Chapter 3. Variation in Root Density Along Stream Banks

The overall goal of this research is to compare the effects of woody and herbaceous vegetation on stream bank erosion. This chapter presents the first of three substudies that address the impact of vegetation on stream bank erosion. Stream bank soils can be viewed as a fiber-reinforced composite material, with the plant roots increasing soil strength and stability. The goal of this study was to quantify root-length density with depth in stream banks as a function of riparian buffer vegetation type and density.

3.1. Methods

To quantify the distribution and density of roots along alluvial stream banks as a function of riparian buffer vegetation type and density, 25 field sites in the Blacksburg, Virginia area ($37^o15'$ N, $80^o25'$ W) were sampled from June through August 2002. Root length density (RLD) and root volume ratio (RVR) with depth, above ground vegetation density, and soil texture were measured at each site. Root length density is the total length of all roots within a unit soil volume. The RLD provides an estimate of the total number of roots and is not skewed by the presence of large roots, as compared with root mass, root volume, or root area ratio (Böhm, 1979). If vegetated soils are viewed as a fiber-reinforced composite material, the RLD represents the number of fibers in the sample. For comparison to previous studies, the root-volume ratio (RVR) was also calculated (Gray and MacDonald, 1989). Root volume ratio represents the total volume of roots per unit soil volume.

To measure root distribution with depth along the stream banks, 10 soil cores were taken at each site using a 7 cm diameter, 15 cm long, soil corer. The adequacy of the sample size of 10 soil cores was determined in a preliminary study, as outlined by Crépin and Johnson (1993) and Elzinga et al. (1998). Cores were taken 30 cm from the top of bank at locations chosen using a stratified random scheme, although samples were constrained to distances greater than 30 cm from any tree bole, due to physical limitations. While Abernethy and Rutherfurd (2001) found root area ratio decreased with distance from isolated tree boles, McGinty (1976) found less horizontal variation in root biomass in a natural hardwood forest than in a pine plantation. He

attributed this to the ability of the wide variety of plant types in a natural forest to fully utilize soil niches. Samples were taken in 15 cm increments to a depth of 105 cm, where possible. The sampling depth of 105 cm was selected because most roots are located in the top one meter of the soil profile and because the bank exposure at most of the sites was approximately one meter (Davidson et al., 1991; Shields and Gray, 1992; Simon and Collison, 2002). At three sites (NR1, ST2, and TC2), restrictive gravel layers at the same elevation as the channel bed limited sampling depth, while at a fourth site (SR4) the extremely dry soil conditions prevented core sampling. Samples for each depth increment were combined to produce one composite core per field site. A total of 1,710 corer volumes were taken to produce 171 composite samples for the 25 cores (one composite core per site). Each composited sample was thoroughly mixed using a small cement mixer (BigCat Mixer Type B, Monarch Industries). Two subsamples, each representing one tenth of the total sample weight, or one soil corer volume, were taken. One subsample was used for root measurements and the second subsample was used for soil particle size analysis. Soil samples were stored in a walk-in cooler (4°C) until they could be processed.

Roots were removed from each sub-sample by hand, washed over a No. 30 (0.5 mm) sieve to remove all soil, and stored in a refrigerator (4°C) until analysis. Dead roots, identified based on root color, flexibility, and strength, were removed from the samples (Böhm, 1979). Root length and root volume were assessed for each of five size classes (Abernethy and Rutherfurd, 2001). These classes are very fine roots (<0.5 mm), fine roots (0.5-2 mm diameter), small roots (2-5 mm diameter), medium roots (5-10 mm diameter) and large roots (10-20 mm diameter) (Böhm, 1979). Roots larger than 20 mm in diameter were disregarded because they contribute little to bank stability and are difficult to sample with a hand corer (Coppin and Richards, 1990). Root length and root volume were measured for each diameter class using a Régent Instruments STD 1600+ scanner and WinRHIZO$_{TM}$ analysis software (Arsenault et al., 1995; Régent Instruments Inc, Quebec, Canada).

Particle size analysis (PSA) was conducted on each distinct soil horizon in the stream banks. Each composite core was evaluated to determine textural changes along the core. The PSA sub-samples were then combined for each increment in the soil horizon. The horizon composite was then thoroughly mixed and passed through a No. 10 sieve. Particle size analyses were conducted following methods outlined by the United States Department of Agriculture (USDA) Soil Survey to determine sand, silt, and clay fractions (USDA, 1996).

To estimate the amount and type of aboveground vegetation, groundcover, shrubs, and trees were measured using 1 m^2, 25 m^2, and 100 m^2 nested quadrats, respectively (Hession et al., 2000). Three sets of nested quadrats were measured at each field site. The parameter measured for each vegetation type was chosen based on ease of measurement and the extent to which the measurement would likely reflect belowground biomass.

Groundcover was defined as all herbaceous vegetation and woody vegetation less than 1 m tall. Any groundcover falling within a 1 m^3 volume was clipped to ground level and divided into woody vegetation, grass, and forbs (Bonham, 1989). These sub-samples were then oven-dried at 60°C and weighed to determine dry biomass in kg/ha. Shrub crown volume (m^3/ha, SCV) was measured by estimating the geometric shape of each shrub and then taking the appropriate measurements to calculate the volume (Bryant and Kothmann, 1979; Bonham, 1989). Tree basal stem area (m^2/ha, BSA) was estimated by measuring the largest and smallest diameter of all trees at breast height of 1.4 m (Bonham, 1989; Davidson et al., 1991). Tree diameter was calculated as the geometric mean of the two measurements (Husch et al., 1982). Trees were distinguished from shrubs based on the stem diameter and the general size and shape of the plant. The tree density (stems/ha, TD), as well as the stand BSA were calculated for each site (Van Miegroet et al., 1984). While tree crown volume may better indicate root biomass than BSA, crown volume is difficult to measure and the large measurement error inherent with this parameter would likely offset the theoretical gains in accuracy. Both trees and shrubs were identified to the genus level.

Using K-means cluster analysis, the sites were split into two categories, Forested and Herbaceous, based on aboveground vegetation measurements (Johnson and Wichern, 1992). The aboveground vegetation quantities, the RLD, and the RVR in each depth increment for the two buffer types were compared using the nonparametric Mann-Whitney test, which tests for differences in the sample median (Neave and Worthington, 1988). Changes in RLD over the two-month sampling period were investigated by conducting Theil-Sen nonparametric linear regressions of RLD versus sampling date for the different buffer types, root diameter classes, and depth increments (Theil, 1950; Sen, 1968; Hollander and Wolfe, 1973). Additionally, plots of RLD versus sample date were visually checked to detect any nonlinear temporal trends in RLD.

Multiple linear regression analysis was conducted to determine the influence of aboveground vegetation type and density, site management, and soil texture on RLD and to develop a relationship to predict the RLD in stream banks. If a relationship can be established between RLD and bank erosivity, an equation predicting RLD could ultimately be used in the design of riparian buffers for stream bank stability. Because BSA can be biased by a few large diameter trees, a new variable, "Tree", was calculated as the product of the BSA and the TD. This parameter was then used in the regression analysis instead of BSA or TD. To address problems of heteroscedasticity and nonlinearity, the root and aboveground vegetation data were log-transformed. Zero values were assumed equal to 10^{-6} to eliminate errors resulting from taking the $\log_{10}$ of zero. Additionally, the impact of grazing or mowing on the herbaceous sites was incorporated in the regression analysis using a binary variable called "Managed": grazed or mowed sites were assigned a one and unmanaged sites were assigned a zero. To eliminate problems with multicolinearity, the partial Pearson product moment correlation coefficients were calculated using Minitab. Stepwise multiple linear regression was then conducted using different sets of uncorrelated parameters. Residuals of all significant regressions were visually evaluated for normality and homoscedasticity using normality and residual plots. Where outliers in the aboveground vegetation densities skewed the regression and the data point did represent an unusual value, the point was removed and the regression rerun. Examples of this include site SR3, which had a number of small saplings that produced an unusually high tree density, and site TC6, which was dominated by honeysuckle and created an unusually large woody groundcover biomass.

3.2. Results and Discussion

3.2.1. Aboveground Vegetation and Soils

Vegetation at the sites ranged from intensively managed pasture to mature riparian forest. Typical groundcover species included wingstem (*Verbesina alternifolia*), poison ivy (*Toxicodendron radicans*), jewelweed (*Impatiens capensis*), raspberry (*Rubus* sp.), and mixed cool season grasses. Wild rose (*Rosa* sp.), box elder (*Acer negundo*), and spice bush (*Lindera benzoin*) were common understory shrubs, while trees such as basswood (*Tilia americana*), hickory (*Carya* sp.), locust (*Robinia* sp.), black walnut (*Juglans nigra*), American sycamore

(*Platanus occidentalis*), and buckeye (*Aesculus* sp.) were present at most wooded sites. Aboveground vegetation measurements for each site are presented in Appendix B.

Based on the quantities and types of aboveground vegetation present, 11 sites were classified as Herbaceous and 14 were classified as Forested using K-means cluster analysis. While trees and shrubs were present at some herbaceous sites, they were generally scattered and did not form a full canopy. Measurements of groundcover biomass and shrub crown volume ranged over several orders of magnitude, reflecting both natural variability and errors inherent in vegetation measurement (Table 3.1). Because trees are generally simple to differentiate, measurements of BSA and TD were less variable. Differences in medians between the two buffer types for each aboveground vegetation measurement were significant at $\alpha = 0.05$, except for forbs and woody groundcover. This is not unexpected as even mature forests have understory vegetation. Median grass and total groundcover biomass were significantly greater for the Herbaceous sites at p=0.0001.

Table 3.1. Aboveground vegetation quantities for forested and herbaceous riparian buffers, southwest, Virginia (mean, median, and range, respectively).

Vegetation Type	Statistic	Forbs (kg/ha)	Grass (kg/ha)	Woody Ground-cover (kg/ha)	Shrub Crown Volume (m^3/ha)	Basal Stem Area (m^2/ha)	Tree Density (stems/ ha)
Forested	Mean	541	188	123	3824	39	998
	Median	305	82	83	3358	34	833
	Range	23-1740	3-970	7-413	0-11,000	19-91	333-2530
Herbaceous	Mean	1006	2015	332	409	2	49
	Median	503	2162	237	0	0	0
	Range	77-3210	720-3270	0-2280	0-1160	0-11	0-233

Many of the sites had uniform soil profiles throughout the top one meter depth, although a few sites had a second lower horizon with greater clay content. Soils ranged from clay loam (CL) to loamy sand (LS) and included Chagrin (Fine-loamy, mixed, active, mesic Dystric Fluventic Eutrudepts), Chagrin variant (Sandy, mixed, mesic, Cumulic Haplumbrepts), Comus (Coarse-loamy, mixed, active, mesic Fluventic Dystrudepts), McGary (Fine, mixed, active,

mesic Aeric Epiaqualfs), Ross (Fine-loamy, mixed, superactive, mesic Cumulic Hapludolls), and Weaver (Fine-loamy, mixed, active, mesic Fluvaquentic Eutrudepts). Water table depths ranged from 75 cm to over 1 m. Detailed particle size analysis data are listed in Appendix C.

3.2.2. Root Length Density

Roots were found at all depths at all sites, including below the water table. Total root-length densities (i.e. all roots < 20 mm in diameter) varied from 16 cm/cm^3 in the top 15 cm of an intensively managed pasture to 0.04 cm/cm^3 at a depth of 1 m in a clay loam soil under a forested riparian buffer. This range of root densities is similar to those found under corn and soybeans on a Plano silt loam in Wisconsin (0.2 cm/cm^3 – 24 cm/cm^3: Mamo and Bubenzer, 2001), but as much as two orders of magnitude less than RLDs reported for riparian meadows in the Sierra Nevada mountains (7 cm/cm^3 – 750 cm/cm^3 Kamyab, 1991; 26 cm/cm^3 – 4650 cm/cm^3: Kleinfelder, 1992). For both the herbaceous and forested buffers, the majority of the roots were less than 5 mm in diameter.

There was wide variability in RLD for both riparian buffer types, outliers were common, and the distributions of RLD were typically positively skewed (Figure 3.1). The largest range in RLD was for very fine roots under herbaceous vegetation at a depth of 0-15 cm (1.37 cm/cm^3 - 10.68 cm/cm^3). Root length density under forest cover was less variable. For both buffer types, the variability generally decreased with increasing depth and root diameter. There were very few medium or large roots in either buffer type at any depth; RLD ranged from 0.00 cm/cm^3 to a maximum of 0.05 cm/cm^3 for medium roots under forested vegetation.

The wide range in RLD could be the result of natural variability or errors due to seasonality and sampling location. McGinty (1976) also found large variation in root biomass in managed pine plantations and natural hardwood forests in the Coweeta watershed in North Carolina. In temperate climates, fine roots go through an annual cycle of decay and regrowth, with larger roots being more perennial (Coppin and Richards, 1990). Peaks in root density under trees and grasses have been reported for both spring/early summer and for fall (Tufekcioglu et al., 1999). Other researchers have detected no seasonal changes in root biomass (McGinty, 1976). Visual observation of plots of RLD versus sample date for the two buffer types and for different root diameter classes and depth increments indicated there was little change in RLD over the two-month sampling period.
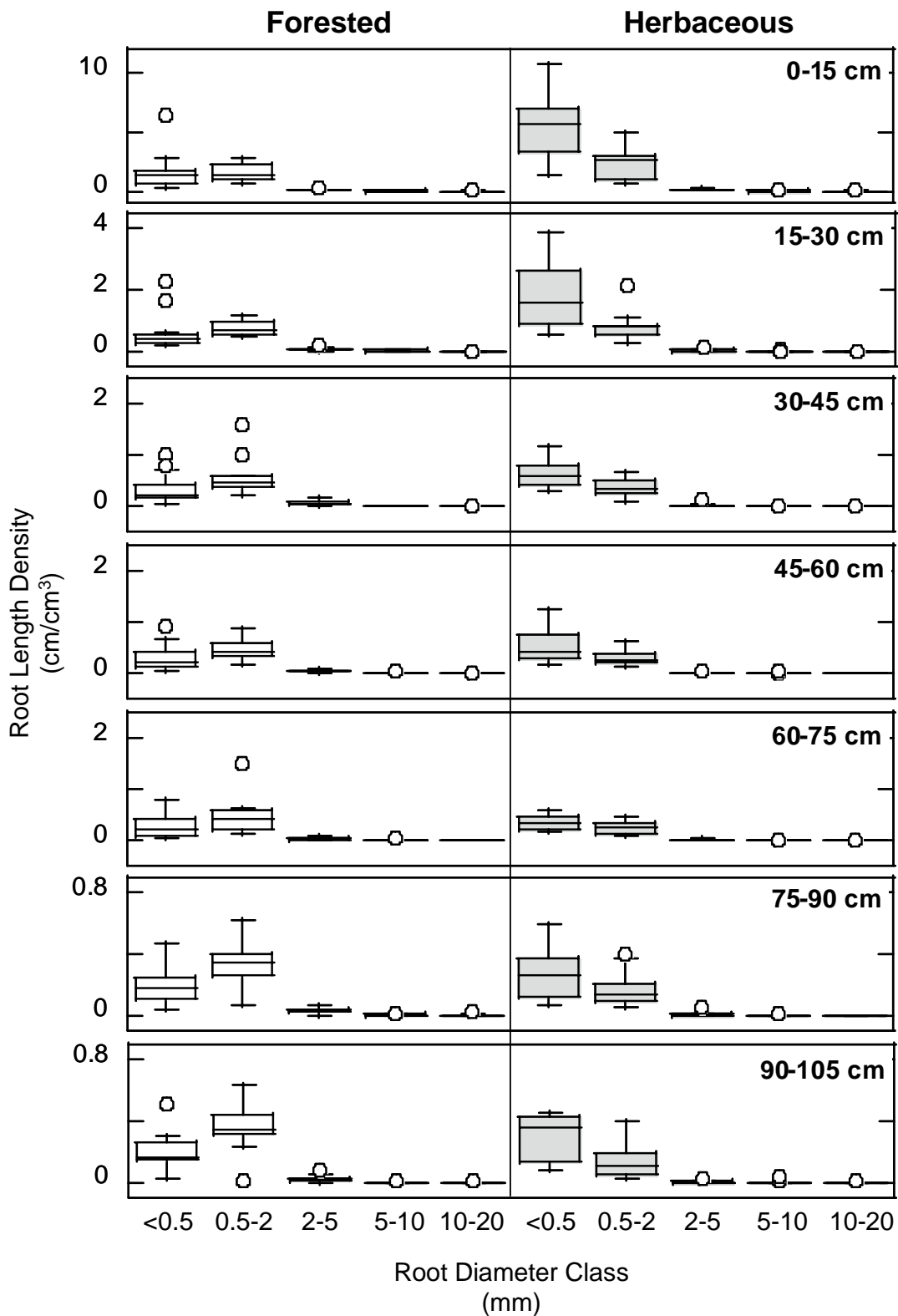
Figure 3.1.   Root length density with depth and diameter class for herbaceous and forested stream banks in southwest Virginia. Upper quartile, median, and lower quartile are shown by the box, while vertical lines indicate the typical range and circles represent statistical outliers.

Nonparametric linear regressions of RLD versus sample date provided little evidence for changes in RLD over the summer; the slopes of 95% of the 144 regression lines were not statistically different from zero ($\alpha = 0.05$). The statistically significant regressions indicate that errors due to seasonal changes in RLD over the course of the sampling period are at most 116%. Considering that total RLD in the study varied over three orders of magnitude and that only 5% of the tested relationships indicated any seasonal differences, it appears errors due to sampling date are relatively insignificant.

