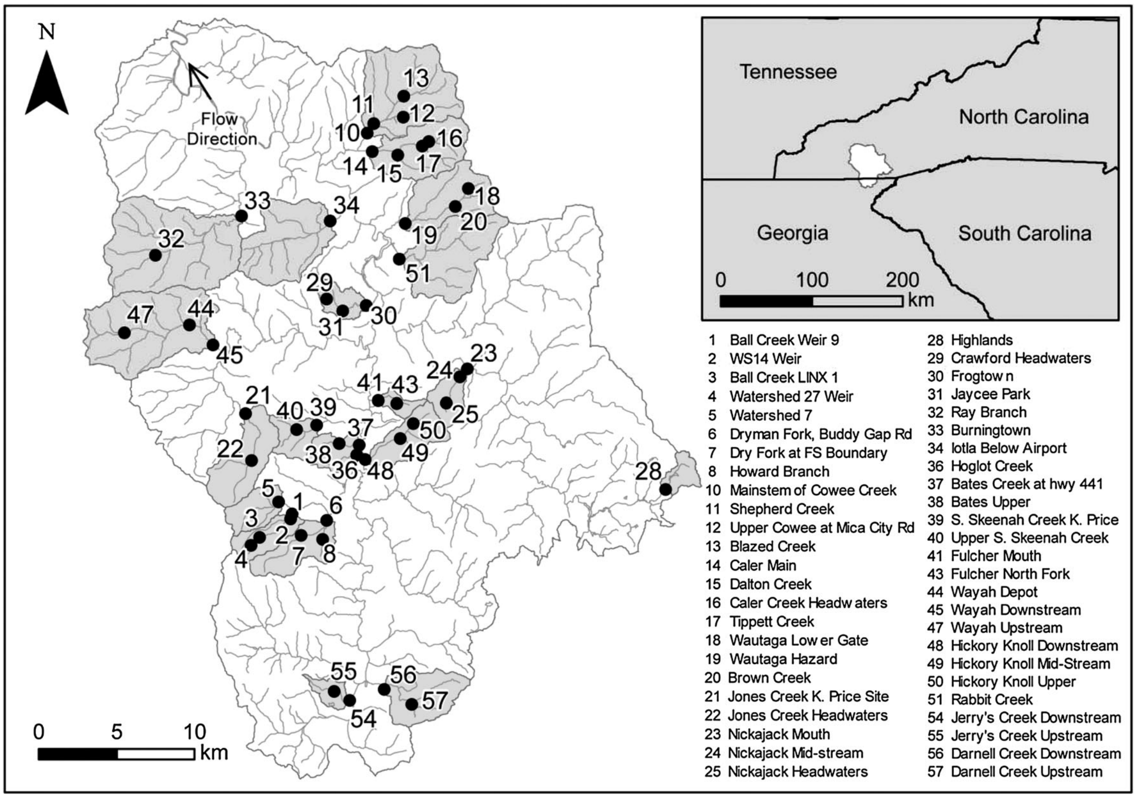

Figure 1. Distribution of surveyed channel reaches within the Upper Little Tennessee River basin.

woody vegetation including both overstory mature trees as well as mid-story and understory shrub layers. These varying riparian conditions allowed us to look at channel conditions across not only full forest and grass riparian zones but also intermediate amounts of riparian forest cover. The 49 study reaches encompassed these four different riparian conditions.

Because of reduced wood inputs and the resulting reduction in channel roughness, we hypothesized that stream segments with little riparian forest would feature reduced active channel widths, reduced channel width variability, reduced wood frequency, and less diverse and simpler habitat. Because of reduced filtration of overland flow from adjacent lands, we hypothesized that stream segments with little riparian forest would feature reduced median particle sizes and increased fine sediment percentages. Effects of riparian condition on channel conditions are of particular interest because riparian conditions can be affected by policy or management actions. From this cross-landscape comparison, we caution that the habitat differences we observed cannot be attributed solely to differences in vegetative condition as they probably also reflect associated differences in local habitat management by riparian landowners (e.g. purposeful wood removal and differential selection of land use based on valley slope).

In many settings, riparian disturbance is coincident with significant changes in watershed hydrologic processes and sediment loading, so separation of riparian vegetation effects from other geomorphic agents is difficult. Peak flow increases due to urbanization cause channels to widen (Booth and Jackson, 1997; Chin and Gregory, 2001), but maintenance of riparian buffers can mitigate or counteract the effects of increased peak flows (Hession *et al*., 2003). Where channel width signals are mixed, other controls such as geology may become dominant (e.g. Miller, 1991). In the Southern Appalachians, most rural residences and small farms are located on valley bottoms where the land is flatter and easier to farm. Valley residents have commonly converted the native forested riparian zone to lawn, pasture or even cropland, leaving either no forested riparian zone or a one-tree wide strip of trees on either side of the channel. Thus, the Upper Little Tennessee River in the Southern Appalachians is an excellent environment for studying effects of riparian vegetation because riparian conversion is common, but levels of development and impervious surface coverage at watershed scales (Table 1) are low relative to established urban land cover thresholds for significant peak flow effects (Booth *et al*., 2002, Schueler *et al*., 2009). Conversely, percentages of forest cover in these basins are high (Table 1), so peak flow effects are assumed to be negligible for all but five of the 49 streams.