The location on the stream banks chosen for core sampling may have also influenced the study results. Soil cores were taken 30 cm from the edge of the top of bank to minimize disturbance of the bank face for future measurements of soil erodibility. To determine if the RLD at 30 cm from the edge of the top of bank was different from that at the bank face, two horizontal cores were taken at two forested and two herbaceous sites (eight cores total). Samples were taken in 15 cm increments to a distance of 105 cm into the bank, at depths of 30 cm and 100 cm from the top of bank.   Results of these investigations indicated there could be a difference in the RLD between the bank face and a core taken normal to the top of bank, 30 cm back from the edge of the top of bank, for sites with dense vegetation growing on the bank face. This difference would likely be most pronounced for gently sloping banks. As illustrated in Figure 3.2 for the horizontal core taken 100 cm from the top of the bank on a bank that was covered with a dense growth of herbaceous vegetation (site EL4, H-V-100), RLD decreased with distance from the bank face. For these sites with dense vegetation growing on the bank face, the RLD at depths greater than 30 cm may be underestimated by as much as an order of magnitude. For the remaining seven horizontal soil cores, no difference in RLD was discernible between soil cores taken at the bank face and those taken deeper in the bank face. Because the soil cores for the vegetated and cut banks were not taken along the same stream reach, the samples from the vegetated banks should not be compared to the samples from the cut banks. Evaluation of these horizontal soil cores suggests the results of this root study may be applicable only for nearly vertical stream banks or stream banks with little vegetation on the bank face. On the other hand, considering that RLD has large variability (Figure 3.1) and that this conclusion is based only on two individual soil cores (as opposed to a sample of several cores for each vegetation and bank type) this limitation should be considered with caution. Further work is needed to determine root density on densely vegetated, gently sloping banks.
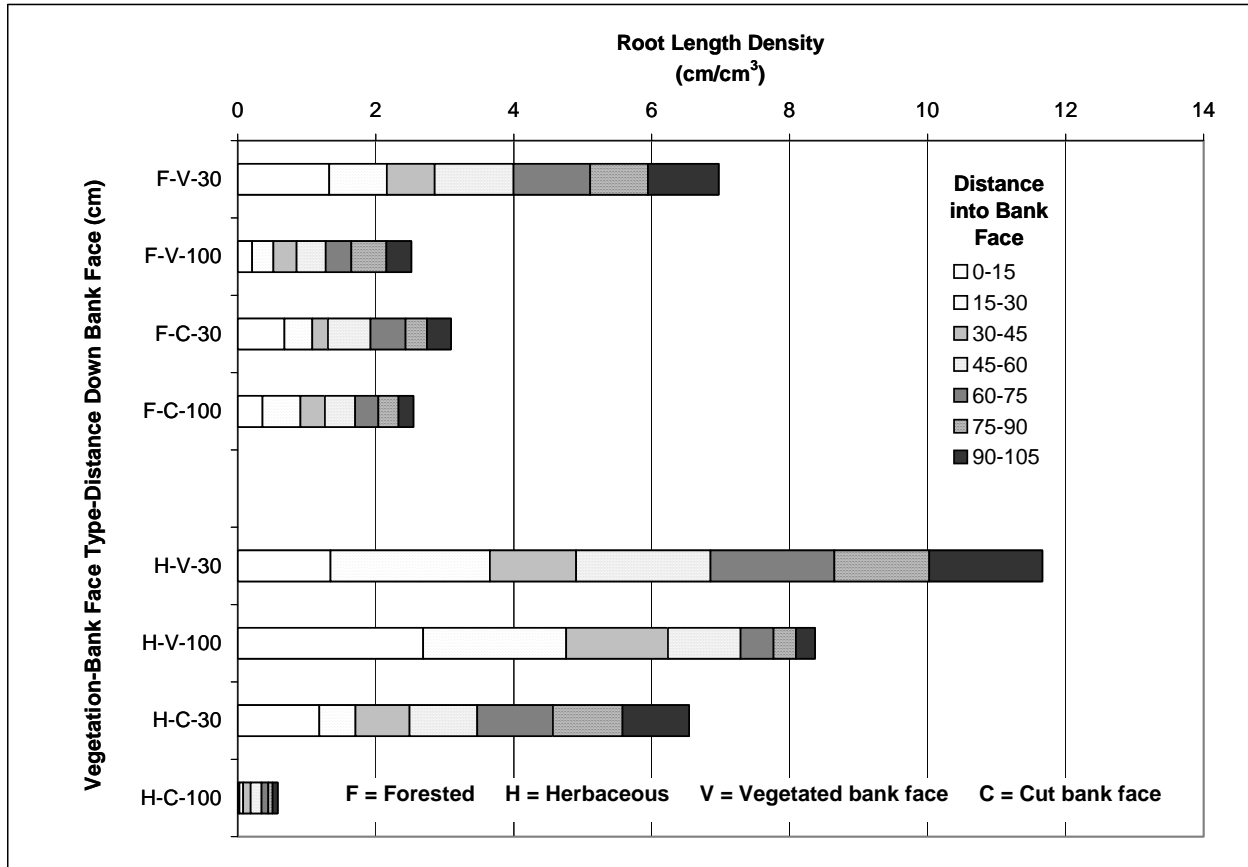
Figure 3.2. Changes in root length density from bank face for herbaceous and woody vegetation on both vegetated and cut stream banks in southwest Virginia.

As would be expected, roots were concentrated in the top of the bank profile (Figure 3.3). Over 55% of the RLD in the forested stream banks was located in the top 30 cm, compared with 75% for the herbaceous vegetation. Roots tend to concentrate in the upper soil horizons because these horizons have higher nutrient and oxygen concentrations and lower bulk densities (McGinty, 1976; Gray and Leiser, 1982; Coppin and Richards, 1990).

The herbaceous buffers had much higher total RLD, as compared to the forested buffers. In the 0-15 cm and 15-30 cm increments, the herbaceous buffers had 2.4 and 1.9 times the root density of the forested buffers, respectively (Figure 3.3). These differences were significant at $p \leq 0.0074$. At depths greater than 30 cm, the distribution of roots was fairly uniform for both buffer types and there were no significant differences in total root densities ($\alpha = 0.05$; Figure 3.3). In their study, Davidson et al. (1991) indicated that roots grew deeper in sandy soils as

compared to clay soils. Shields and Gray (1992) also cited the low moisture content of the sandy
levee soils as a reason for the deep root growth they observed. Similar conditions could have
resulted in the deep herbaceous root growth observed in this study. During the summer of 2002,
the mid-Atlantic US states experienced a major drought. Precipitation was 80% of normal for
the summer and 89% of normal for the previous three-year period (VADEQ, 2002). Very dry
soils and unusually low water table levels were noted during the field sampling. Combined with
the friable loamy soils, these conditions could have promoted deep root growth in the study
stream banks (Holtz, 1983).

Median Root Length Density
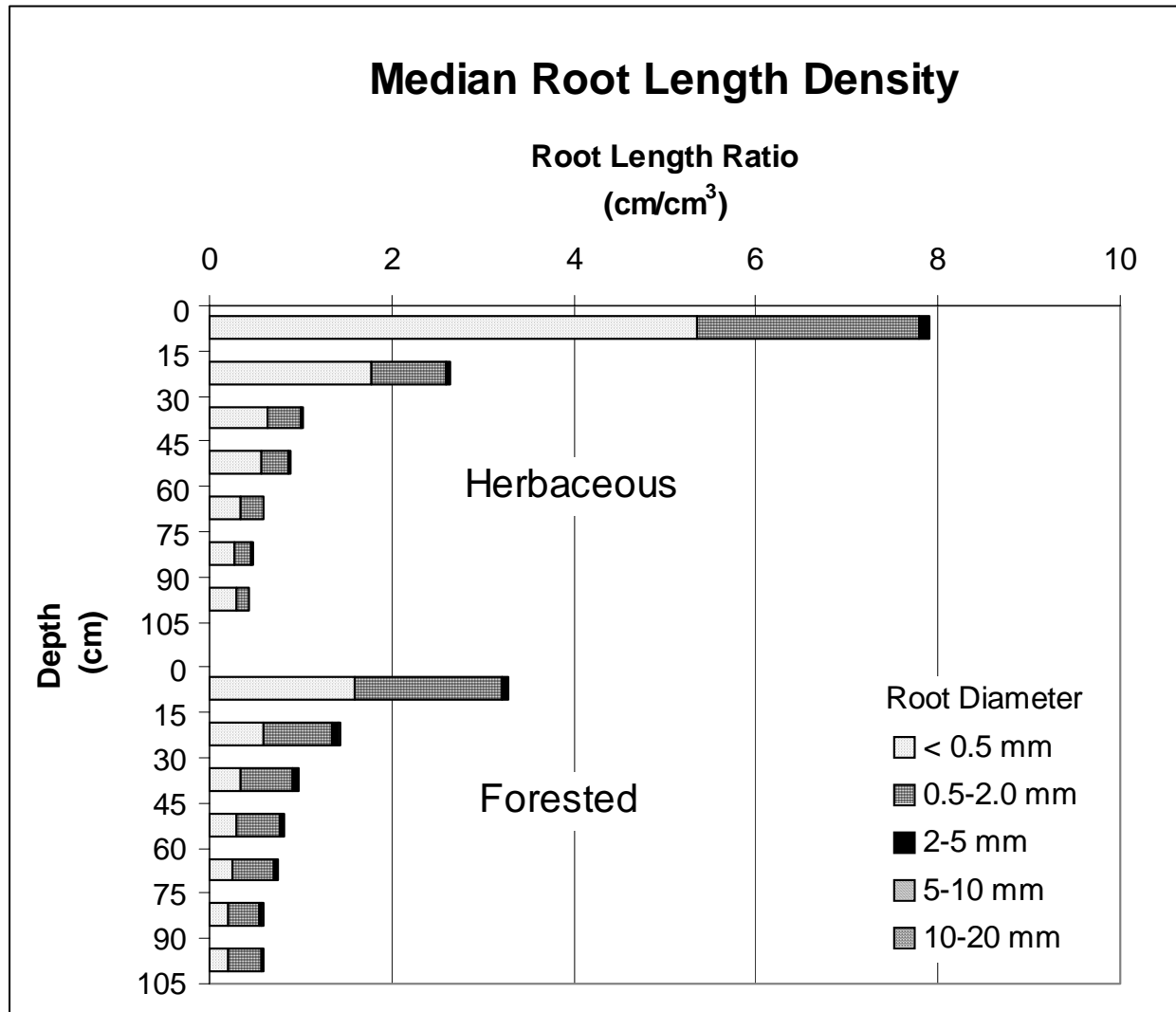
Root Length Ratio
(cm/cm^3)

Figure 3.3. Median root length density with depth for forested and herbaceous riparian buffers,
southwest Virginia.

Table 3.2. Median root length density (RLD) by root diameter and depth for forested and herbaceous riparian buffers in southwest Virginia. Statistically significant differences in median RLD between vegetation types indicated by different letter (α = 0.05). Median RLD for forested buffers shown in italics. Large roots with 10 mm < D < 20 mm not shown due to lack of roots and statistically similar results).

Core Depth Increment (cm)	D < 0.5 mm (cm/cm^3)	0.5 mm < D < 2.0 mm (cm/cm^3)	2 mm < D < 5 mm (cm/cm^3)	5 mm < D < 10 mm (cm/cm^3)	All D < 20 mm (cm/cm^3)
0-15	5.759[a]	2.706[a]	0.076[a]	0.002[a]	8.397[a]
	1.336[b]	*1.427[a]*	*0.056[a]*	*0.003[a]*	*3.073[b]*
15-30	1.573[a]	0.814[a]	0.038[a]	0.000[a]	2.362[a]
	0.389[b]	*0.682[a]*	*0.052[b]*	*0.012[b]*	*1.168[b]*
30-45	0.588[a]	0.345[a]	0.006[a]	0.000[a]	1.038[a]
	0.219[b]	*0.479[b]*	*0.057[b]*	*0.015[b]*	*0.859[a]*
45-60	0.424[a]	0.269[a]	0.005[a]	0.000[a]	0.831[a]
	0.217[b]	*0.410[b]*	*0.048[b]*	*0.007[b]*	*0.772[a]*
60-75	0.353[a]	0.245[a]	0.006[a]	0.000[a]	0.664[a]
	0.214[a]	*0.426[b]*	*0.034[b]*	*0.001[a]*	*0.688[a]*
75-90	0.268[a]	0.138[a]	0.008[a]	0.000[a]	0.460[a]
	0.184[a]	*0.344[b]*	*0.035[b]*	*0.002[b]*	*0.590[a]*
90-105	0.353[a]	0.109[a]	0.001[a]	0.000[a]	0.484[a]
	0.169[a]	*0.342[b]*	*0.019[b]*	*0.000[a]*	*0.593[a]*

Greater differences between the buffer types can be seen by evaluating the distribution of roots by diameter class (Figure 3.3). The herbaceous sites are dominated by very fine roots (diameter < 0.5 mm) at all depths and they have significantly greater very fine RLD than forested sites to a depth of 60 cm ($p < 0.02$). Below 60 cm there is no significant difference in very fine RLD between the vegetation types. For the remaining diameter classes, the forested RLDs were generally greater below 30 cm ($\alpha = 0.05$; Table 3.2).

To evaluate the changes in total RLD with depth, a model in the form of $y = ax^b$ was fit to the data, where y is the total RLD and x is the average increment depth (Sims and Singh, 1978). Using results from the forested sites, $b = -0.68$ ($r^2 = 0.50$, $p = 0.000$), while $b = -1.2$ for the herbaceous sites ($r^2 = 0.75$, $p = 0.000$). These exponents indicate total RLD decreases with depth, but at a greater rate for stream banks with herbaceous vegetation. These results are

similar to those of Shields and Gray (1992) who used root area ratio as the dependent variable and found that b = -1.15 (r^2 = 0.39, p = 0.01) for herbaceous vegetation. The high r^2 for herbaceous vegetation in this study indicates a strong relationship between total RLD and depth. For woody vegetation, Shields and Gray (1992) calculated a lower b, in the range of –0.24 to –0.29 (r^2 < 0.21, p > 0.18). McGinty (1976) reported similar results (b = -0.25, r^2 = 0.99, p not given) for an Appalachian hardwood forest using root biomass. The greater magnitude of the exponent in this study suggests root density in eastern forested riparian buffers is more strongly affected by depth than in a dry sand levee or an upland forest. This could be the result of differences in soil texture or depth to groundwater. Abernethy and Rutherfurd (1998) cited shallow rooting depths as the reason trees along headwater streams are subject to windthrow.

3.2.3. Root Volume Ratio

The root volume ratio was calculated for comparison to other research that evaluated root area ratio (RAR) or root biomass (Davidson et al., 1991; Abernethy and Rutherfurd, 2001; Simon and Collison, 2002). Median RVR for roots < 20 mm in diameter ranged from 0.0009 at 90-105 cm to 0.0215 at 1-15 cm for herbaceous cover and from 0.0037 at 90-105 cm to 0.0179 at 15-30 cm for forested cover (Figure 3.4). While similar RAR values were presented for woody vegetation by some researchers (Greenway et al., 1984; Gray and MacDonald, 1989; Shields and Gray, 1992), they are an order of magnitude greater than those measured by several other researchers (Wu, 1976; Dunaway et al., 1994; Abernethy and Rutherfurd, 2001; Simon and Collison, 2002). These differences in root density may be the result of an imperfect correlation between RVR and RAR and/or variations due to climate, soils, and vegetation type, age, and density.

The results for RVR showed a statistically greater overall root volume (all root diameters < 20 mm) in the forested stream banks at all depths, except in the top 15 cm (Figure 3.4, Table 3.3). While the herbaceous buffers had 59% greater overall root volume in the upper 15 cm of the riparian buffers, this difference was not statistically significant (α = 0.05; Table 3.2). These results differ from those reported by Shields and Gray (1992), who found similar RARs for herbaceous and woody vegetation below 20 cm in sand levees in California. This difference may be the result of drier conditions and greater rooting depths in the sand levees, as compared to the loamy soils and wetter climate of the Appalachian mountains. Summing down the bank face, the

Median Root Volume Ratio
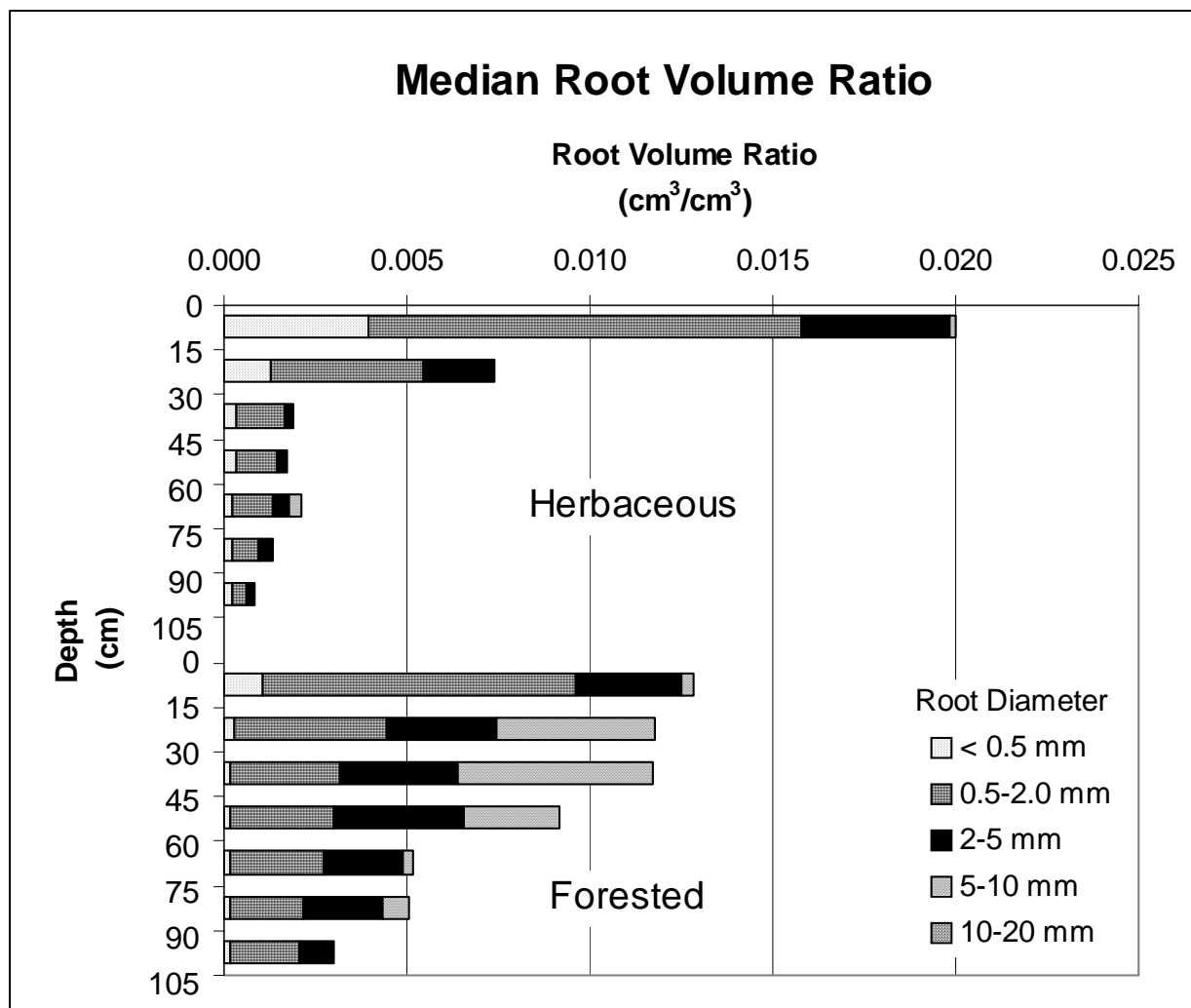
Root Volume Ratio
(cm^3/cm^3)

Figure 3.4. Median root volume ratio with depth for forested and herbaceous riparian buffers in southwest Virginia.

median total RVR for the woody stream banks was twice the RVR for the banks with herbaceous cover. Similar results were noted for root biomass by Davidson et al. (1991).

As with RLD, RVR was concentrated in the upper part of the stream bank. The majority of the root volume, 73%, was in the upper 30 cm of the herbaceous stream banks. In comparison, the upper 30 cm of the forested stream banks contained only 41% of the total forested RVR. The distribution of RVR with depth was much more uniform for the wooded sites. These results are similar to findings by other researchers. Simon and Collison (2002) reported a relatively even distribution of RAR for sycamore (*Platanus occidentalis*), which is found in this study area. Davidson et al. (1991) found 74% of the tree root biomass and 79% of

the herbaceous root biomass in the top 20 cm of red clay soils in northwestern Wisconsin and east-central Minnesota. Shields and Gray (1992) reported that 43% of the total root area was located in the top 30 cm for woody vegetation, although only 50% of the herbaceous RAR was located in the top 30 cm. As noted previously, these differences are likely due to variations in soil type and climate.

Table 3.3. Median root volume ratio (RVR, %) by root diameter and depth for forested and herbaceous riparian buffers in southwest Virginia. Statistically significant differences in median percent RVR between vegetation types indicated by different letter ($\alpha = 0.05$). Median percent RVR for forested buffers shown in italics. Large roots with 10 mm < D < 20 mm not shown due to lack of roots and statistically similar results).

Core Depth Increment (cm)	D < 0.5 mm (%)	0.5 mm < D < 2.0 mm (%)	2 mm < D < 5 mm (%)	5 mm < D < 10 mm (%)	All D < 20 mm (%)
0-15	0.395[a]	1.184[a]	0.405[a]	0.016[a]	2.148[a]
	0.108[b]	*0.854[a]*	*0.288[a]*	*0.033[a]*	*1.352[a]*
15-30	0.127[a]	0.416[a]	0.199[a]	0.000[a]	0.695[a]
	0.029[b]	*0.418[a]*	*0.297[b]*	*0.435[b]*	*1.792[b]*
30-45	0.036[a]	0.129[a]	0.026[a]	0.000[a]	0.306[a]
	0.018[b]	*0.299[b]*	*0.323[b]*	*0.529[b]*	*1.272[b]*
45-60	0.035[a]	0.108[a]	0.027[a]	0.000[a]	0.217[a]
	0.018[b]	*0.285[b]*	*0.351[b]*	*0.265[b]*	*1.061[b]*
60-75	0.020[a]	0.115[a]	0.041[a]	0.034[a]	0.339[a]
	0.014[b]	*0.260[b]*	*0.213[b]*	*0.030[a]*	*1.131[b]*
75-90	0.023[a]	0.071[a]	0.037[a]	0.000[a]	0.119[a]
	0.014[a]	*0.201[b]*	*0.220[b]*	*0.072[b]*	*0.686[b]*
90-105	0.023[a]	0.040[a]	0.018[a]	0.000[a]	0.092[a]
	0.016[a]	*0.192[b]*	*0.093[b]*	*0.000[a]*	*0.371[b]*

Unlike RLD, the distribution of RVR across the diameter classes was dominated by the fine and small diameter roots. The RVR under both vegetation types was dominated by fine roots (0.5 mm < D < 2.0 mm), representing 33% and 53% of the total median RVR for the forested and herbaceous sites, respectively. Similar results were reported by Simon and Collison

(2002) for herbaceous vegetation, although roots greater than 5 mm in diameter accounted for much of the woody RAR. This may be because roots with diameters less than 1 mm are difficult to detect and darker woody roots that are similar in color to the upper soil horizons may be missed with the profile wall method. Comparing RVR for the two buffer types in each diameter class with depth, the herbaceous buffers had significantly greater very fine root volume (D < 0.5 mm) in the upper 60 cm, while the forested buffers had significantly greater volumes of fine and small roots below 30 cm (0.5 mm < D < 5 mm, $\alpha = 0.05$).

3.2.4. Regression Analysis

Analysis of Kendall's tau revealed that several aboveground vegetation parameters were correlated. Basal stem area was positively correlated with other measures of woody vegetation, including SCV ($\tau = 0.46$, approx. p = 0.0014) and TD ($\tau = 0.65$, approx. p = 0.0000). In contrast, a dominance of trees was inversely related to measures of groundcover: BSA was negatively correlated with both grass biomass and total groundcover biomass ($\tau = -0.59$, approx. p = 0.0000; $\tau = -0.51$, approx. p = 0.0004, respectively). Similar, stronger correlations were found between grass and total groundcover biomass and TD ($\tau = -0.70$, approx. p = 0.0000; $\tau = -0.64$, approx. p = 0.0000, respectively). Similarly, SCV is positively correlated to TD ($\tau = 0.43$, approx. p= 0.0024) and negatively correlated to overall groundcover ($\tau = -0.52$, approx. p =0.0003). These results are unsurprising since eastern US forested riparian buffers are often composed of a tree canopy with a shrub and sapling understory. Additionally, grass and other groundcovers would not be present in large quantities under the shade of a mature forest (Coppin and Richards, 1990). There was also some positive correlation between total groundcover and forbs ($\tau = 0.49$, approx. p = 0.0007) and total groundcover and grass ($\tau = -0.62$, approx. p = 0.0000). This positive correlation shows the general dominance of grasses and forbs over woody groundcover at the sites.

Stepwise multiple linear regressions were conducted for both RLD and RVR at the seven depth increments for the five diameter classes. Statistically significant regressions are presented in Tables 3.4 and 3.5 for RLD and RVR, respectively; the slopes were statistically significant at α=0.05. Coefficients of determination (r^2) ranged from 0.181 for fine RVR at depths of 90-105 cm to 0.598 for fine RVR at depths of 75 – 90 cm. McGinty (1976) evaluated the impact of 17 soil and vegetation parameters on root biomass in the top 30 cm of soil under a hardwood forest

and found that no single parameter could attribute for more than 16% of the total variability in root biomass. While results of this study indicate aboveground vegetation types and densities are significant in explaining root density, other factors, such as soil bulk density, moisture content, and nutrients, may play a major role in the growth and distribution of roots in stream banks (Gray and Leiser, 1982; Coppin and Richards, 1990; Abernethy and Rutherfurd, 2000). McGinty (1976) believed the local soil and climatic conditions around each sample had the greatest influence on root biomass (D < 25 mm). Results from this study suggest aboveground vegetation type and density will provide a rough estimate of root density in stream banks, but the accuracy of this prediction could likely be improved with further study.

Table 3.4. Root length density regression equations for Appalachian headwater stream banks with forested and herbaceous riparian buffers: slopes significant at $\alpha = 0.05$.

Root Diameter Class (mm)	Depth Increment (cm)	Root Length Density Regression Equation*	Equation p-value	r^2
< 0.5	0-15	16.5 + 0.0162 Grass	0.000	0.420
< 0.5	15-30	4.63 + 0.00664 Grass	0.000	0.527
< 0.5	30-45	3.36 + 0.00145 Grass	0.007	0.275
< 0.5	45-60	-1.93 + 0.00146 Grass + 0.0782 %Sand	0.004	0.394
< 0.5	90-105	0.06 + 0.0411 %Sand	0.048	0.181
0.5 - 2.0	45-60	2.72 +0.000383 SCV + 0.00165 WGC	0.003	0.415
0.5 - 2.0	60-75	2.27 +0.000558 SCV	0.002	0.351
0.5 - 2.0	75-90	1.87 + 0.00139 TD	0.003	0.330
log(0.5 - 2.0)	90-105	0.860 - 0.000171 TGC - 0.0261 %Clay	0.002	0.477
2 - 5	30-45	0.639 - 0.000183 Grass	0.019	0.215
2 - 5	30-45	0.210 + 0.0122 BSA	0.013	0.250
2 - 5	45-60	0.144 + 0.00752 BSA	0.002	0.343
2 - 5	60-75	0.102 + 0.000330 TD	0.001	0.377
2 - 5	75-90	0.125 + 0.000240 TD	0.004	0.328
2 - 5	90-105	0.0354 + 0.00613 BSA	0.003	0.372
5 - 10	30-45	0.0266 + 0.00214 BSA	0.003	0.326
10 - 20	60-75	0.0076 + 0.000049 TD	0.010	0.253
< 20	0-15	33.0 + 0.0204 Grass	0.002	0.359
< 20	15-30	12.5 + 0.00720 Grass	0.001	0.400
< 20	60-75	7.27 + 0.000778 SCV - 0.233 %Clay	0.008	0.356

* Grass = dry grass biomass in kg/ha; %Sand = soil sand content; SCV = shrub crown volume in m^3/ha; WGC = dry woody groundcover biomass in kg/ha; TD = tree density in stems/ha; TGC = total dry groundcover biomass in kg/ha; BSA = tree basal stem area in m^2/ha; and %Clay = soil clay content. Root length density in mm/cm^3.

For both RLD and RVR, the quantity of very fine roots (D < 0.5 mm) in the soil was best predicted by the quantity of grass present in the riparian buffer (Tables 3.4 and 3.5). This influence decreased with increasing depth, as indicated by the decreasing slopes of the regression equations with depth (Tables 3.4 and 3.5). At depths greater than 60 cm, increased very fine RLD was also associated with increases in the percentage of sand in the soil. Dunaway et al. (1994) also determined a weak positive relationship between root volume ratio and the percent sand ($r^2 = 0.28$) for wet meadows in the Sierra Nevada Mountains. Higher percentages of sand in the lower soil horizons would likely create drier, less restrictive growing conditions, thus encouraging deeper growth of very fine roots. At depths greater than 30 cm, roots with diameters of 0.5 – 5.0 mm were positively correlated to woody vegetation parameters (SCV, BSA, or TD) and negatively correlated to groundcover biomass (grass or total groundcover) and the soil clay content (depths of 90-105 cm). These results reinforce the findings that, below 30 cm, woody riparian vegetation produces greater quantities of larger diameter roots. Also, increases in clay content restrict root growth. No statistically significant relationships were found for roots with diameters greater than 0.5 mm at shallow depths (< 30 cm), suggesting multiple factors influence root growth near the soil surface. Few significant relationships were developed for medium and large roots because many sites had no roots larger than 5 mm in diameter. Considering all root diameters, grass biomass best predicted total RLD in the top 30 cm of the stream bank. At depths greater than 30 cm, increases in total RLD and total RVR were associated with increased woody vegetation (SCV, BSA, or TD) and decreased grass biomass (Tables 3.4 and 3.5). Increases in clay content at a depth of 60-75 cm appeared to decrease total RLD. The large relative variability in SCV and forb and woody groundcover biomass could have prevented the development of meaningful relationships between these parameters and root density.

3.2.5. *Implications for Stream Bank Stability*

The results of this study have implications for the management of riparian areas for stream bank stabilization. As discussed in the introduction section, soil erodibility is strongly affected by root density. In a laboratory study of meadow soil erodibility, Kamyab (1991) found

Table 3.5. Root volume ratio regression equations for Appalachian headwater stream banks with forested and herbaceous riparian buffers: slopes significant at $\alpha = 0.05$.

Root Diameter Class (mm)	Depth Increment (cm)	Root Volume Ratio Regression Equation*	Equation p-value	r^2
< 0.5	0-15	1272 + 1.03 Grass	0.001	0.380
< 0.5	15-30	360 + 0.423 Grass	0.000	0.443
< 0.5	30-45	231 + 0.113 Grass	0.006	0.301
< 0.5	45-60	211 + 0.0906 Grass	0.020	0.224
ln(0.5 – 2.0)	30-45	8.26 - 0.000280 TGC	0.001	0.395
ln(0.5 – 2.0)	45-60	8.00 - 0.000389 Grass	0.001	0.418
0.5 – 2.0	75-90	769 + 1.31 TD	0.000	0.598
0.5 – 2.0	90-105	606 + 33.3 BSA	0.000	0.503
ln(2 – 5)	30-45	8.14 - 0.000937 Grass	0.001	0.429
2 – 5	45-60	1048 + 2.14 TD	0.001	0.401
[1+(2 – 5)]^0.5	60-75	21.2 + 0.0272 TD	0.002	0.366
2 – 5	75-90	707 + 34.4 BSA	0.024	0.221
ln[1+(2 – 5)]	90-105	8.07 - 0.00134 TGC	0.000	0.501
5 – 10	30-45	992 + 77.1 BSA	0.007	0.284
ln(< 20)	30-45	8.15 + 0.0296 BSA	0.001	0.406
ln(< 20)	45-60	9.22 – 0.000608 Grass	0.003	0.331
log(< 20)	75-90	3.20 + 0.0132 BSA	0.008	0.292

* Grass = dry grass biomass in kg/ha; TGC = total dry groundcover biomass in kg/ha; SCV = shrub crown volume in m^3/ha; TD = tree density in stems/ha; BSA = tree basal stem area in m^2/ha. Root volume ratio in cm^3/m^3.

soil erodibility was most significantly influenced by the fine RLD. While the herbaceous buffers in this study had a much greater total RLD than the forested buffers, the roots were largely composed of very fine roots concentrated in the upper 30 cm of the stream bank. Within a stream channel, hydraulic shear stress is a function of depth; the greatest shear stresses are applied to the bank toe. At depths greater than 30 cm, the forested sites had significantly greater fine and small RLD than herbaceous sites ($p < 0.03$; Table 3.2). Additionally, overall root volume for diameters less than 20 mm was significantly greater below 15 cm depth for the forested sites. This indicates that while forested stream banks have a lower overall root length density, the density and volume of fine and small roots is higher where the greatest hydraulic stresses are applied. Thus, for nearly vertical banks (those without significant vegetation growth

on the bank face), woody vegetation may provide better protection against scour of the bank toe. This finding is particularly applicable for meandering streams where the region of highest shear stress, the outside of meander bends, is typically very steep and has little herbaceous vegetation on the bank face. Additionally, considering that previous research showed root tensile strength (N/m^2) decreases with increasing root diameter, and that bank failure typically occurs low in the bank profile, these results suggest that woody vegetation also provides greater geotechnical reinforcement of stream banks (Greenway et al., 1984; Abernethy and Rutherfurd, 2001; Simon and Collison, 2002).

While the results of this root study are not applicable to gently sloping stream banks with dense herbaceous vegetation, due to the sampling methodology, these type of banks typically only occur on the inside of meander bends where the shear stress is lower. The stream bank form of greatest concern are nearly vertical banks on the outside of meander bends where the shear stress is high and vegetation density on the bank face is low.

3.3. Summary and Conclusions

Measurements of RLD and RVR varied greatly among the sites. In general, RLD decreased with increasing depth and root diameter. Over 55% and 75% of the total RLD and 41% and 73% of the RVR were concentrated in the top 30 cm of the stream bank for forested and herbaceous buffers, respectively. Herbaceous sites had significantly greater total RLD in the top 30 cm than the forested sites ($\alpha = 0.05$). At depths greater than 30 cm, there was no significant difference in total RLD. The forested sites had significantly greater total RVR below 15 cm. There were also differences in the distribution of roots by diameter class. The herbaceous sites were dominated by very fine roots, while the forested sites had a greater quantity of fine roots.

Results of the regression analysis indicate the quantity of grass in the riparian buffer strongly influences the density of very fine roots in the top 30 cm of the stream bank. At depths greater than 30 cm, the quantity of roots with diameters greater than 0.5 mm is significantly influenced by the amount of woody vegetation present in the riparian buffer. These findings

reinforce the conclusion that woody vegetation produces significantly greater root length and volume in stream banks below depths of 30 cm.