Others have shown that replacement of a forested riparian zone with shrubs or grass causes channels less than 20 m

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Table I. Stream reach and basin characteristics

Site ID	Riparian class	Drainage area (km^2)	Slope	Channel width (m)	Channel width st. dev.	Wood frequency (p/m)	Per cent forest	Per cent agric.	Per cent built	D_{50} (mm)	Per cent fines	Power index
1	3	7.17	0.009	5.93	0.76	0.03	97.44	0.00	2.19	57	13	0.066
2	3	0.62	0.144	3.27	1.31	0.21	100.00	0.00	0.00	17	19	0.089
3	3	1.03	0.060	3.89	1.52	0.45	94.35	0.00	3.75	44.1	15	0.062
4	3	0.38	0.198	4.14	1.55	0.50	98.88	0.00	0.93	54	8	0.076
5	3	0.59	0.064	2.21	0.71	0.11	100.00	0.00	0.00	17	18	0.038
6	1	10.78	0.011	4.49	0.71	0.03	95.09	2.13	1.67	51.5	16	0.118
7	3	5.73	0.041	5.82	1.00	0.13	98.25	0.46	0.55	62	17	0.232
8	3	0.85	0.043	2.34	0.72	0.13	99.65	0.12	0.23	17	37	0.037
10	3	29.14	0.017	7.19	1.50	0.09	91.89	3.36	2.59	64.5	7	0.488
11	0	3.95	0.039	1.97	0.66	0.00	90.58	4.69	3.31	17	16	0.153
12	1	5.27	0.038	3.30	0.96	0.02	91.20	4.05	1.74	58.5	2	0.198
13	3	5.46	0.049	3.89	1.00	0.05	98.19	0.12	0.98	50	21	0.268
14	0	17.38	0.006	3.47	0.48	0.00	82.93	5.46	3.64	20.5	29	0.102
15	2	3.51	0.036	2.39	0.48	0.07	87.53	2.02	1.66	47	2	0.127
16	2	4.80	0.058	2.58	0.68	0.04	94.78	0.37	0.00	50	14	0.281
17	2	2.38	0.055	2.91	0.64	0.02	90.24	0.19	4.27	17.5	27	0.130
18	0	2.61	0.072	2.44	0.52	0.00	64.14	1.39	24.49	17	24	0.188
19	1	16.60	0.012	3.89	0.79	0.00	73.35	6.01	14.39	36.5	20	0.195
20	3	2.25	0.079	2.64	1.03	0.09	94.16	0.94	0.00	11	23	0.177
21	2	15.30	0.017	8.66	1.65	0.12	92.29	2.70	2.35	65	9	0.253
22	3	8.06	0.033	5.74	1.65	0.14	98.88	0.00	0.52	85.5	12	0.265
23	1	6.04	0.019	3.41	1.08	0.03	94.47	1.16	2.55	60	12	0.112
24	1	5.53	0.035	3.85	1.20	0.01	94.95	1.17	2.24	42	23	0.196
25	3	1.51	0.076	2.39	0.73	0.09	98.16	0.00	1.84	19.5	30	0.114
28	3	1.94	0.002	8.56	1.33	0.37	50.55	0.97	46.90	44.5	24	0.003
29	0	0.51	0.023	0.78	0.38	0.00	64.90	12.86	17.59	16	18	0.012
30	1	5.28	0.009	2.71	0.66	0.01	29.73	13.99	47.77	14.5	22	0.049
31	0	2.73	0.001	1.61	0.55	0.00	32.44	14.13	43.94	28	16	0.003
32	3	5.16	0.026	6.96	1.06	0.07	94.71	0.59	1.09	49	18	0.132
33	3	2.56	0.007	9.43	0.89	0.15	83.64	5.19	2.22	70.5	2	0.018
34	0	23.74	0.001	6.34	0.87	0.01	57.73	22.34	6.58	1	78	0.020
36	0	2.09	0.010	2.21	0.70	0.00	65.52	10.09	11.98	11.5	15	0.020
37	1	6.46	0.014	2.77	0.50	0.02	62.59	12.89	13.03	12	5	0.093
38	1	2.81	0.016	2.72	0.70	0.00	82.47	8.98	3.79	34.5	6	0.046
39	1	6.13	0.003	3.25	0.41	0.00	85.31	3.32	4.66	68.5	9	0.019
40	1	2.32	0.024	1.87	0.38	0.00	87.61	4.95	3.38	45.5	14	0.055
41	1	2.66	0.011	2.51	0.49	0.01	62.57	12.76	14.76	41.5	10	0.030
43	0	0.85	0.039	1.44	0.43	0.00	71.32	9.22	12.67	14	21	0.034
44	1	30.28	0.010	7.92	0.42	0.02	91.68	0.61	3.10	65.5	15	0.303
45	2	35.83	0.026	8.33	0.87	0.00	88.83	1.73	3.29	81	4	0.922
47	3	6.48	0.073	6.92	2.11	0.17	89.74	0.00	6.77	55.5	7	0.470
48	1	10.63	0.013	3.96	0.57	0.00	90.11	2.16	3.78	65	20	0.135
49	1	5.92	0.039	3.65	0.64	0.03	95.95	0.61	1.11	56	3	0.230
50	2	3.93	0.027	3.70	0.84	0.01	97.06	0.14	0.29	55	10	0.105
51	0	23.63	0.007	5.34	0.78	0.02	68.25	18.88	6.78	16	23	0.168
54	0	3.41	0.009	1.59	0.42	0.00	49.34	31.63	17.17	12	18	0.031
55	1	1.55	0.033	1.25	0.73	0.00	92.09	5.86	1.41	5	39	0.051
56	3	12.26	0.032	7.91	1.15	0.03	99.21	0.01	0.06	110	10	0.390
57	3	2.61	0.072	1.63	0.65	0.09	99.17	0.00	0.00	33.00	5.00	0.189

wide to narrow (e.g. Anderson *et al*., 2004, Sweeney *et al*., 2004, Faustini *et al*., 2009), with resulting loss in the quantity of aquatic habitat area. Within headwater streams <10 m wide draining 0.1 to 20 km^2 sub-basins of a mostly forested watershed (Coweeta Cr.) versus a moderately forested watershed (Skeenah Cr.) of the Upper Little Tennessee River system in our study area, Leigh (2010) found that the degree of channel narrowing was progressively more apparent in smaller watersheds. For example, he found active channel beds of streams at 0.2 km^2 almost quadrupled in size going from grassed to forested reaches, whereas those at around 2.0 km^2 only doubled in width. Similarly, Murgatroyd and

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Ternan (1983) found that forested sections of the same river featured channels three times wider than unforested sections. The forested reaches were also shallower (see Liquori and Jackson, 2001 for a similar W/D ratio effect), and Murgatroyd and Ternan attributed the differences to increased channel roughness in the forested reaches and greater streambank resistance to erosion in the grassed reaches. Leigh (2010) proposed similar explanations for the difference in channel morphology between grassed and forested stream reaches. Wynn *et al*. (2004) found that streambanks with herbaceous vegetation featured very high fine root densities in the top 30 cm of streambanks, while streambanks with trees featured deeper and larger root distributions. Allmendinger *et al*. (2005) offered a different explanation for narrowing of non-forested reaches, which focuses on the effectiveness of the relative rates of cutbank erosion and lateral accretion of floodplains. They indicated that very high rates of lateral floodplain accretion are mediated by grassy vegetation (trapping sediment) on the insides of meander bends, such that the lateral accretion rates exceed cutbank erosion rates and result in channel narrowing. In this study, we did not address the effects of riparian vegetation on bankfull width or channel cross-sectional area, because these channel size relationships have been recently explored by others in the region (e.g. Faustini *et al*., 2009, Leigh, 2010), but active channel width is part of the suite of physical habitat characteristics we addressed.

STUDY AREA

All of the study streams are located within the Upper Little Tennessee River basin above the US Geological Survey Needmore gauge (Figure 1), encompassing the area between and around the towns of Franklin and Highlands, NC and Dillard, GA. Topography is rugged with steep slopes and relatively flat colluvial and alluvial valleys. Most human settlement has occurred and persisted in the valleys. Elevations range from 537 m at the basin outlet to 1661 m at the highest elevation of the drainage divide. The climate is wet and cool. Average annual precipitation is spatially variable, with 30-year precipitation averages in the valleys ranging from 1382 to 1824 mm/year and mean valley air temperatures around 12.7 °C (North Carolina State Climatologist). The PRISM precipitation data from the Oregon State University climate group indicates even greater precipitation variability, ranging from 1350 to 2050 mm/year across the area (PRISM Climate Group, 2013), but with generally greater precipitation at higher elevations. Without human intervention, forest would cover all but recently disturbed areas (e.g. landslides and forest fires) and outcrops of bedrock, and aquatic biotic diversity would be very high in this 'hotspot of biodiversity'.

Gragson and Bolstad (2006) summarized the history of human activity in the region as follows. Around AD 800, Native Americans began widespread valley agriculture, but Native American populations were drastically diminished by disease after trading contacts with Europeans in the latter 1600s. Throughout the 1800s, most Native Americans remaining (Cherokees) were relocated to Oklahoma, and settlers mostly of European descent acquired the land and farmed the valleys and lower slopes. Around 1900, logging and mining became widespread. Agriculture was practised on about 10% of the total area (Davis, 2000). Much non-forested land reverted to forest during outmigration following World War II, but in the last 20 years, new immigrants to the area have not only recolonized the valleys but also built view homes high on the hillslopes in some areas. Our sample included basins both with and without hillslope development and five streams on the urban end of the spectrum. The town of Franklin, NC (population 3900, seat of Macon county) encompasses the basin of Crawford Branch, one of two urban streams in the study sample (sites 29–31), and the vacation town of Highlands, NC (permanent population of 924, summer population of 10,000–15,000) covers much of the basin for site 28.

An important criterion of our site selection was that the surveyed channels, floodplains and terraces were within alluvium. Bedrock reaches and sills are fairly common in the smallest tributaries in steep catchments, and they also occur sporadically in the predominantly alluvial reaches within catchments larger than 5 km^2. Bedrock reaches and sills impose their own unique influence on channel form, so we focused on alluvial reaches in order to isolate human-induced riparian influences, rather than those imposed by the geologic template.