In the top 30 cm of the bank face, there were no significant differences in RLD for roots greater than 0.5 mm in diameter ($\alpha = 0.05$) between the buffer types, while at depths greater than 30 cm, the forested sites had significantly greater ($\alpha = 0.01$) fine, small, and medium RLD than the herbaceous sites. This finding has significant implication for the use of vegetation in stream bank stabilization. Research by Kamyab (1991) indicated soil erosion was strongly influenced by the quantity of fine roots present. While the herbaceous buffers in this study had a much greater total RLD than the forested buffers, the roots were largely composed of very fine roots that provide less reinforcement against stream bank erosion than the larger diameter roots. This finding suggests that woody vegetation provides equal or greater reinforcement of stream banks at all depths, as compared to herbaceous vegetation. For stream banks greater than 30 cm, streamside forests likely provide greater erosion resistance than herbaceous vegetation. While the herbaceous roots had a greater overall RLD, the roots were concentrated in the upper 30 cm of the stream bank. Within a stream channel, hydraulic shear stress is a function of depth; the greatest shear stresses are applied to the bank toe. At depths greater than 30 cm, the forested sites had significantly greater fine and small RLD than herbaceous sites ($p < 0.03$). Additionally, overall root volume for diameters less than 20 mm was significantly greater below 15 cm depth for the forested sites. This indicates that while forested stream banks have a lower overall root length density, the density and volume of roots with diameters greater than 0.5 mm is higher where the greatest hydraulic stresses are applied. Thus, for nearly vertical banks in excess of 30 cm (those without significant vegetation growth on the bank face), woody vegetation may provide better protection against scour of the bank toe. This finding is particularly applicable for meandering streams where the region of highest shear stress, the outside of meander bends, is typically very steep and there is little herbaceous vegetation on the bank face.

Further study on the effects of root density on stream bank erodibility is necessary. Given the large variability in root density found in this and other studies, future studies should include a large number of root samples taken at the bank face. Results based on a few samples or limited areas may be misleading and may not be applicable beyond the localized environment (McGinty, 1976). The results of this study also illustrate the differences resulting from

measurements based on root length versus root volume or root area. Comparing Figures 3.2 and 3.3, it is evident that root volume measurements are biased by larger roots. For studies where the density of roots in the soil is important, RLD will more accurately represent the overall fiber content than RVR.

Chapter 4. Riparian Vegetation Effects on Freeze-Thaw Cycling and Desiccation of Stream Bank Soils

The overall goal of this research is to compare the effects of woody and herbaceous vegetation on stream bank erosion. This chapter presents the second of three substudies that address the impact of vegetation on stream bank erosion. Subaerial processes, such as freeze-thaw cycling and desiccation cracking reduce soil strength by decreasing soil structures. Researchers have suggested this structural damage leads to an increase in soil erodibility (Wolman, 1959; Lawler, 1993).   Because vegetation affects soil properties and local microclimates, it has direct, but multidimensional impacts on subaerial processes. The goal of this study was to quantify the effect of vegetation on freeze-thaw and desiccation activity in stream bank soils.

4.1. Methods

4.1.1. Paired Reach Evaluations

To evaluate the effects of riparian vegetation type on subaerial processes, six of the twenty-five field sites were paired (Table 4.1). Each field site consisted of a 2nd-3rd order stream with alluvial banks and a relatively homogeneous vegetated riparian buffer over a reach of at least 30 stream-meters. The three sets of paired sites (six sites total) included one herbaceous riparian buffer and one forested buffer in close proximity along the same stream with a similar aspect and soil type. Pictures of the paired sites are in Appendix E. Aboveground vegetation was measured using nested quadrats as described in Chapter 3 and these parameters are summarized in Table 4.1 for each paired site.

Soil temperature and soil water potential (SWP) were measured every 30 minutes for one year starting in May 2002. Soil temperature was measured using Campbell Scientific 107 probes (-35°C to +50°C, ± 0.7^{o}C), while Watermark 200 sensors were used to measure SWP (0 kPa to 200 kPa, ± 3 kPa). Six sets of ST and SWP probes were installed 1 cm deep in the bank face at each site and data were recorded using a Campbell Scientific CR10X datalogger and AM416 multiplexer in a weather-proof enclosure (Figures 4.1-4.2). Three sensor sets were installed in the upper bank, 30-45 cm from the top of the bank, at a horizontal spacing of approximately 1m.

Table 4.1. Characteristics of paired field sites.

Site Name	EL3	EL4	SC6	SC7	TC1	TC2
River or stream	East Fork of the Little River	East Fork of the Little River	Sinking Creek	Sinking Creek	Tom's Creek	Tom's Creek
Latitude/Longitude	N 36° 58.347' W 80° 18.940'	N 36° 58.335' W 80° 18.985'	N 37° 18.425' W 80° 30.132'	N 37° 18.566' W 80° 30.327'	N 37° 14.550' W 80° 27.912'	N 37° 14.289' W 80° 28.374'
Stream Order	3	3	3	3	2	2
Watershed Area (km^2)	240	240	165	165	35	35
Buffer Type	Forested	Herbaceous	Herbaceous	Forested	Herbaceous	Forested
Basal Stem Area (m^2/ha)	53	0	3	60	0	39
Tree Density (stems/ha)	600	0	67	933	0	933
Shrub Crown Volume (m^3/ha)	501	0	601	6260	0	1261
Forbs (kg/ha)	1027	137	3213	597	2250	563
Grass (kg/ha)	217	3257	720	180	2162	47
Woody Groundcover (kg/ha)	227	280	237	190	0	73
Soil Texture[+]	LS	LS	SL	SL	SiL	SL
Soil Series	Comus	Comus	Chagrin	Chagrin	Weaver	Weaver
Bank Exposure (m)	2.3	2.1	1.5	1.7	1.3	0.9
Aspect (^{o}E of true N)	178°	178°	113°	68°	15°	72°
Bank Angle	55°	55°	35°	50°	90° upper 30 cm 45° lower bank	40o
Elevation (m NGVD29*)	655	655	558	552	579	576

[+] LS = Loamy sand, SL = Sandy loam, SiL = Silty Loam

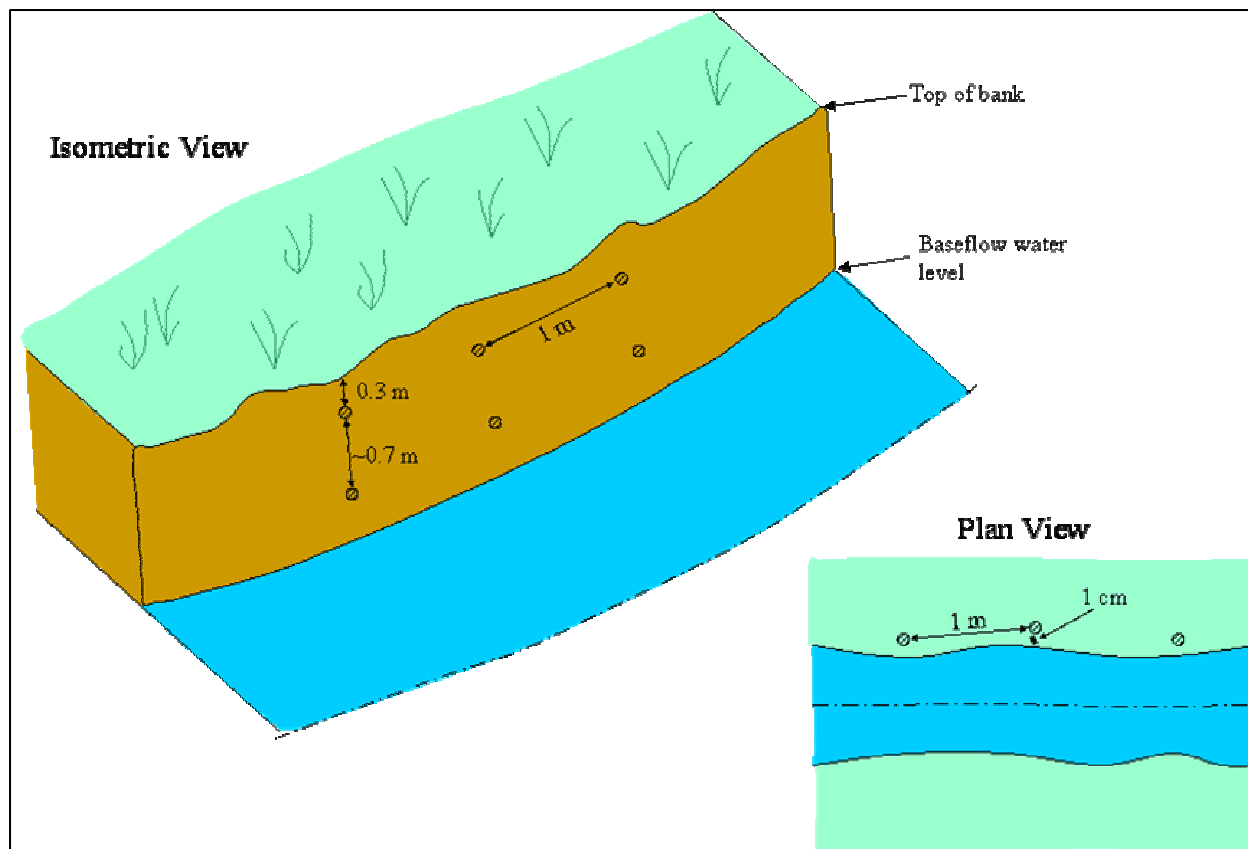* US National Geodetic Vertical D atum of 1929

Figure 4.1. Soil temperature and water potential sensor placement in stream banks.

Three sensors sets were also placed in the lower bank at distances of 70-100 cm from the top of bank. Sensor location and spacing at each site depended on the specific bank height and angle, locations of distinct soil horizons, and other site-specific considerations (Table 4.1).

Air temperature and precipitation were also measured. Air temperature was measured at each forested site using a thermocouple and a reference temperature thermister, while precipitation was measured at each herbaceous site with a tipping bucket rain gage. Due to mechanical problems with the rain gages due to birds and spider webs, little accurate precipitation data was collected. Weather data was also available from the National Weather Service in Blacksburg and the Virginia Tech Kentland research farm at Whitethorne, Virginia.

To determine the effects of vegetation type on stream bank temperature and moisture regimes, two data periods were analyzed. Data from June through August were used to evaluate summer conditions (92 days total), while data from December through February were used to

Figure 4.2. Installation of site SC6.

represent winter conditions. Due to a major flooding event on February 22, 2003 that damaged the monitoring equipment at several sites, the winter record does not contain data for the last week of February. Additionally, gaps in the winter record for each site exist where sensors were exposed by frost heave or bank scour during floods. The total length of the winter soil temperature record is 62 days. In addition to problems with sensor exposure, the Watermark soil water potential sensors ceased functioning once the sensors froze. As a result of frozen sensors and sensor exposure, only two time periods were available to evaluate winter soil water potential: 12/12/02 through 12/25/02 and 12/31/02 through 1/6/03.

Soil temperature and SWP measurements from the three sets of sensors were averaged for each 30 minute reading for the upper and lower banks at each site. These were then used to determine daily minimum and maximum ST, daily ST range, and average daily SWP. Soil water

potential readings greater than the wilting point (150 kPa) were considered indicative of "dry" conditions (Brady, 1984). The number of 30-minute periods that the stream banks had a SWP above 150 kPa were summed and the total amount of time the stream banks were "dry" was calculated.

Before the number of freeze-thaw cycles (FTC) could be calculated, the freezing point for the soil pore water was determined. Because the soil pore water is not pure water, the freezing point is less than zero. The freezing point depression for water can be determined using the following equation:

$$\Delta T = -K_f m \qquad\qquad 4.1$$

where ΔT is the change in the freezing point of the solution, K_f is a constant equal to 1.86 K·kg/mol for water and m is the solution molality (mol/kg). Considering water has a density of 1 g/cm^3, molarity (mol/l, M) can be used instead of molality for aqueous solutions. Assuming a typical soil salt concentration of 0.01 M, the expected freezing point for soil pore water would be approximately -0.02°C (Peach, 1965). Major soluble soil cations (K^+, Ca^{2+}, Mg^{2+}, Na^+) were measured during the jet test study (Chapter 5) and average soil salt concentrations were 0.005 M, which would produce a 0.01°C depression of the freezing point. In a laboratory study of needle ice formation, Branson et al. (1996) placed soil temperature and moisture sensors on the surface of intact soil blocks and at depths of 1, 3, 5 and 10 cm. They noted that soil heave resulting from ice formation commenced when the soil temperature reached -1.5°C. The environmental conditions were stabilized to maintain the freezing front at the soil surface. Under these conditions the soil temperature at 1 cm depth remained just above zero and did not decrease until the freezing was intensified and the freezing front moved into the soil mass. Ultimately, the soil temperature indicative of ice formation at the soil surface is a function of sensor accuracy, soil salt and moisture content, and sensor depth in the bank face. Considering the factors discussed above and that the accuracy of the 107 probes is ± 0.7°C, it is likely that ice formation occurred in the surface soil whenever the temperature readings at a depth of 1 cm were in the range of -1.5 °C to 0.7°C.

To determine the actual freezing point for each sensor, a histogram of temperatures recorded around zero was constructed. Based on the premise that the soil temperature would remain constant throughout the freezing process, it was assumed that the temperature near 0^oC that was most frequently recorded was the actual freezing point of the surface soil. Additionally, each temperature time series was plotted to confirm the results from the histograms. Extended periods of constant temperature near zero were considered indicative of soil freezing at the bank surface. Using the determined freezing point for each temperature time series, the number of FTC and the total, average, and median freezing durations were calculated.

Because the data were strongly serially correlated, standard statistical comparisons could not be made. Instead, ST values from each herbaceous buffer were plotted versus the corresponding values from the forested buffer for both summer and winter. Linear regression analyses were conducted using the nonparametric Theil-Sen method (Theil, 1950; Sen, 1968; Hollander and Wolfe, 1973) and compared to lines with a 1:1 or 45% slope. Statistically significant differences between the calculated slopes were determined using the Mann-Whitney test (Neave and Worthington, 1988), while the Wilcoxon Signed Rank Test was used to determine if the regression slopes were significantly different from 1.0 (Wilcoxon, 1945; Hodges and Lehmann, 1963; Daniel, 1990).

4.1.2. Freeze-Thaw Cycling Analysis

At the remaining 19 field sites ST was measured using Onset TMC50-HA water/soil temperature sensors (-40^oC to $+100^oC$, $\pm0.5°$ at 20°C) connected to a HOBO® H8 Outdoor/Industrial 4-Channel External Logger. Soil temperature readings were recorded every 30 minutes for one year starting in May 2002. One sensor was installed in the upper bank, 30-45 cm from the top of the bank, and a second sensor was placed in the lower bank at distances of 53-150 cm from the top of bank. Sensor location at each site depended on the specific bank height and angle, locations of distinct soil horizons, and other site-specific considerations.

The freezing point for each sensor was determined using the methods described above and the number of FTC and the total, average, and median durations frozen (TDF, ADF, MDF, respectively) were calculated for each sensor with a complete data record during the period of 12/1/02 to 2/20/03. The relative effect of aboveground vegetation densities and site physical characteristics on each of these parameters was investigated using regression analysis. The site

characteristics considered were site elevation, bank angle, bank aspect, average stream width and depth at baseflow, bank exposure, the sensor distance from baseflow water levels, soil texture, and average soil organic carbon content. Bank aspect was expressed as the absolute value of the degrees from north: banks facing due east and due west had the same values as they theoretically received similar quantities of solar radiation with only a difference in timing.

Average soil organic carbon was determined for the upper and lower stream banks as part of the jet test study to be described in Chapter 5. A soil sample was taken for each jet test (2-4 per site, depending on site conditions). The soil samples were air dried and analyzed for organic carbon using the Walkley-Black method (Walkley and Black, 1934; Jackson, 1958; Allison, 1965).

The independent variables were normalized by subtracting the mean and dividing by the standard deviation. Because both the upper and lower sensor at each site had the same values for aboveground vegetation densities, the data were split into upper and lower bank sets and stepwise regression was conducted using Minitab. The residuals were visually assessed for independence and normality; multicolinearity was evaluated using variance inflation factors (VIF; Montgomery and Peck, 1982). In cases where a single independent variable was found to be significant, the regression analysis was repeated using the nonparametric Theil-Sen method to confirm the relationship (Theil, 1950; Sen, 1968; Hollander and Wolfe, 1973). Where outliers in the aboveground vegetation densities skewed the regression and the data point did represent an unusual value, the point was removed and the regression rerun. Examples of this include site SR3, which had a number of small saplings that produced an unusually high tree density, and site TC6, which was dominated by honeysuckle and created an unusually large woody groundcover biomass (WGC).

To confirm and reevaluate the analysis of stream bank freezing, principal components analysis (PCA) was applied to the four dependent parameters using Minitab. The variances explained by the resulting axis scores were evaluated using Jackson's (1993) broken stick model (as discussed in Shaw, 2003). Those axes that explained significant amounts of variation were examined to determine the underlying physical significance of the axis. If a physical basis for the axis scores could be determined, regression analysis was conducted using the axis scores as the dependant variable, following the procedures described above.

4.1.3. Vertical Variations in Subaerial Processes

Differences in summer soil water potential and winter freezing between the upper and lower banks were evaluated. At each of the paired sites, the median difference in daily SWP between the upper and lower banks over the summer was calculated. For each of the 25 sites with a sufficient data record, the differences in the number of FTC and the total, average, and median durations frozen between the upper and lower banks were calculated. The Wilcoxon Signed Rank Test was used to test if the differences were significantly greater than zero (Wilcoxon, 1945; Hodges and Lehmann, 1963; Daniel, 1990).

4.2. Results and Discussion

Monthly precipitation and minimum and maximum air temperatures for Blacksburg, Virginia are plotted in Figure 4.3. During the summer of 2002, the mid-Atlantic US states experienced a major drought. Precipitation was 80% of normal for the summer and 89% of normal for the previous three-year period (VADEQ, 2002). The winter was typical for the region, with periods of several days when air temperatures remained below freezing.