METHODS

Sites were selected to encompass a wide range of basin areas, land cover types, riparian conditions and water quality characteristics (Webster *et al*., 2012). We used satellite imagery, 2003 photo imagery, topographic maps and pedestrian surveys of the study area to characterize basin, site and reach characteristics of each potential study reach draining catchments ranging from 0.38 to 35.83 km^2 (Table 1). We constrained the sites to wadeable streams without appreciable direct channel manipulation (without riprap or recent human engineering such as straightening, although some of these channels may have been straightened in the past). Sites without cooperative land owners were excluded from the analysis. Final characterization of land cover, specifically the percentage of forest, agricultural and developed (built) cover in each basin, was determined from 2006 Landsat imagery (Coweeta LTER Synoptic Sampling

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Program, 2009). Developed area included any roads (including unpaved roads), residential areas and commercial areas. Much of the developed area consisted of low density residential lands. The contributing basins for 44 of the streams were dominated by forest and agricultural cover (Table 1) with less than 18% developed land in these basins. The built environment covered less than 12% of the basin area in 38 of the 49 basins. The five stream segments featuring more than 20% developed lands in their basins were sites 18 (24%, draining a subdivision at the top of the Watauga basin), 27 (28%, on the outskirts of Franklin), 28 (47%, Highlands, NC), 30 and 31 (44% and 48%, both on Crawford Branch in Franklin). However, even the most developed basins in Franklin, NC, featured more than 30% forest cover.

At each site, a uniform 150-m section of stream was surveyed. Within each reach, the active and bankfull channel widths were measured every 5 m, where active channel width was defined as the vegetation-free channel bed from left vegetation break to right vegetation break. A uniform stream length was used because these surveys were conducted in conjunction with biological surveys, reported elsewhere, for which a uniform sampling length was required. The minimum, average and maximum average active channel widths were 0.78, 4.04 and 9.72 m (Table 1), so the corresponding survey reaches comprised 192, 37.1 and 15.9 times the active channel widths, respectively. The analyses presented here focus on the active channel widths for several reasons: (i) active channel width is more closely associated with aquatic habitat availability; (ii) bankfull widths are often difficult to determine in these streams (Zink *et al.*, 2012), and active channel widths are subject to less observer bias; and (iii) characterizing bankfull width variability is constrained by the limited availability of floodplain features (Zink *et al.*, 2012), so large numbers of bankfull widths could not be measured for calculating and comparing the standard deviations of bankfull widths. In actuality, bankfull widths were tightly correlated with active channel widths ($r^2 = 0.97$) and were about 1 m greater and increased at a slightly greater rate (the slope of the bankfull to active channel width regression was 1.16). Furthermore, the effects of riparian vegetation on channel dimensions including bankfull widths in the region have been recently explored by others (Faustini *et al.*, 2009 and Leigh, 2010).

Riparian conditions at each reach were visually categorized as follows: greater than 10 m forested riparian zone on both sides of the stream (class 3), variable forested buffer between 3 and 10 m in width (class 2), a narrow, usually single tree forested buffer between 1 and 3 m in width (class 1), and no forested buffer, with grass or pasture growing to the stream bank with an occasional tree (class 0). Observers kept a running tally of the areas associated with various mesoscale habitat units including cascades, riffles, pools, alcoves (slow shallow areas on channel margins), pocket water (small pools around boulders), runs, glides and obstructions (wood jams, debris jams, boulder jams, cobble jams and mixed jams). The diversity of mesoscale habitat types was calculated for each site using the Shannon–Weiner diversity index:

$$\mathrm{H} = -\sum_{i=1}^{n} p_i \ ln \ p_i$$

where n = number of mesoscale habitat types and p_i = proportion of area covered by mesoscale habitat type i (Shoffner and Royall, 2008). For graphical analysis, these habitat units were condensed into four broader categories of slow water (pools, alcoves and pocket water), fast water (riffles and cascades), simple habitat (runs and glides) and obstructions. All wood exceeding 10 cm diameter and 1.0 m length was tallied. We conducted a Wolman pebble count ($N = 100$) on the coarsest riffle in each stream reach, and we calculated the median particle size and the per cent fines (less than 2 mm diameter). Slopes were measured from the upstream end of riffles over three riffle-to-riffle sequences with a level, rod and tape, and the average slope was calculated.

The simplest common channel width (w) models take the form:

$$\mathrm{w} = \alpha \mathrm{A}^{\beta}$$

where basin area (A) is used as a surrogate for the amount of streamflow in the absence of flow or climate information for each location. We used this model to evaluate the mean trend of channel width as a function of basin area for streams with fully forested riparian zones (riparian class 3) and pasture/grass riparian zones (riparian class 0). Effects of local riparian conditions were evaluated graphically, with different symbols for each riparian class. Similarly, large wood frequency (pieces/m) was also plotted against drainage area, and graphical analysis was again used to evaluate the effects of local riparian condition. We used some other published regional channel width versus drainage area relationships (Faustini *et al.*, 2009 and Leigh, 2010) to evaluate the generality of our channel width findings.

Many investigators have found that median particle size (D_{50}) and per cent fines are related to either basin area or slope or the combination of these factors expressed as stream power or unit stream power (Hack, 1957, Petit *et al.*, 2005). Bed particle size distributions are also affected by land use as it affects erosion processes and sediment loading, and indeed Price and Leigh (2006) found coarser particle size distribution in basins with more forest cover. We used Akaike information criteria (AIC) to assess the relative support for models predicting D_{50} and per cent fines from the following variables and combinations thereof: basin area, channel slope, a power index computed as the

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product of channel slope and basin area (a surrogate for flow), per cent forest cover in the basin and per cent agricultural cover in the basin. The following eight multi-variate models were considered: area + %for., slope + %for., area + %ag., slope + % ag., power index + %ag., power index + % for., power index + %for. + %ag. and the global model (all variables). Each of the five individual variables (area, slope, %for., %ag. and power index) was also included in the candidate models, for a total of 13 models. Potentially important variables not considered in these candidate models are the effects of historical land use (Harding *et al.*, 1998, Bain *et al.*, 2012), basin geology, basin ruggedness and local riparian vegetative condition because such data were either unavailable or categorical.