The impacts of soil desiccation was observed at several sites throughout the summer, particularly on stream banks without vegetation. Figure 4.4 shows the typical surface cracking described by Robinson et al. (2000). This picture was taken at site ST3. The banks at ST3 face southeast and were dry most of the summer. Dry soil peds would pop off the bank face and be entrained in the stream flow. Stream bank soil desiccation also had more severe impacts on bank stability. Site TC7 has a mature forested buffer, but due to channel incision, the stream banks are undergoing retreat. During the summer of 2002, the bank soil became very dry and large chunks of bank soil fell from mid-bank, collecting as a miniature talus slope at the toe of the slope (Figure 4.5). This loose material was removed in subsequent winter floods. In the picture, a distinct wetting front can be observed on the upper bank due to a small summer storm event.

The winter provided several opportunities for stream bank freezing and FTC was frequently observed, particularly at sites with mature forest. Figure 4.6 shows needle ice that commonly formed on the toe of SC7. This site had fine grained soils and experienced significant degradation from FTC. More commonly, the surface soil at several sites would freeze and thaw, leaving a loose layer of soil that Lawler (1993) described as "puffy" (Figure 4.7). This layer was friable and easily removed by touch. Where banks were cantilevered, soil would freeze in the
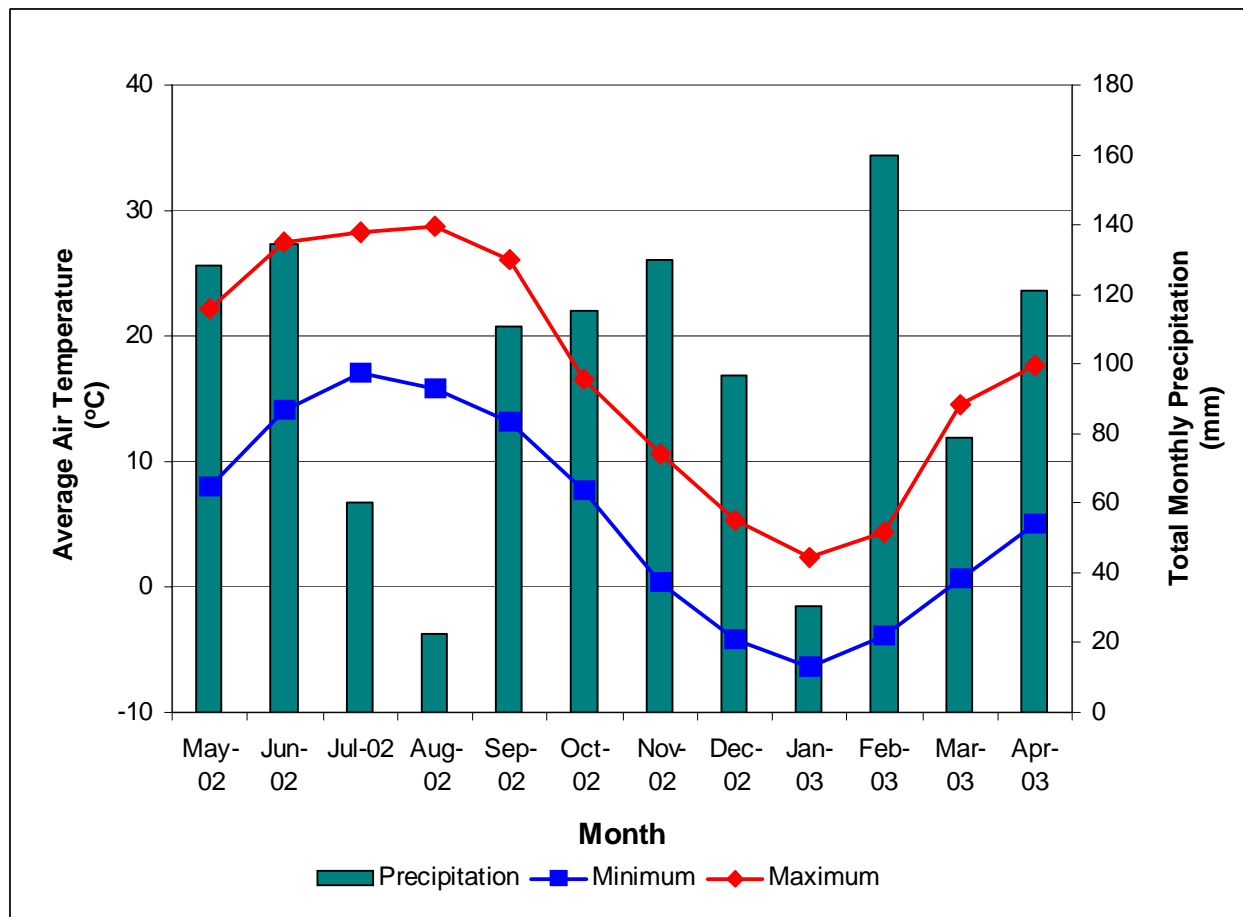
Figure 4.3.   Monthly air temperature and precipitation for Blacksburg, Virginia for May 2002 through April 2003.

upper cantilevered bank and fall down the slope upon thawing (Figure 4.8). Also observed were erosional notches, as described by Lawler (1993). These bank features occur during rises in stream stage when the warmer stream water thaws a frozen bank (Figure 4.9).

4.2.1. Paired Reach Evaluations

4.2.1.1. Summer Soil Temperature

Average daily stream bank STs are shown in Table 4.2. Differences in average minimum ST and ST range between the upper and lower banks at each site and between forested and herbaceous buffer sites were slight and within sensor error. The average daily maximum ST in the upper bank was slightly higher under the herbaceous buffers at two of the paired sites: 1.5^{o}C and 3.8^{o}C

Figure 4.4 Soil desiccation cracking at site ST3.

Figure 4.5.   Stream bank degradation at site TC7 resulting from
severe soil desiccation. Camera bag is
approximately 18 cm in width.

Figure 4.6. Needle ice in the stream bank toe at site SC7.

higher for the EL and SC sites, respectively. Differences in ST between vegetation types for the
lower banks was less than the 0.7°C sensor error for all the paired sites. The effect of vegetation
type on stream bank ST is more evident in a plot of the herbaceous daily temperature range
versus the forested daily temperature range for the upper and lower stream banks (Figures 4.10
and 4.11). The slopes of all the regression lines are significantly different from 1.0 at $\alpha = 0.01$.
These plots show that the summer stream bank ST under herbaceous vegetation generally had
greater diurnal fluctuations than under forested vegetation. This large diurnal temperature range
is likely due to the higher SWP under herbaceous vegetation, as discussed in the following
section. Water has a high specific heat capacity and acts as a thermal buffer, reducing
fluctuations in soil temperature. Additionally, by June, the forested sites had a closed canopy
and the soil was well shaded. Vegetation at two of the herbaceous sites did not reach full

Figure 4.7. Loose soil at site TC4 resulting from freeze-thaw cycling.

Figure 4.8. Accumulation of upper bank soil at mid-bank as a result of freeze-thaw cycling at site ST3.

Figure 4.9. Erosional notch observed at site ST3.

maturity and full soil coverage until late July. The exception to this is the lower banks of the Sinking Creek sites. The vegetation at the herbaceous Sinking Creek site (SC6) was very dense and shaded the entire bank face early in the summer. Also, the banks at the herbaceous site were slightly lower than those at the forested site (bank exposure of 1.5 m versus 1.7 m), so the lower sensors at SC6 were close to the water level and remained moist much of the summer.

The effects of solar radiation on stream bank ST can be seen in Figure 4.12. Figure 4.12 shows the air temperature, solar radiation, and ST for a south-facing stream bank along Tom's Creek covered with sparse WGC (TC6). This site had only temperature sensors, but the data are used to illustrate the importance of soil exposure on summer bank temperatures. At this site, soil temperature had a range in excess of $20^{o}C$ and reached peak temperatures of over $40^{o}C$. Additionally, the soil temperature peaked around 1:30 PM, while air temperature did not peak until late afternoon (5:00 – 6:00 PM). On cloudy days, bank ST was similar to air temperature. Similar extreme STs were reported by Lawler (1992) for an east-facing bank on the River Arrow,

Table 4.2. Average daily soil temperature and water potential conditions for summer and winter at paired sites, southwest, Virginia.

	EL3 Upper Bank	EL3 Lower Bank	EL4 Upper Bank	EL4 Lower Bank	SC6 Upper Bank	SC6 Lower Bank	SC7 Upper Bank	SC7 Lower Bank	TC1 Upper Bank	TC1 Lower Bank	TC2 Upper Bank	TC2 Lower Bank
Depth from Top of Bank (cm)	45	100	45	100	30	80	30	80	35	70	35	70
Mean Min. Summer Bank Temperature (^{o}C)	17.9	17.6	17.9	17.7	17.9	17.9	18.1	18.1	18.0	17.7	18.2	18.3
Mean Max. Summer Bank Temperature (^{o}C)	21.7	21.9	23.2	22.4	21.9	20.8	18.1	21.4	21.6	22.0	21.6	21.5
Mean Daily Summer Bank Temperature Range (^{o}C)	3.9	4.3	5.4	4.7	4.0	2.8	3.6	3.3	3.7	4.3	3.4	3.2
Mean Daily Bank SWP (kPa)	65	66	80	76	69	51	52	42	100	14	43	1
Bank SWP Range (kPa)	3-174	2-189	2-190	1-180	2-160	2-111	2-170	1-127	41-172	1-32	2-113	0-12
Duration SWP>150 kPa (days)	2.6	4.4	10.0	17.2	2.3	0.0	4.0	0.0	5.0	0.0	0.0	0.0
Mean Daily Min. Winter Bank Temperature (^{o}C)	0.1	0.1	-0.1	0.5	1.4	2.2	0.2	1.2	-0.4	0.7	0.2	0.2
Mean Daily Max. Winter Bank Temperature (^{o}C)	3.5	5.6	1.1	2.0	2.1	3.3	1.7	2.4	1.3	2.0	2.0	1.6
Mean Daily Winter Bank Temperature Range (^{o}C)	3.4	5.5	1.2	1.5	0.7	1.0	1.5	1.2	1.8	1.4	1.7	1.4
Total Duration Frozen (days)	27.0	20.1	32.8	21.0	28.4	4.8	30.5	15.2	32.7	28.7	30.4	29.3
Average Duration Frozen (hrs)	30.8	21.0	56.2	83.9	170.1	116.0	121.8	91.1	78.6	172.2	104.3	175.6
Median Duration Frozen (hrs)	14.0	14.5	16.7	21.7	136.5	116.0	20.7	99.5	23.7	143.0	11.0	134.2
Freeze-Thaw Cycles (#)	21	23	14	6	4	1	6	4	10	4	7	4
Mean Daily Winter Bank SWP (kPa)*	11	9	6	6	5	4	4	3	3	3	4	7

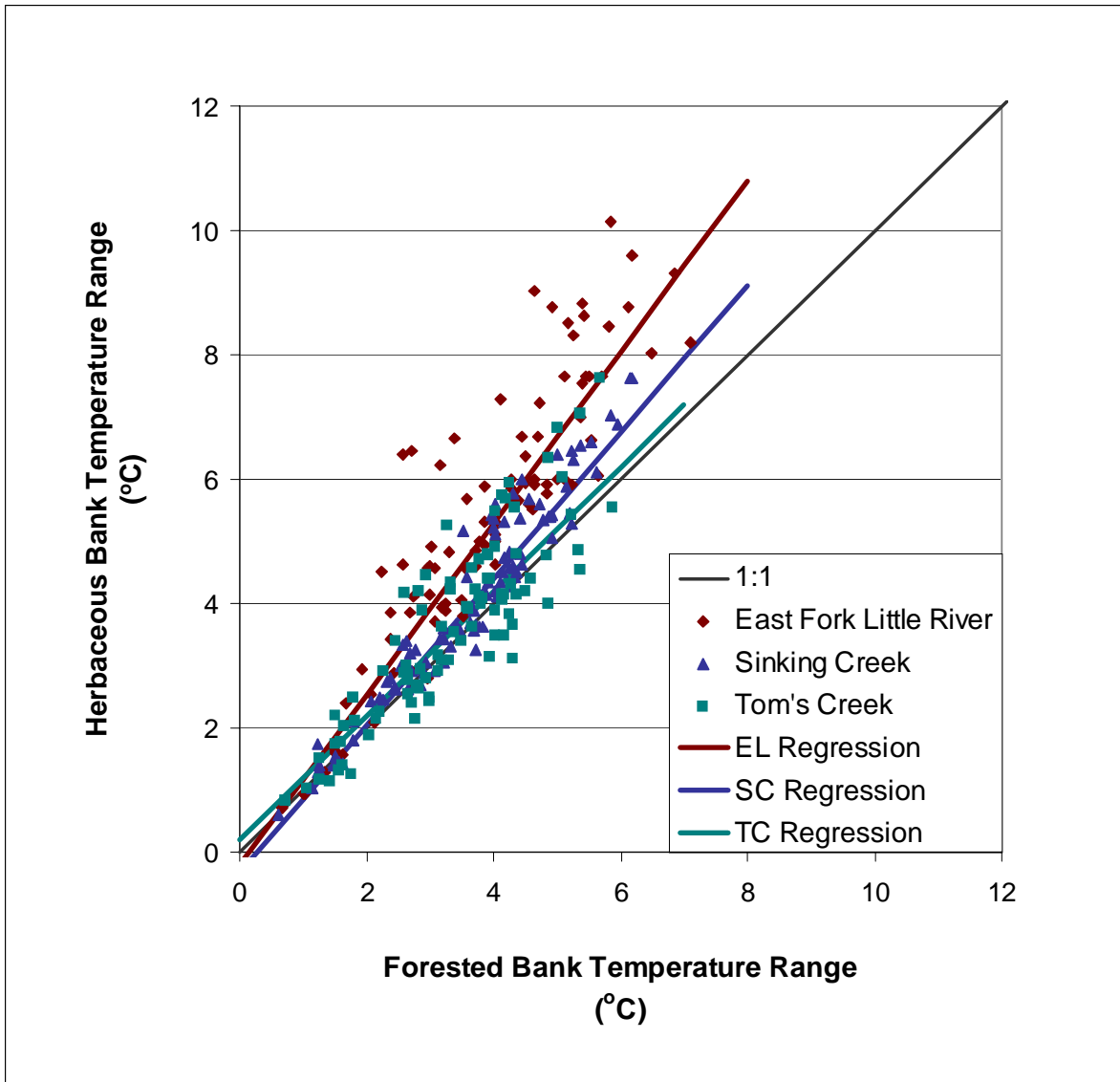* Data from 12/12/02 through 12/25/02 and 12/31/02 through 1/6/03 only.

Figure 4.10. Range in summer upper bank soil temperature as a function of vegetation type for Appalachian headwater streams in southwest Virginia.

Warwickshire, UK. This extreme heating was noted to cause peeling away of the surface bank soil.

The effect of herbaceous vegetation growth through the summer on stream bank ST was investigated by plotting herbaceous ST versus forested ST for each month in the summer for both upper and lower banks for each pair. All the regressions were significant at $p<0.0001$ and were significantly different from month to month at $p \leq 0.002$. In general, the slopes of the lines
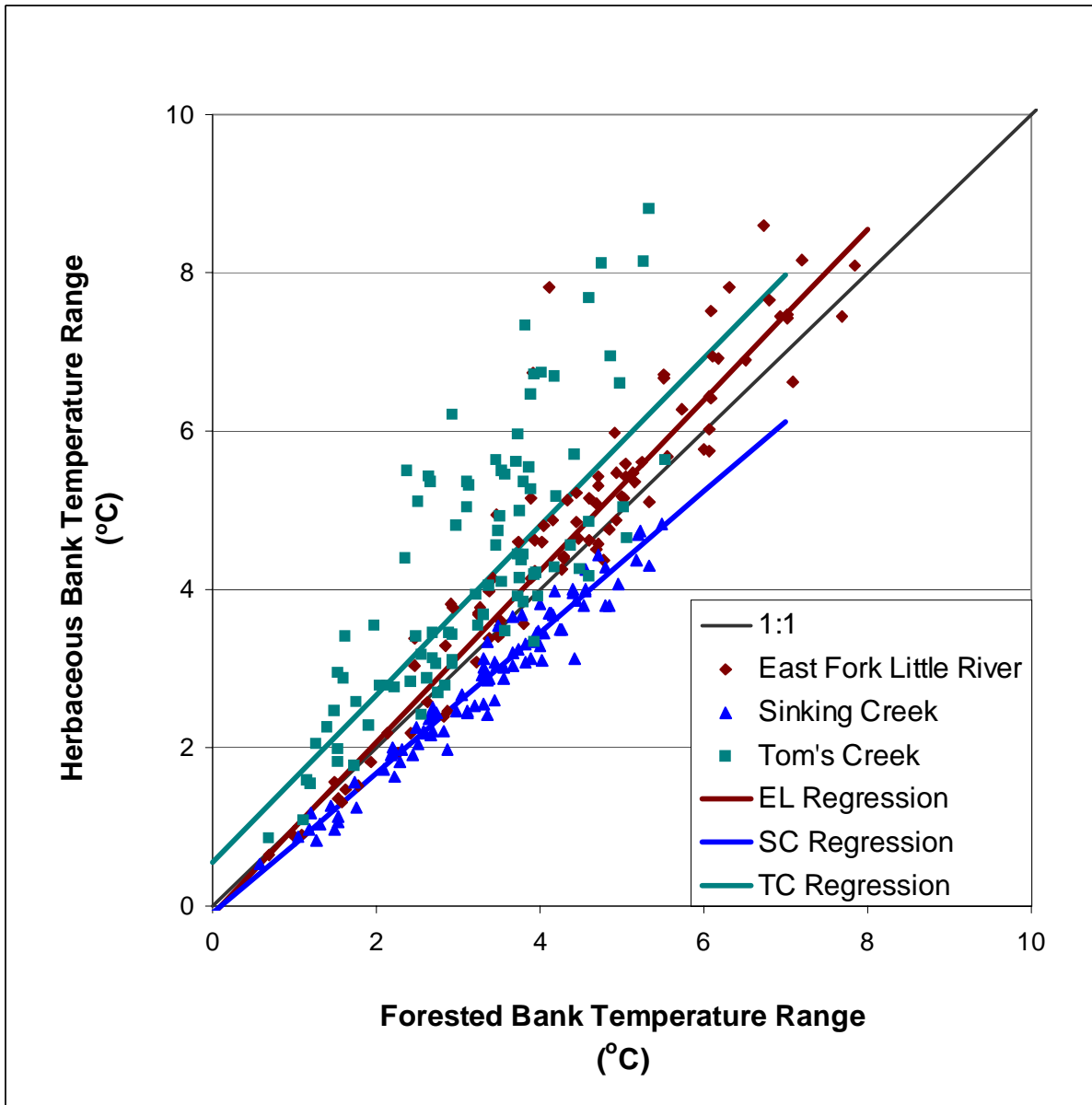
Figure 4.11. Range in summer lower bank soil temperature as a function of vegetation type for Appalachian headwater streams in southwest Virginia.

decreased from an average of 1.11 in June to 1.02 in July and 0.98 in August. Figure 4.13 illustrates the results for the sites on the East Fork of the Little River (EL3 and EL4). These results indicate that as the summer progressed and the herbaceous vegetation matured, differences in ST between the vegetation types decreased. By the end of the summer, STs under forest cover were slightly higher than under herbaceous cover.