The standard deviation of the active channel width was calculated for each reach from the 31 widths measured every 5 m over 150 m. We used these standard deviations to test the hypothesis that channel widths would be more variable in streams with more riparian forest cover. We used analysis of variance to test the differences in the means of the channel width standard deviations across the four categories of riparian vegetative condition.

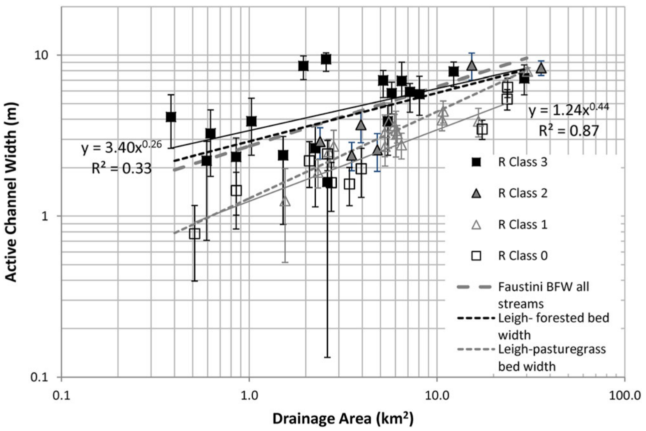

Figure 2. Relationship of active channel width versus drainage area for different observed reach-scale riparian conditions. Each point is the mean of 31 active channel widths taken over each 150-m reach, and whiskers portray plus and minus one standard deviation of the active channel widths in each reach. Power functions are fitted to the riparian class 0 and class 3 streams. Leigh's (2010) bed width relationships for two drainages in the Upper Little Tennessee closely match the active channel width relationships collected here. The regional bankfull width (BFW) relationship of Faustini *et al.* (2009) for both disturbed and undisturbed Southern Appalachian streams is shown in the dashed grey line.

RESULTS

Active channel widths of streams with fully forested riparian zones were 2 to 6 m wider than those of streams without forested riparian zones over the 0.38- to 35.83-km^2 range of drainage areas encompassed in the study set (Figure 2). For streams draining less than 10 km^2, active channel widths of grass/pasture streams were one/third to six/tenths the width of forested streams. These relationships compared very well with nearby streams studied by Leigh (2010) and Faustini *et al.* (2009) (Figure 2). The South Appalachian regional bankfull width equation for both disturbed and undisturbed streams developed by Faustini *et al.* (2009) runs through the middle of our active channel width data sets (Figure 2). The power functions fitted by Faustini *et al.*, 2009, Leigh, 2010, and Zink *et al.* (2012) are steeper than those for our active channel widths, suggesting that bankfull widths increase with basin area faster than do active channel widths. When related to drainage area, the forested and unforested buffer active channel width relationships were convergent and predicted to cross at a basin area of 260 km^2 and a channel width of 14.6 m. Similar convergence of the basin area relationships has been seen locally (Leigh, 2010) and in a previous meta analysis (Anderson *et al.*, 2004).

Even single-tree buffers (riparian class 1) were associated with wider channels than unbuffered streams (Figure 2). Over the range of streams in this data set, active channel widths in the riparian class 1 streams were generally 0.5 to 2 m wider than riparian class 0 streams. There were few (only six) intermediate forest buffers (riparian class 2) streams within our data set, but active channel widths for five of the six fell as expected between the class 0 and class 3 regression lines and always above the class 1 data points.

Within stream reaches, the standard deviations of active channel width ranged from 0.38 to 2.11 m, averaging 0.85 m. Standard deviations of active channel widths were related to riparian vegetative condition (Figure 3A). Riparian class 3 streams had much higher and significantly different standard deviations of channel width than riparian class 0 or 1 streams (Dunn's pairwise multiple comparisons $p < 0.05$). We tested whether the standard deviation of active channel width was related to drainage area, and it was not ($p = 0.59$). However, because the standard deviation of channel width was invariant with drainage area, the coefficient of variation decreased as channel width increased, and this decrease can be seen in the channel width relationships (Figure 2).

The frequency of large wood in full forest buffered channels decreased with basin area and ranged from 0.03 to 0.5 pieces/m (Figure 4). All full forest buffered streams featured some large wood within the surveyed reach. Wood frequency was dramatically reduced when the riparian forest was not present (Figure 4). Eight of 10 class 0 streams featured zero pieces of wood in the 150-m survey reach, and the other two streams had very low wood frequencies. Six of 15 class 1 streams also had zero wood, while the other nine had less than 0.033 pieces/m.