4.2.1.2. Summer Soil Water Potential

Stream bank SWP was measured to evaluate the potential effects of vegetation type on soil desiccation and cracking. While low soil moisture content can increase the resistance of soil to erosion, desiccation of clay soils can cause soil cracking and exacerbate soil erosion (Thorne,1982). Changes in stream bank SWP over the summer can be seen in Figure 4.14, which illustrates SWP for the Sinking Creek sites. During periods with no rainfall, the stream banks dried gradually. Following rainfall, the SWP dropped rapidly to near 0 kPa. This pattern is typical of that reported by Simon et al. (1999) for tensiometers at a depth of 30 cm and a distance of approximately 1 m from the bank face. In general, the lower banks had a lower mean
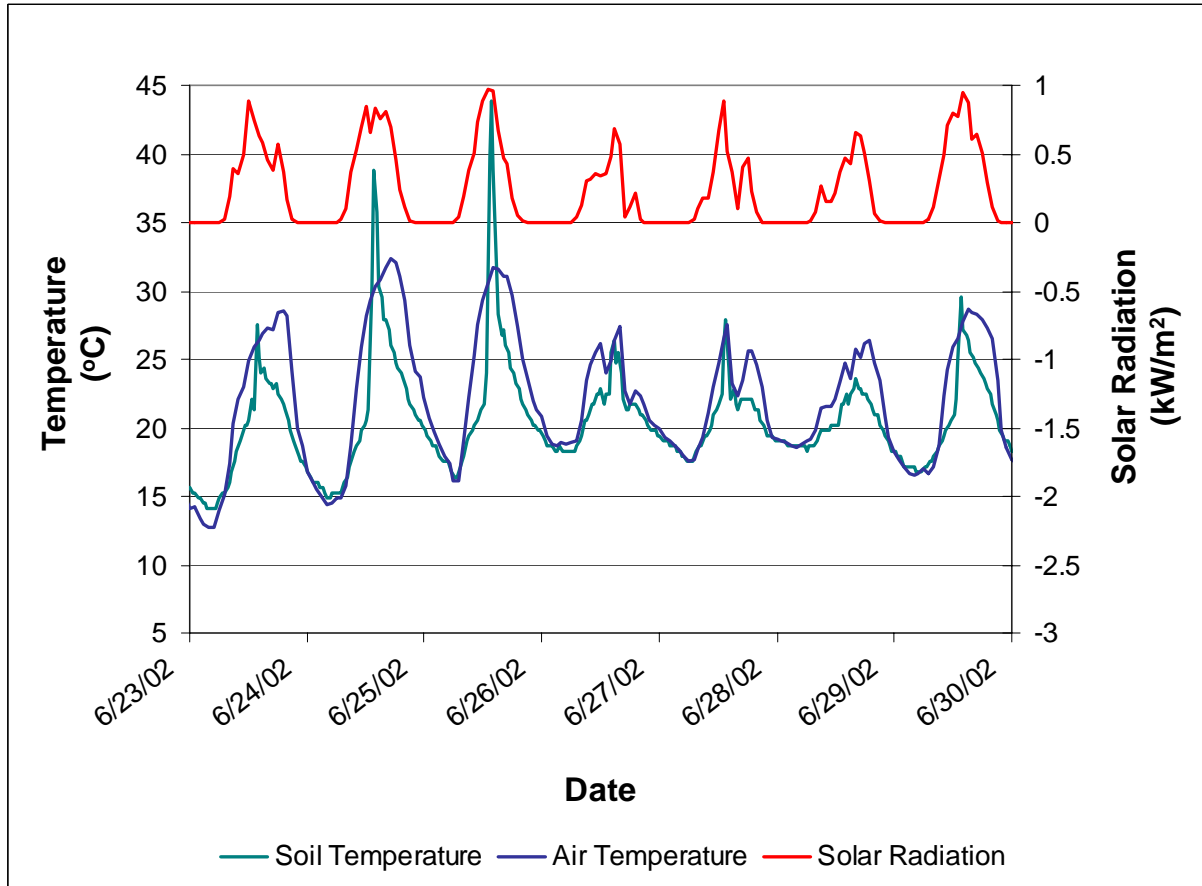

Figure 4.12. Effect of solar radiation on stream bank soil temperature for an Appalachian headwater stream in southwest Virginia.
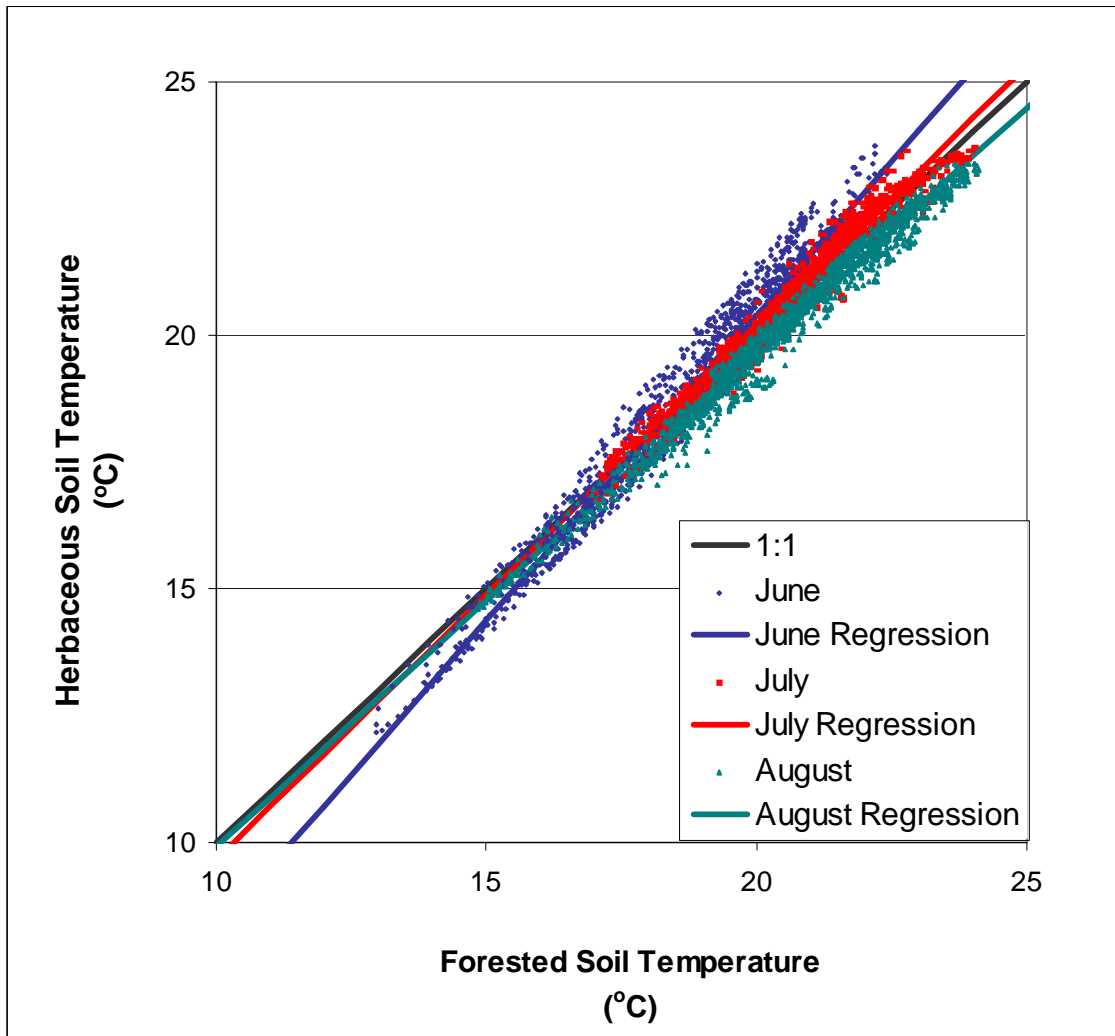
Figure 4.13. Effect of growing season length on upper bank summer soil temperatures, East Fork of the Little River, near Pilot, Virginia.

daily SWP than the upper banks (Table 4.2). This is expected since capillary action would draw water upward from the water table into the stream bank. The effects of bank height and soil texture on SWP can be seen in the range of differences in average daily SWP between upper and lower banks for the three pairs. There was little difference in SWP between the upper and lower banks at the EL sites (-1 kPa and 4 kPa, respectively, for EL3 and EL4). These stream banks are twice as high as at the other sites and the soil texture is coarser; therefore, these sites are less likely to be influenced by capillary action. The lower sensors at the EL sites were located more than a meter above baseflow and appeared unaffected by the water table. In contrast, there was a
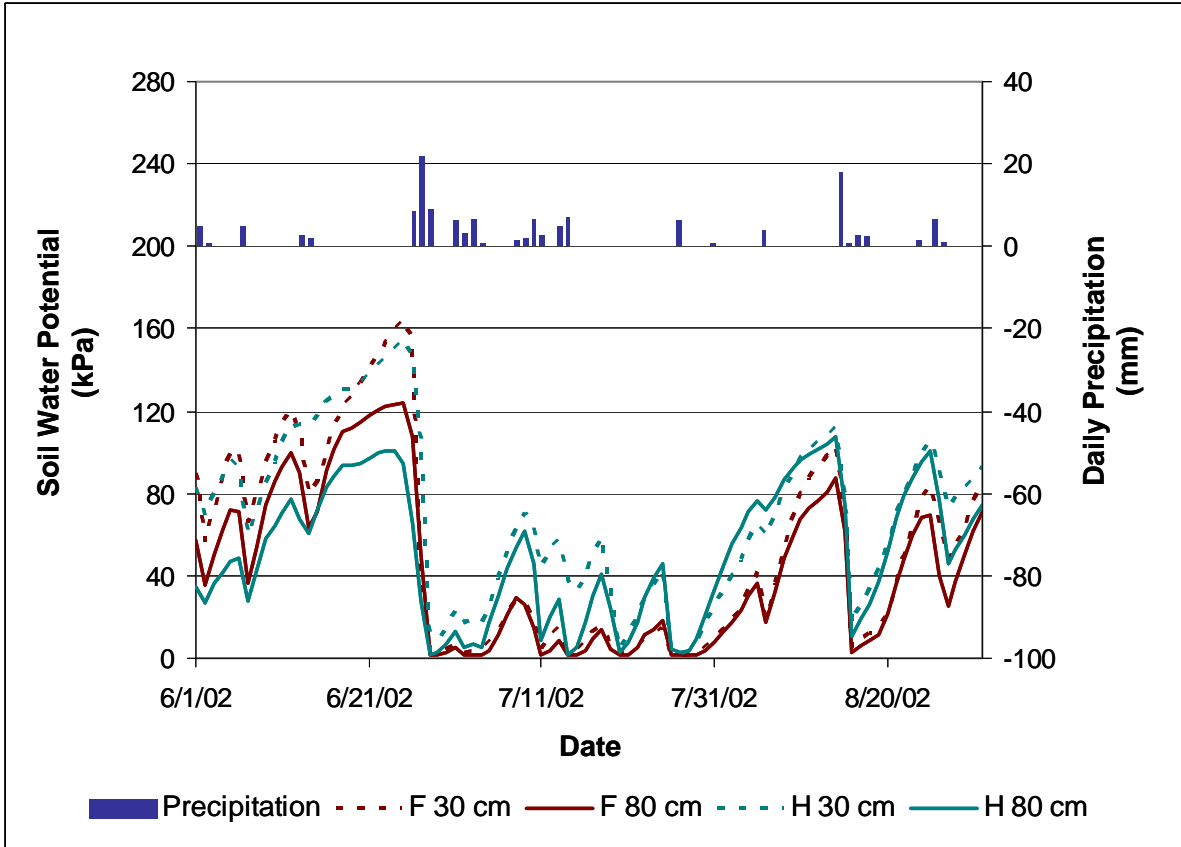
Figure 4.14. Summer stream bank soil water potential along Sinking Creek near Newport, Virginia for Herbaceous (H) and Forest (F) sites.

difference of 86 kPa and 42 kPa between the upper and lower bank average daily SWP for TC1 and TC2, respectively. The stream banks along Tom's Creek are 0.8-1.2 m high and consist of soils with finer texture than those present in the floodplain of the East Fork of the Little River The lower bank heights and finer soil texture resulted in lower soil water tensions in the lower banks at these sites. Soil loss due to desiccation cracking was observed on the upper bank at TC1, despite the presence of herbaceous roots. The lower banks, which had fewer roots but a lower SWP, remained stable throughout the summer. The bank heights and soil textures at the SC sites are intermediate between those at the EL and TC sites. Differences of 18 kPa and 10 kPa in average daily SWP between the upper and lower banks for the herbaceous and forested sites, respectively, were measured. Despite the high SWP values measured at the EL and SC sites, desiccation cracking was not observed at these sites due to the lower clay content of the

soils. It was observed, though, that the soils were very fragile when dry and would crumble upon contact.

Differences between upper and lower bank SWP can also be seen in the number of days the stream banks were above the wilting point (150 kPa; Table 4.2). For both the SC and TC sites, the average daily SWP in the lower banks remained below 150 kPa, despite a record drought. The upper banks at these sites were above the wilting point for a total of 2.3 to 5.0 days during the summer. The opposite effect occurred at the EL sites, where the lower banks under both the forested and herbaceous buffers were drier than the upper banks. At EL3 and EL4, the lower banks had SWPs in excess of 150 kPa for 10.0 and 17.2 days, respectively, as compared to a total of 2.6 and 4.4 days, respectively, for the upper banks. This represents an almost four-fold increase in the time the lower banks were extremely desiccated, as compared to the upper banks. The lower slopes of EL3 may have been drier because SWP tends to increase with depth under forest cover (Simon and Collison, 2002). Additionally, the drier lower slopes may have been the result of a decrease in groundcover density down the bank face at both sites. Since these banks face south, evaporation from the soil surface was likely very high. Anderson et al. (1982) studied the stability of a high roadway embankment and observed an increase in clay cracking on sparsely vegetated parts of the embankment. In contrast, areas that were densely vegetated by grass developed few desiccation cracks.

As illustrated in Figure 4.14, there were differences in SWP between vegetation types for both the upper and lower sensors, with the greatest differences occurring in the upper banks. In general, the herbaceous sites were drier. This is likely caused by reduced shading of the soil surface in the early summer and the fact that evapotranspiration under herbaceous vegetation is concentrated on the bank surface due to the relatively shallow herbaceous root system. For the TC sites, the average daily SWP at the herbaceous site was 57% and 50% greater than the SWP at the forested site for the upper and lower banks, respectively. This may be due to the fact that the stream banks at this site are higher in the herbaceous buffer and are bare. The nearly vertical upper banks at TC1 were frequently desiccated and soil aggregates fell from the top of the bank into the stream throughout the summer. The average daily SWPs for the upper and lower herbaceous banks along Sinking Creek were 27% and 17% higher than for the forested banks, respectively, and 19% and 13% higher, respectively, along the East Fork of the Little River. The dense growth of herbaceous vegetation on the bank faces at SC6 and EL4 likely shaded the bank

surface and reduced evaporation from the soil. The differences in SWP between the herbaceous and forested buffers at the EL sites were probably lower than at the SC or TC sites because the EL banks face south and the forested bank face (EL3) is not well shaded by ground cover or the trees growing at the top of the bank.

These results suggest that the distance above stream base flow, soil texture, soil exposure, and vegetation type control stream bank soil water potential. Fine texture soils that are close to the water table are able to maintain soil moisture through capillary action. Additionally, shading by vegetation reduces increases in soil temperature and evaporative losses from the soil surface (Holtz, 1983). The benefits of shading by vegetation may be offset in the case of herbaceous vegetation. Dense herbaceous vegetation on the bank face appears to increase SWP through evapotranspiration. A similar effect was not observed under forested cover, likely due to differences in the root morphology between the two vegetation types. In a study of high shrink-swell clays in the Sudan, Zein el Abedine and Robinson (1971) noted dryer surface soils under predominately grass vegetation than under largely forested conditions. While these results indicate the effects of vegetation on stream bank SWP, the impact of high SWP on stream bank erosion ultimately depends on the specific stream bank soil type and how susceptible it is to cracking or loss of structural strength upon drying.

4.2.1.3. Winter Soil Temperature and Freeze-Thaw Cycling

Mean daily minimum ST ranged from -0.4°C in the upper bank of TC1, where there was herbaceous vegetation and a bare, cut bank, to 2.2 $^{\circ}$C in the lower bank of SC6, which was gently sloping with a dense herbaceous cover across the entire bank face. Mean maximum daily temperatures ranged from 1.1°C in the upper bank at EL4 (heavy herbaceous growth) to 5.5 $^{\circ}$C in the lower bank at EL3 (forested with thin groundcover). Differences in stream bank temperatures appeared due mostly to differences in vegetation density on the bank than actual vegetation type. Stott (1997) compared winter stream bank temperature under spruce forests to those under moorland vegetation and found the forested banks were an average of 3.7°C warmer than the open moorland banks. Several researchers have shown that vegetation moderates soil temperatures and reduces soil freezing as compared to bare soils (Atkinson and Bay, 1940; Kohnke and Wekhoven, 1963; Pikul and Allmaras, 1985).
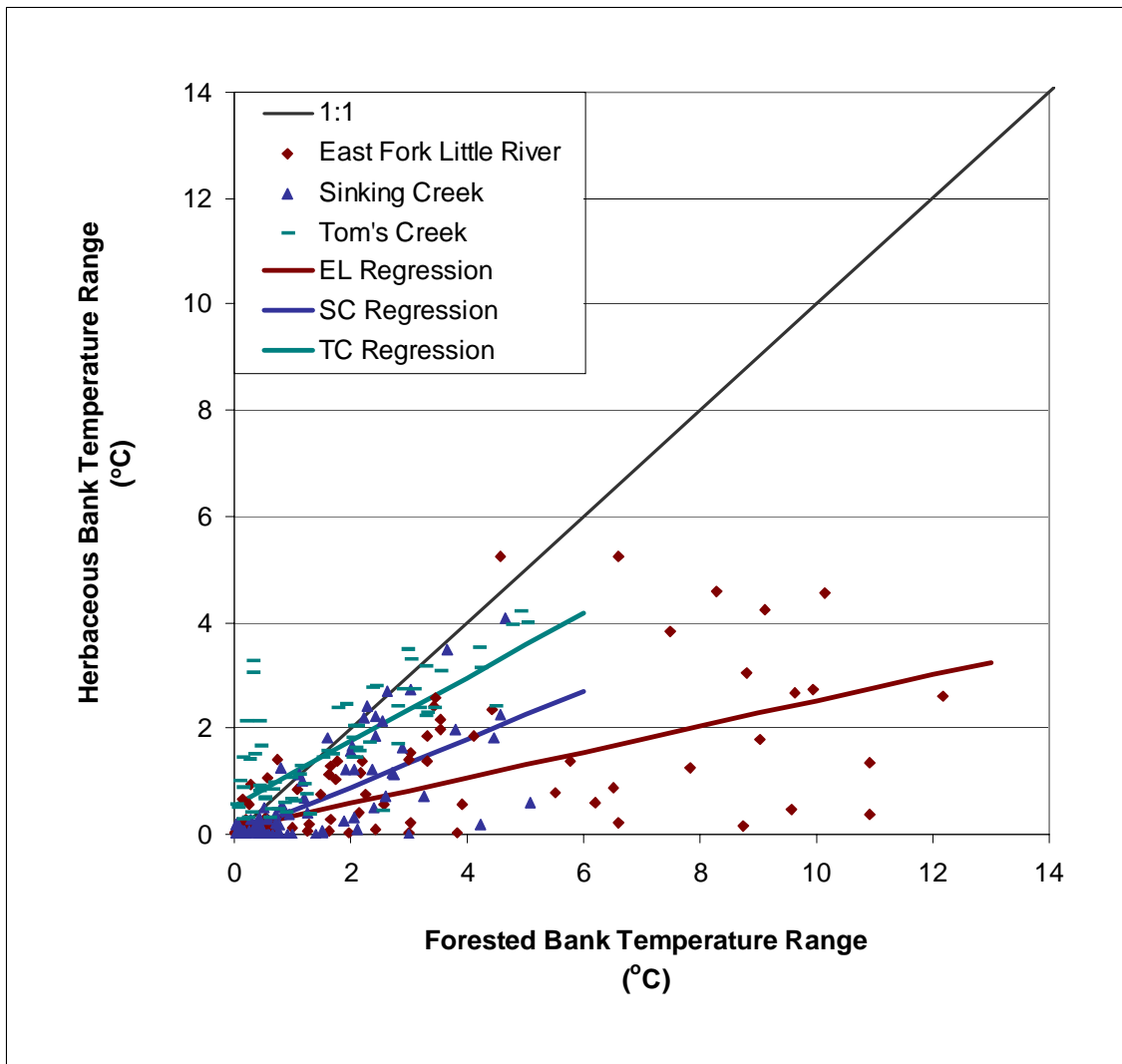
Figure 4.15. Range in winter upper bank soil temperature as a function of vegetation type for Appalachian headwater streams in southwest Virginia.

The insulating effects of dense groundcover can be seen in the average daily temperature range. SC6 had an average diurnal temperature range of only 0.7°C, compared with an average diurnal change of 1.5°C at the forested site, SC7. The forested sites generally had little groundcover or leaf litter on the bank face during the winter (see Appendix E for site photographs). The thermal buffering by the dead herbaceous vegetation is further illustrated by examining plots of herbaceous bank temperature range versus the corresponding forested bank temperature range for the upper bank (Figure 4.15). The regression for each site was significant at $\alpha<0.0001$ and each regression slope was significantly less than 1.0 at $\alpha<0.001$. The daily
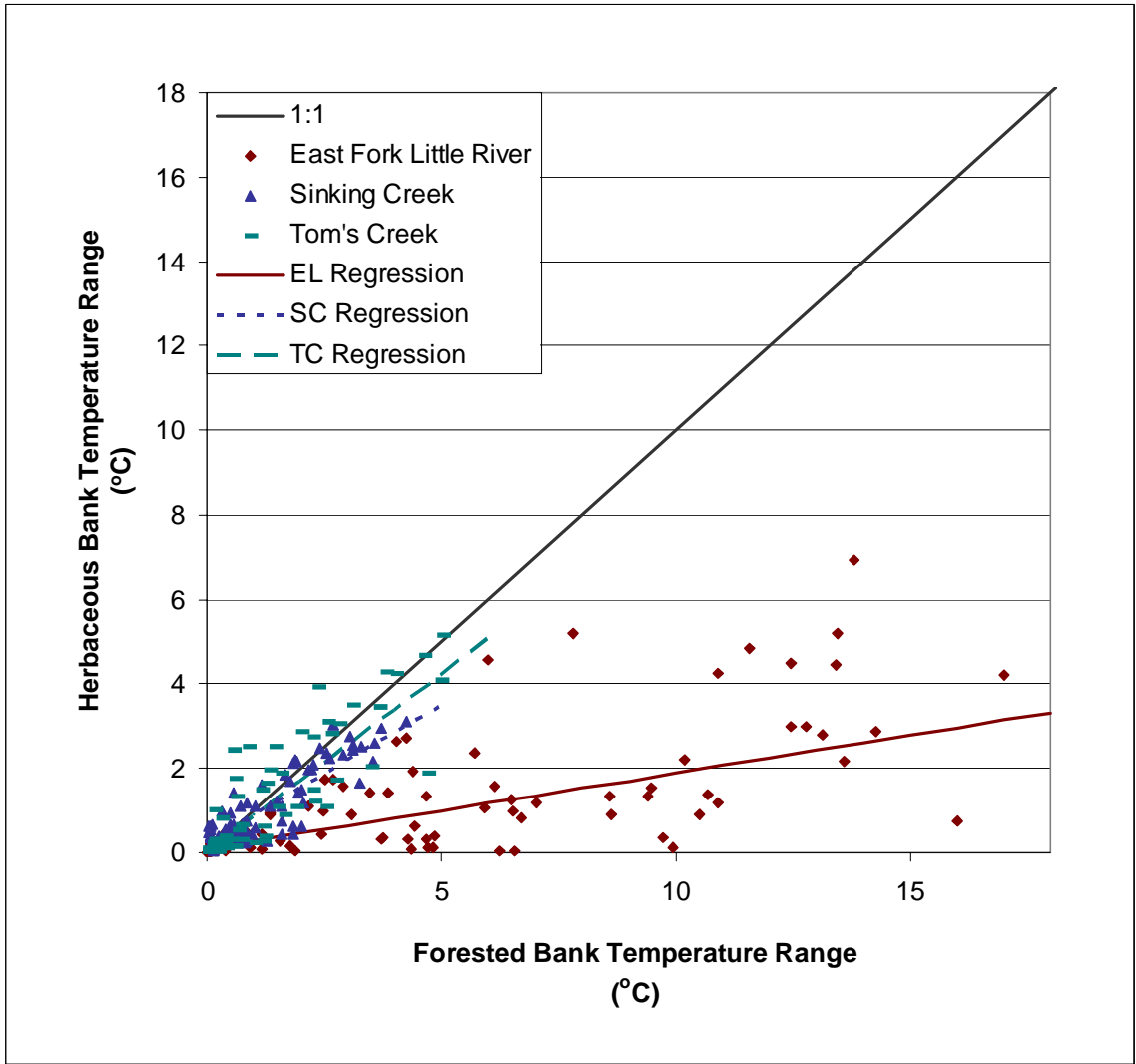
Figure 4.16. Range in winter lower bank soil temperature as a function of vegetation
type for Appalachian headwater streams in southwest Virginia.

temperature range for the forested sites is significantly higher than that for the herbaceous sites.
The greatest difference in diurnal temperature range among the paired sites is along the East
Fork of the Little River where the banks face south. The least difference between the two
vegetation types occurs along Tom's Creek: the banks along Tom's Creek face north-east and the
banks at the herbaceous site (TC1) are bare. The scatter of points for the TC sites about the 1:1
line indicates that even without leaves, the woody vegetation at TC2 still provided some
insulation to the stream bank, likely a result of reduced wind velocities. Results for the lower

bank were similar (Figure 4.16). Stott (1997) reported a greater range in winter temperature for moorland streams, as compared to streams under spruce forests. While these results appear to contradict those of Stott, they actually support the idea that a dense vegetative cover insulates stream banks, as the spruce forest in the Kirkton Glen likely provided greater cover than the open moorland vegetation.

The effects of soil exposure on FTC can be evaluated by comparing the duration of bank freezing and the number of FTCs at the sites along the East Fork of the Little River. The upper and lower bank temperature ranges at the forested site, EL3, were 3.4^{o}C and 5.5^{o}C, respectively. These were the highest diurnal fluctuations recorded among the sites. This is likely because this forested south-facing bank was bare for most of the winter. In contrast, the banks under herbaceous vegetation experienced average diurnal fluctuations of only 1.2^{o}C and 1.5^{o}C for the upper and lower bank, respectively. Additionally, while the upper forested banks were frozen for almost six days less than the herbaceous banks, they underwent 50% more FTCs. The difference is even more extreme along the lower bank, where the forested site had almost four times the number of FTCs as the herbaceous site (23 vs. 6). This is further exemplified by the differences in the MDF and ADF at each site. The MDF and ADF are similar at EL3 where there are high rates of FTC (Table 4.2). At EL4 where there is a low occurrence of FTC, the average duration frozen is almost four times the median duration frozen for both the upper and lower banks, indicating that once the banks were frozen, they remained so for long periods of time. A similar pattern occurred in the upper banks of SC7, TC1, and TC2. This low rate of FTC is likely due to reduced solar exposure at the herbaceous site, EL4, resulting from both insulation of the bank by a dense cover of dead herbaceous vegetation and shading by a steep hill on the opposite bank.   Across the river from EL3 and EL4 was a forested hill that was steeper and higher across from EL4. Because the sun is lower in the winter at this latitude, less sunlight hit the stream bank at EL4 during the winter.

The effect of vegetation type on freeze-thaw cycling is clearer at the remaining sites. Along Sinking Creek, the forested site (SC7) experienced more freeze-thaw cycling and the stream banks were frozen over a longer duration during the winter. Frequent freeze-thaw cycling and needle ice were observed at SC7 throughout the winter and the stream bank was often covered with a dusting of loose soil (Figures 4.6 and 4.17).   Site SC6 had a slightly more eastern

Figure 4.17. Loose soil on bank face of SC7 due to freeze-thaw cycling.

aspect than SC7 and the dense herbaceous cover on the bank face maintained that stream bank at a higher temperature throughout the winter. This is illustrated by lower diurnal temperature ranges at SC6, as compared to SC7.   These results are confirmed by research on cropland that demonstrated that crop residue may reduce freeze-thaw cycling (Pikul and Allmaras, 1985). Bohn (1989) showed that stream banks under grass vegetation had significantly higher minimum temperatures and significantly lower maximum temperatures as compared to bare banks.

The influence of dense groundcover is confirmed by examining winter soil temperatures for two research sites at the Virginia Tech Kentland research farm. Site TC6 (Figure A.23) is an south-facing bank with a heavy growth of honeysuckle (*Lonicera* sp.). Located slightly downstream on the opposite bank, site TC7 (Figure A.24) is a largely bare, actively eroding bank
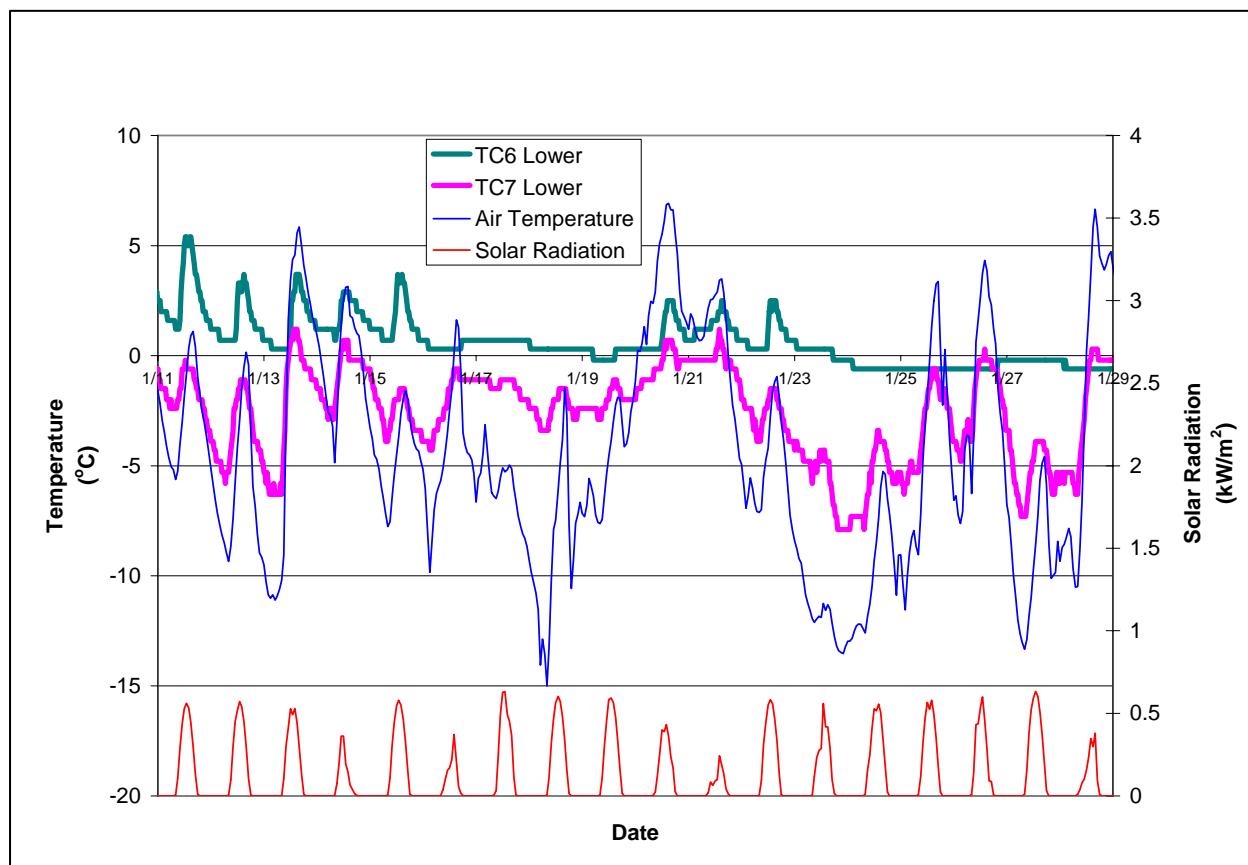
Figure 4.18. Effect of dense groundcover on soil temperatures for a headwater stream in southwest Virginia. Site TC6 is covered with honeysuckle (*Lonicera* sp.), while the banks at TC7 were largely bare under the mature riparian trees.

with a mature forested riparian buffer. Figure 4.18 shows the lower bank soil temperatures for TC6 and TC7 from January 11, 2003 through January 29, 2003, with the air temperature and solar radiation measured at the research farm. This figure shows that the stream bank soil temperatures generally follow the diurnal pattern of the air temperature, but that the stream banks at TC6 were about 5°C warmer than those at TC7 and were usually greater than ambient air temperatures. The stream banks at TC7 remained frozen for much of the period. Initial differences in soil temperature between the two sites may be due to differences in site aspect. Differences due to vegetation can be observed during the two periods from January 17 through January 20 and from January 22 through January 25. During these two periods air temperatures remained below 0 °C. Soil temperatures at TC7 dropped in response, indicating the freezing

front had moved well into the bank face. In contrast, the bank soils at TC6 remained near zero and did not respond as rapidly as TC7 to later increases in air temperature. The afternoons of January 25 and 26, air temperatures rose well above $0\,^{\circ}C$ and the TC7 STs slightly exceeded those of TC6. During these periods, the soil at TC6 remained frozen and did not undergo diurnal temperature changes and FTC, despite the fact that TC6 has a southerly aspect and those days were sunny. This response is likely due to the insulation of the dense WGC present at TC6 that reduced fluctuations in temperature. It is also possible that the dense groundcover reduced evaporation from the soil and maintained higher soil moisture content at TC6, as compared to TC7, even though TC6 received greater solar exposure. The increased soil moisture would also reduce fluctuations in soil temperature.