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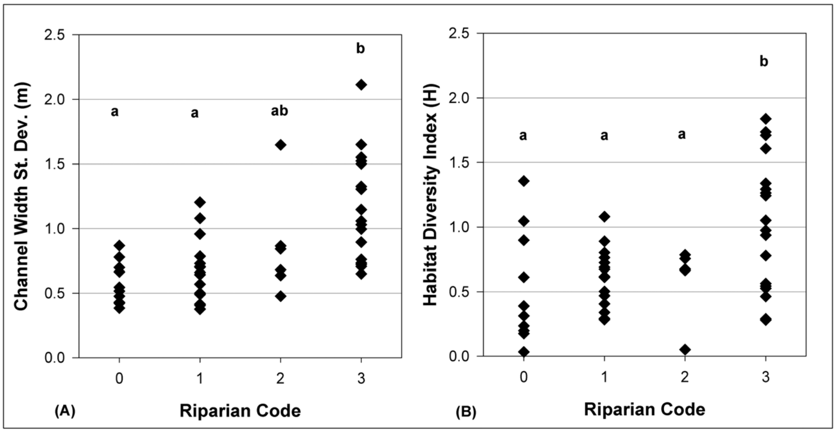

Figure 3. (A) Distributions of the standard deviations of channel width by riparian class. Means are different (Kruskal–Wallis analysis of variance on ranks). Distributions that do not share a letter have different median standard deviations of active channel width according to Dunn's multiple comparison test. Streams with fully forested riparian zones have greater variability in channel width than streams with less than 3 m of riparian forest. (B) Habitat diversity scores (Shannon–Weiner index) for stream segments in each riparian class. Distributions that share a letter are not significantly different. The mean habitat diversity scores are higher for riparian class 3 streams than for all other riparian classes.

The proportion of obstruction habitat was strongly associated with large wood frequency ($r^2 = 0.58$, $p < 0.0001$, Figure 5), indicating that the presence and abundance of wood was important for the formation of jams and other flow obstructions (Jackson and Sturm, 2002). Cobbles and boulders were plentiful in these streams, but streams without wood featured very little obstruction habitat.

Habitat diversity scores were higher in the forested streams than in streams of all other riparian types (analysis of variance, Tukey's post test, *p*-values of 0.017 compared against class 0, 0.028 for class 1, and 0.046 for class 2, Figure 3B). Because of the relationship between riparian cover and woody debris frequency, streams with forested buffers had much higher proportions of obstruction habitat and much less simple habitat (runs and glides) than other streams (Figure 6). Conversely, riparian classes 0 and 1 streams featured very little obstruction habitat and high proportions of simple habitat, sometimes reaching 100% (Figure 6). Taken together, these data indicate that conversion of riparian forests to grass or pasture results in channel simplification, with particular reduction in the amount of obstruction habitat.

Bed particle size metrics were sensitive to watershed characteristics and land use. For both D_{50} and per cent fines, the global model (basin area, channel slope, power index, % forest cover and % agricultural cover) was well supported and could not be discounted (Table 2). For both D_{50} and per cent fines, the predictive model with the most support

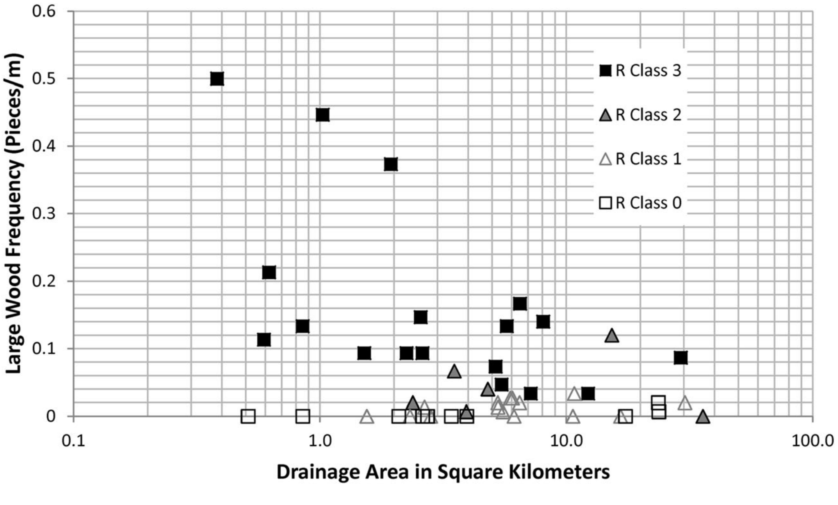

Figure 4. Large wood frequency versus drainage area by riparian class.

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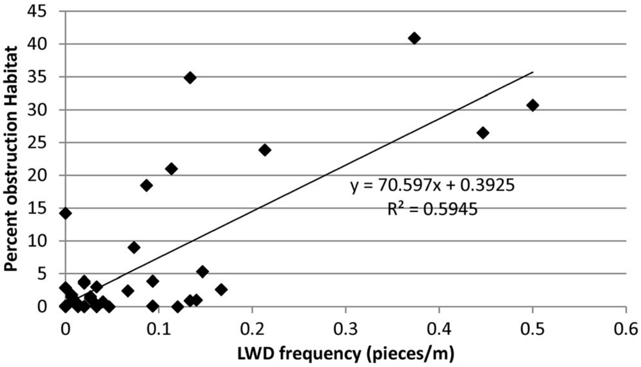

Figure 5. Relationship of the percentage of obstruction habitat (obstruction habitat includes all forms of jams and steps including wood, debris, rock or mixed steps) to large wood frequency. Wood frequency explains 59% of the variance of obstruction habitat percentages ($p < 0.0001$).

included the power index and the percentage of agricultural cover in the watershed. As agricultural cover increased, D_{50} decreased (Figure 7) and per cent fines increased. Conversely, as the power index increased, D_{50} increased (Figure 7) and per cent fines decreased. AIC does not support the analysis of categorical variables, but graphical analysis suggested that D_{50} was partly explained by local riparian condition (Figure 8), with uniformly low D_{50} values observed in riparian category 0 streams. D_{50} values were highly variable in categories 2 and 3 streams, but almost all values in these streams were higher than those observed in category 0 streams. As with active channel width, even a one-tree buffer appeared to have positive effects on median particle size (Figure 8).