When the stream banks are bare at a herbaceous site, the temperature difference between a forested and herbaceous site are reduced. The upper and lower banks at the Tom's Creek sites were frozen for approximately the same duration: the upper and lower stream banks at the herbaceous site were frozen for 32.7 and 28.7 days, respectively, while those at the forested site were frozen for 30.4 and 29.3 days, respectively. The forested vegetation did slightly reduce the number of FTCs in the upper bank, as compared to a bare bank with herbaceous vegetation on top (7 FTCs versus 10 FTCs, respectively). This difference may be the result of higher wind speeds in the hayfield with scattered trees as compared to the dense forest surrounding TC2. There was no difference in FTC for the lower banks. Since Tom's Creek is entrenched in the field site, the lower banks were likely more protected than the upper banks. Greater differences between a forested site and a herbaceous site with cut banks would probably be seen if the banks did not face north as the banks at these sites did.

4.2.1.4. Winter Soil Water Potential

Due to problems with sensor exposure and malfunction during the winter, little SWP data is available. During December 2002 and the beginning of 2003, the stream bank soil at all the sites remained near saturation. Seasonally higher precipitation and reduced evapotranspiration would act to minimize soil desiccation during the winter. This is typical for non-incised stream banks in humid regions (Simon and Collison, 2002). While there were slight differences in SWP between the upper and lower banks and between sites, these differences are mostly within the sensor error of $\pm\,3$ kPa. The forested banks at EL3 were slightly drier than the herbaceous banks

at EL4. This small increase in SWP was probably the result of increased exposure to solar radiation due to aspect, local topography, and lack of vegetative cover. The low SWP values indicate all the sites had sufficient soil moisture to experience FTC during sub-zero air temperatures. This was confirmed by field observations of FTC at each site during the winter.

4.2.2. Regression Analysis of Freeze-Thaw Cycling

The number of FTC, the TDF, MDF, and ADF, and the additional site parameters used in the regression analysis are tabulated in Appendix F. Differences in the four freezing parameters indicate the thermal behavior of the bank over the winter. Some of the sites (such as SR4 Lower) underwent frequent FTC, often freezing overnight and thawing during the day. These sites have a high number FTC (34) and a large TDF (30.3 days), while the MDF and ADF are low and roughly equal (15.5 hrs. and 21.4 hrs., respectively). This is similar to rates cited by Lehrsch (1998), who noted that unvegetated soils in south-central Idaho may experience as many as 30-40 FTCs in one winter. These cycles may occur over periods ranging from hours to weeks (Hershfield, 1974). In contrast, sites such as SC1 Upper and SR1 Lower were frozen much of the winter, but rarely thawed, resulting in a low number of FTC (4 and 2, respectively) and long TDF, MDF, and ADF (58.0 days, 186.5 hrs. and 348.3 hrs.; 38.2 days, 458.5 hrs., and 458.5 hrs., respectively). Large differences between the median and average durations frozen are typical of sites that experienced moderate FTC (e.g. 15.5 hrs. and 42.3 hrs., respectively, for NR1 Upper). From mid-January to mid-February 2003, southwestern Virginia experienced very cold weather with daytime high temperatures frequently below 0°C and nighttime temperatures as low as -18°C. Several of the stream banks completely froze during this period and remained frozen for several days, creating a distinct difference between the median and average durations frozen. One of the sites, SC6 Lower, remained unfrozen much of the winter, and experienced only one FTC. As discussed in the paired site analysis (Section 4.2.1.3), this site had a dense cover of herbaceous vegetation that remained on the bank throughout the winter and acted as insulation (Figure 4.19).

Stepwise multiple linear regression was conducted for both the lower and upper banks to determine which site and vegetation characteristics influenced stream bank freezing. For the lower banks, highly significant relationships were found for the number of FTC and the total and average durations frozen (TDF and ADF). These three freezing parameters were predicted by

Figure 4.19. Dense winter cover on stream bank at site SC6.

both the aboveground vegetation density and site parameters. For the upper banks, however, the only significant regression found was for the total duration frozen (TDF). It is unclear why significant results were found primarily for the lower banks. The lower banks generally had a higher moisture content, which made determining the freezing point easier and likely created fewer errors in the freezing parameters for the lower bank. Also, the upper banks were more exposed to unmeasured, external forces, such as wind, which may have played a significant role in their thermal behavior. Table 4.3 lists the equations, the p-values, and the coefficients of determination. The regression equations and coefficients were all significant at $\alpha = 0.05$.

In addition to these standard regressions, PCA was used to consolidate the freezing parameters into a single value (Shaw, 2003).   Several analyses were conducted and the most

significant one was produced using the parameters FTC, ADF, and MDF. The first axis had an eigenvalue of 2.46 and explained 82% of the variation in the data. The eigenvalue loadings for FTC, ADF, and MDF were 0.505, -0.597, and -0.623, respectively. Plotting the second axis scores versus those of the first axis revealed that low scores on the first axis were correlated with a low occurrence of FTC. The total duration frozen was not helpful in describing the thermal behavior of the stream banks because a high total duration could be the result of several short FTC or a few extended frozen periods. To determine which vegetation and site parameters most influenced the resulting PCA scores, stepwise regression was conducted in Minitab. This produced a highly significant regression that explained almost 97% of the variance in the PCA scores. The resulting equation is listed in Table 4.3. With the exception of the intercept term, the coefficients for the PCA regression equation were significantly different from zero at $\alpha = 0.05$.

As indicated by the r^2 values in Table 4.3, the thermal behavior of the stream banks can be largely explained by physical site characteristics and vegetation densities. These results confirm findings from the paired site analysis and further support the idea that riparian vegetation plays a major role in subaerial processes during the winter. Increases in tree BSA

Table 4.3. Freeze-thaw cycling regression equations using normalized independent variables for Appalachian headwater streams in southwest Virginia (normalized variables indicated with subscript "N").

Bank Location	Regression Equation*	Regression p-value	r^2
Lower	$FTC = 12.1 + 4.53\ BSA_N - 5.47\ Depth_N - 3.94\ S+C_N$	0.001	0.726
Lower	$TDF = 1.47 + 0.166\ Grass_N - 0.167\ S+C_N - 0.0821\ Degrees_N + 0.0988\ BSA_N$	0.000	0.854
Lower	$ADF = 109 + 79.9\ Depth_N - 86.0\ Degrees_N + 32.8\ WGC_N + 60.7\ S+C_N - 59.1\ Elev_N - 33.5\ Silt_N - 22.9\ BSA_N$	0.000	0.973
Lower	$PCA\ Axis\ 1 = 0.009 - 1.04\ Depth_N + 0.490\ BSA_N - 0.976\ S+C_N + 1.05\ Degrees_N + 0.770\ Elev_N - 0.359\ WGC_N + 0.417\ Silt_N$	0.000	0.969
Upper	$TDF = 1.66 + 0.0927\ Elev_N + 0.123\ Width_N + 0.0709\ Silt_N$	0.002	0.614

* FTC = number of freeze-thaw cycles; BSA = tree basal stem area; Depth = average stream depth; S+C = combined soil silt and clay content; TDF = total duration frozen; Grass = dry grass biomass; Degrees = degrees from true north; ADF = average duration frozen; WGC = dry woody groundcover biomass; Elev = site elevation; Silt = soil silt content; PCA Axis 1 = Axis 1 scores from PCA analysis.

resulted in increases in the number of FTC and the total amount of time the lower stream banks were frozen. This is reflected in a corresponding decrease in ADF. In contrast, large amounts of grass or WGC appear to insulate the stream banks, as reflected in the increases in both lower bank TDF and ADF with increases in groundcover. While the stream banks are frozen longer under heavy groundcover, they do not go through repeated FTC. In heavily forested areas where groundcover is sparse, the soil is exposed to solar radiation during the winter and the stream banks are more likely to thaw. This finding is supported by the results showing that both TDF and ADF decrease with more southerly aspects (high Degrees from north), while the total number of FTC increases.

The stream bank soil texture plays a significant role in winter freezing (Tables 4.1 and 4.2) . Increases in the soil silt-clay content were correlated with decreases in both the number of FTC and the TDF in the lower bank. Because fine-grained soils have a smaller pore size distribution, they are more likely to be affected by capillary action and have a higher moisture content than coarser textured soils, particularly in the lower part of the stream bank. This increased soil moisture acts as a thermal buffer, reducing the likelihood of soil freezing. In contrast, increases in the soil silt fraction alone appeared to increase the number of FTC and the ADF in the lower banks and increase the TDF in the upper bank. This result suggests that soils high in silt were more likely to freeze, experiencing both greater FTC and extended periods frozen while increases in soil clay content appear to decrease the occurrence of FTC. Since it appears logical that the silt-clay and silt contents of the stream bank soils would be correlated, the parameters were evaluated to determine if multicolinearity influenced the regression results. Analysis of Pearson's r, Spearman's ρ, and Kendall's τ coefficients indicated the two parameters were highly uncorrelated (r = -0.0651, p = 0.8108; ρ = -0.0529, p = 0.8375; τ = -0.0167, p = 0.9283, respectively). Additionally, all variance inflation factor (VIF) values for the regression coefficients were less than 5, indicating multicolinearity is not a problem (Montgomery and Peck, 1982). Thus, it appears the relative fraction of silt and clay has a significant influence on winter subaerial processes.

It is interesting to note that the soil silt-clay fraction in the upper bank was highly negatively correlated with average stream width (r = -0.8548, p = 0.0000; ρ = -0.7884, p = 0.0008; τ = -5673, p = 0.0007, respectively). This finding is confirmed by field observations at

the study sites that the smaller streams were cut into existing fine-grained residuum and the banks had distinct soil horizons, while the banks of the larger rivers were fluvial in origin, dominated by sands, and are more uniform with depth. While it is commonly held that the silt-clay content of stream banks increases downstream (Lawler et al., 1999), these results suggest that, in headwater areas, the silt-clay content actually decreases downstream. As previous research has shown that stream banks high in silt-clay content are more resistant to fluvial entrainment (Thorne and Tovey, 1981; Osman and Thorne, 1988) but more susceptible to subaerial processes (Couper, 2003), Lawler's (1992) theory that subaerial processes dominate stream bank retreat in the upper reaches of stream systems is supported. However, considering that the majority of all stream miles in a watershed are lower order streams, the relative importance of bank retreat due to subaerial processes, particularly with regard to watershed sediment yield, needs to be reconsidered.

The size of the stream also impacts subaerial processes in both the upper and lower banks. Increases in average stream depth resulted in decreases in the number of FTC and increases in the ADF in the lower bank. As with soil moisture, the water in the stream likely acted as a thermal buffer for the lower stream bank, reducing fluctuations in soil temperature. This finding supports suggestions by Grissinger et al. (1981) that base flow depth should be considered in channel stability assessments. In contrast, high average stream width appears to increase the TDF of the upper bank. This increase in TDF could be the result of increased exposure to both winds and atmospheric cooling that would occur adjacent to a larger river where the vegetation would not form a complete canopy. These results also imply that studies of SAP in abandoned channels (Thorne and Lewin, 1979) may not accurately reflect the impact of SAP on stream bank retreat.

As would be expected, the elevation of the stream bank also influenced winter stream bank temperatures. Sites at higher elevations experienced a greater number of FTC in the lower bank and a higher overall duration frozen in the upper bank. This would be expected since air temperatures generally decrease with increasing elevations, providing more opportunities to freeze and maintaining frozen conditions longer.

4.2.3. Vertical Variations in Subaerial Processes

Differences in soil desiccation and freezing between the upper and lower stream banks were evaluated. The median differences between the upper and lower bank average daily SWP during the summer of 2002 ranged from 0 kPa at EL3 to 93 kPa at TC1 (Table 4.4). Using both a t-test and the signed rank test, the mean and median differences in summer average daily SWP were tested to determine if they were significantly different from zero (Thompson, 1936; Dixon and Mood, 1946; Hettmansperger and Sheather, 1986). The results show that, with the exception of the sites on the East Fork of the Little River, the upper banks were drier on average than the lower banks. The negative minimum differences in daily SWP likely resulted from saturation of the upper banks during small rainfall events that did not cause a large increase in stream stage. This finding suggests the upper banks are more susceptible to desiccation cracking than the lower banks. Prosser et al. (2000) noted that the upper banks of an ephemeral gully in Australia were dryer than the lower banks. Desiccation of the clay soil caused cracking and spalling of soil on the upper banks.

Table 4.4. Difference between upper and lower bank summer mean daily soil water potential in Appalachian headwater streams in southwest Virginia (H represents a herbaceous riparian buffer and F represents a forested riparian buffer).

Parameter	EL3 (H)	EL4 (F)	SC6 (H)	SC7 (F)	TC1 (H)	TC2 (F)
Mean Daily SWP Difference (kPa)	-1*	3	18	10	86	42
Median Daily SWP Difference (kPa)	0*	1*	10	4	93	32
Minimum Daily SWP Difference (kPa)	-36	-21	-16	-18	38	2
Maximum Daily SWP Difference (kPa)	27	30	81	47	137	105

* Not significantly different from zero at $\alpha = 0.05$, n = 92.

In general, lower bank soil temperature was slightly higher than upper bank soil temperature (Table 4.2). Differences in the number of FTC and the TDF, ADF and MDF between upper and lower banks were calculated for all sites with a complete data record over the winter for both the upper and lower banks (n = 13). There was a median increase of 3.5 FTC for

the upper bank, as compared to the lower bank (p = 0.06). Additionally, the upper banks were frozen for a median of 18.4 days longer than the lower banks (p = 0.002). These results suggest that the lower banks are less susceptible to FTC than the upper banks. Lawler (1993) also noted similar vertical variations in bank temperature on the River Ilston in the UK. This was likely because the lower bank is less exposed to winds and atmospheric cooling, was closer to the relatively warmer stream water, and had a higher soil moisture content.

The decreased summer SWP and increased winter freezing of the upper banks suggest that subaerial processes act predominately on the upper banks. This is supported by field observations throughout the study: the upper banks were generally more fragile than the lower banks and it was common, particularly in the winter, to find an accumulation of loose sediment from the upper bank at the toe of the stream bank. Considered in the light of stream bank retreat processes, this indicates there exists what Couper (2003) called a "vertical zoning" of erosive mechanisms: subaerial processes act mainly on the upper banks while fluvial entrainment dominates removal of the lower banks.

In addition to contributing soil directly to the stream system, SAP weaken the surface soil and make it more susceptible to fluvial entrainment. For a given stream discharge, Lawler (1986) measured less bank erosion during the summer than the winter. He attributed the difference in bank erosion to the "preparation" of the bank soils by FTC. In a study of stream bank retreat along the River Bollin-Dean in the UK, Knighton also noted that freezing increased weaknesses in bank soil and decreased the shear stress required for erosion. The extent of bank "preparation" influenced erosion more than the soil texture. Lawler (1993) observed significant bank erosion when FTC was followed by high stream stage. Similar observations were made during this study. On February 22, 2003, a large out of bank flood event occurred, following significant FTC during January and February. Stream banks that had been stable throughout storms during the summer and fall experienced large amounts of stream bank retreat. At site ST3, over 60 cm of stream bank was removed during this single event.

4.3. Summary and Conclusions

Extremes in summer stream bank soil temperature and moisture content appear to be most influenced by soil exposure to sunlight and night time atmospheric cooling. Exposure to sunlight is impacted by bank aspect, bank angle, vegetation type, density, and stage, and local

99

topography. Results of this study showed that stream banks with herbaceous vegetation had average maximum daily summer soil temperatures 0.3 $^{\circ}$C to 1.6 $^{\circ}$C higher and average summer diurnal temperature ranges up to 1 $^{\circ}$C greater than forested stream banks. Because forests achieve a full canopy early in the spring, they better protect stream bank soils against extreme heating and evaporation from the soil surface, as compared with the herbaceous vegetation. Differences in stream bank soil temperature decreased during the growing season as the herbaceous vegetation matured.

Increases in summer daily average soil water potential of 13% to 57% were observed under herbaceous vegetation, as compared to woody vegetation. Since herbaceous vegetation on the bank face draws moisture predominately from the surface soil, the stream bank surface under herbaceous vegetation is drier than under woody vegetation. As forests have deeper roots, they are able to draw moisture from a greater soil volume. The reduced surface evapotranspiration and solar exposure under forests minimized the occurrence of soil surface desiccation and cracking, as compared to herbaceous vegetation.

In contrast to summer conditions, the deciduous forest buffers provided little protection for stream banks during the winter. With the absence of a dense canopy, the stream banks under mature deciduous forest cover were exposed to solar heating and night time cooling, which increased the diurnal soil temperature range and the occurrence of freeze-thaw cycling. During this study, the forested stream banks experienced average diurnal temperature ranges two to three times greater than stream banks under dense herbaceous cover (average diurnal ranges of 1.2 $^{\circ}$C – 5.5 $^{\circ}$C versus 0.7 $^{\circ}$C – 1.8 $^{\circ}$C) and underwent as many as four times the number of freeze-thaw cycles (4 – 23 FTCs versus 1 – 14 FTCs). This conclusion was supported by field observations of frequent disruptions of the bank face by freeze-thaw events at all of the forested sites. Because dense vegetation remained on the bank face of the herbaceous sites throughout the winter, it insulated the stream banks and reduced diurnal fluctuations in soil temperature. Bare, cut stream banks under herbaceous vegetation behaved in a similar fashion as the forested banks.

Results of this study suggest that vegetation plays a major role in regulating stream bank soil moisture and temperature regimes. In headwater areas with clay soils susceptible to desiccation cracking, woody vegetation may provide the best protection against degradation by subaerial processes. In areas with silty soils prone to freeze-thaw cycling, a dense groundcover

may provide more protection against soil loss due to freeze-thaw cycling than just deciduous woody vegetation.