DISCUSSION AND CONCLUSIONS

Streams without forested riparian zones exhibited narrower and simpler channels with less wood, lower habitat diversity, fewer obstructions, higher proportions of run and glide habitat, and less variability in active channel width. They also appeared to feature smaller median particle sizes, although the size distributions of bed sediments were strongly associated with both basin land use and watershed characteristics. Channel narrowing associated with loss of forest riparian cover was distinct, as active channel widths of forested streams were 2 to 6 m wider than comparable streams with grass/pasture riparian zones.

Many stream reaches in the study area featured tree cover in the first 1 to 3 m from the bank, and typically such buffers were only one tree wide. These one-tree buffers provided measurable and ecologically significant improvements in channel conditions over grass/pasture buffers. Streams with one-tree buffers were a little wider with slightly more wood, larger median particle sizes and less simple habitat than grass/pasture streams. In addition, one-tree buffers provided some shade as an added benefit to stream conditions, although it was not measured in our study. There were too few stream reaches within the intermediate buffer class (class 2) to draw strong inference about the relative benefits of intermediate levels of buffering, but these streams generally fell between the class 1 and class 3 streams for most measured channel variables except wood.

Lack of wood in streams without wide forested buffers likely resulted from both low recruitment (e.g. Warren *et al.*, 2009) and active removal of wood by local residents. Discussions with local landowners revealed that wood

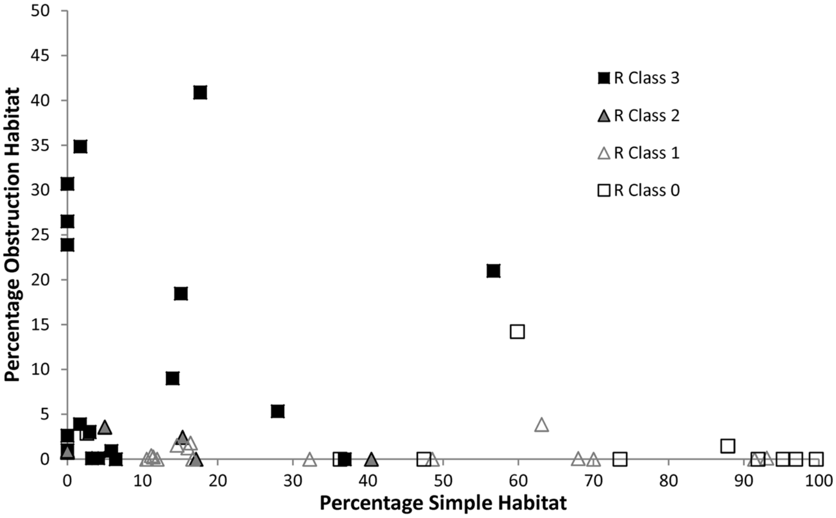

Figure 6. Scatter plot of percentages of simple habitat and obstruction habitat by riparian code. Classes 0 and 1 streams with little riparian forest feature high percentages of simple habitat and very little obstruction habitat. With one exception, streams with full forested buffers feature very little simple habitat and often feature large fractions of obstruction habitat.

Table II. Candidate models for explaining median particle size (D_{50}) and per cent fines in the bed substrate (% fines) ranked by adjusted AIC scores

Median particle size (D_{50})					% fines				
Model	AICc	Δ_i	W_i	% max. W_i	Model	AICc	Δ_i	W_i	% max. W_i
Power index, %ag	435.524	0.0000	0.30409	100	**Power index, %ag**	386.671	0.00000	0.17316	100
Global model	435.531	0.0078	0.30290	99.6	**%ag**	386.770	0.09915	0.16479	95
Area, %ag	436.956	1.4321	0.14860	49	**Power index**	386.878	0.20720	0.15612	90
Power index %for, %ag	437.900	2.3759	0.09270	31	**Global model**	386.916	0.24542	0.15316	88
Power index, %fors	438.180	2.6562	0.08058	27	Power index, %fors	388.393	1.72236	0.07319	42
Slope, %ag	439.694	4.1708	0.03778	12	Area, %ag	389.027	2.35652	0.05330	31
Power index	441.328	5.8047	0.01669		Slope, %ag	389.063	2.39200	0.05236	30
Area, %for	443.213	7.6893	0.00651		%for	389.070	2.39933	0.05217	30
Slope, %for	443.709	8.1855	0.00508		Power index, %for, %ag	389.114	2.44325	0.05104	29
%ag	444.158	8.6344	0.00406		Area, %for	391.083	4.41289	0.01906	11
%fors	447.077	11.5531	0.00094		Area	391.169	4.49823	0.01827	11
Area	452.398	16.8741	0.00007		Slope	391.221	4.55008	0.01780	10
Slope	457.190	21.6666	0.00001		Slope, %for	391.488	4.81702	0.01558	9

Models with high support are indicated in bold.
AIC, Akaike information criteria.

removal was a common practice, and Coweeta Long Term Ecological Research (LTER) social scientists are now investigating stream management practices as part of a larger study of landowner attitudes about stream and riparian conditions. Furthermore, reach slopes were higher for streams with forested buffers than for streams with converted buffers (Kruskal–Wallis test with Tukey pairwise comparisons, $p = 0.01$ for forest versus grass and $p = 0.04$ for forest versus one-tree buffer). This could suggest that forested riparian zones affect not only the active channel width but also the riffle crest to riffle crest slope. Alternatively, it could mean that landowners preferentially converted riparian zones on lower gradient streams because such riparian zones were more attractive and valuable for farming. The latter explanation seems most likely to us.

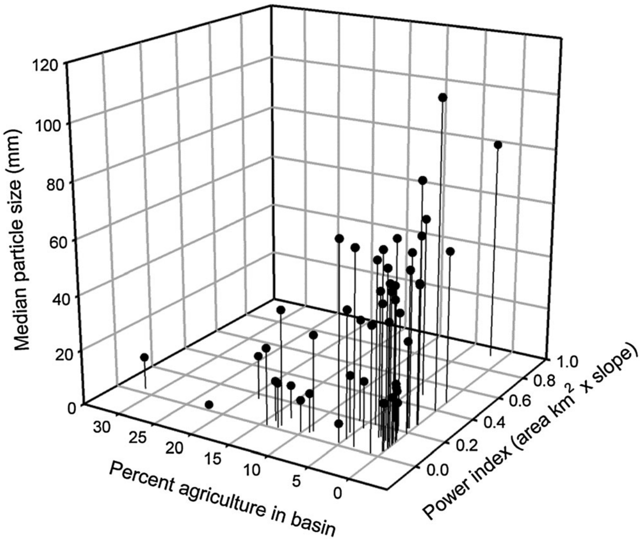

Figure 7. Variation of median particle sizes with respect to the stream power index and the percentage of forest in the basin. Higher median particle sizes occur in streams with larger power indices and lower percentages of agriculture and vice versa.

Stream water quality attributes vary in their relative response to watershed scale versus near stream stressors. Webster *et al.* (2012) evaluated water chemistry in this set of streams and found that nitrate concentrations and specific conductivity in nearby streams were explained largely by watershed land cover, whereas riparian conditions had significant effects on summer turbidity. Generalizing, riparian vegetation exerts little or only partial control on some water

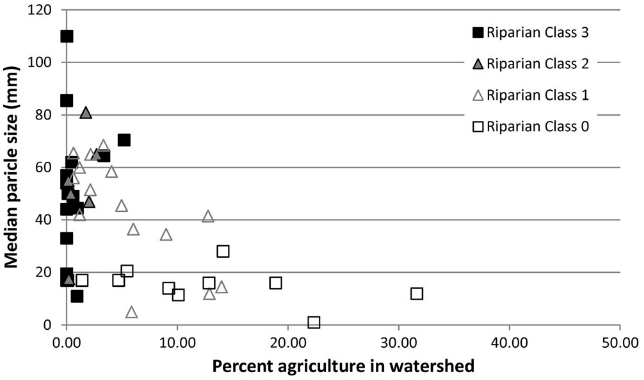

Figure 8. Median particle size is most strongly affected by per cent agriculture in the basin and stream power, but there still seems to be an effect of riparian vegetation. For all levels of agriculture, the riparian class 0 streams tended to have the lowest median particle sizes.

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quality characteristics. This study demonstrated, however, that riparian vegetation strongly affects many aspects of local stream morphology known to affect aquatic biota. As a result of the channel and water quality changes that accompany riparian forest conversion to pasture and grass, previous investigators in this same region have found that fish assemblages in reaches without forested buffers were dominated by warmwater fishes characteristic of the Piedmont, rather than by sculpin, darters and benthic minnows native to this mountainous area (Jones *et al*., 1999; Scott, 2001; Burcher *et al*., 2008). McTammany *et al*. (2007) also found that local riparian condition strongly affected stream metabolism in this region and concluded that restoration of riparian shade would substantially assist in restoring more natural stream metabolism. While riparian forest restoration is not a panacea for curing all water quality problems, restoration of forest riparian zones of even modest widths would substantially improve habitat conditions for native aquatic biota.

Were riparian forest restoration instituted on these streams, the resulting rate of channel enlargement is unknown, but it can be expected that bank erosion would accelerate during the adjustment period. Lyons *et al*. (2000) concluded that riparian forest restoration is likely to result in a temporary increase in downstream sediment loads. This observation has been made to us by local residents who complain that riparian trees cause bank erosion. This is a legitimate concern, but without riparian trees, the habitat quality and quantity for many of the native aquatic species is diminished.

These results reinforce and extend the more localized previous findings of Leigh (2010) and Price and Leigh (2006) by showing that their somewhat spatially limited observations can reliably be scaled-up to the entire Upper Little Tennessee River basin. Furthermore, our results compare favourably with broader regional equations that predict bankfull width (Faustini *et al*., 2009). This has important implications for regional modelling of stream width and associated habitat conditions.

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