DOI: 10.1007/s00267-002-2909-y

Effects of Soil Conditions on Survival and Growth of Black Willow Cuttings

STEVEN D. SCHAFF*
S. REZA PEZESHKI
Department of Biology
The University of Memphis
Memphis, Tennessee 38152, USA

F. DOUGLAS SHIELDS, JR.
National Sedimentation Laboratory
USDA-ARS
Oxford, Mississippi 38655, USA

ABSTRACT / Current streambank restoration efforts focus on providing bank stability, enhancing water quality, and improving woody habitat using native vegetation rather than traditional engineering techniques. However, in most cases harsh site conditions limit restoration success. A two-year field study was conducted at Twentymile Creek, in northern Mississippi, investigating edaphic factors governing the survival of black willow (*Salix nigra*) cuttings used for streambank restoration. Low height growth, above-ground biomass production, and average leaf area were observed in willow cuttings grown in plots subjected to moisture deficits. However, sediment texture emerged as the dominant factor determining willow post growth, health, and survival. Shoot biomass, leaf biomass, and total above-ground biomass were 15-, 10-, and 14-fold greater for large willow cuttings (posts) grown in plots with sandy sediments relative to those grown in plots with similar moisture and soil redox potential but with silt and clay sediments. Average leaf size, average leaf mass and specific leaf area were all lower in fine textured plots. Under moisture conditions present at our sites, coarse-grained sediment (sand) was more conducive to willow growth, biomass production, and survival than were fine-grained sediments (silt/clay). Our results strongly suggest that soil texture and moisture conditions can determine restoration success. Therefore, it is critical that site conditions are factored into the selection of project locations prior to the initiation of willow planting restoration projects.

In an investigation of several channelized river systems, Hupp (1992) suggested that the unassisted recovery of stream channels was a predictable multiphase process. According to this model, up to 15 years was required before streambank stabilization was initiated by colonization of woody species such as willow (*Salix* spp.), birch (*Betula* spp.), and maple (*Acer* spp.), with riparian community recovery requiring an average of 65 years. Other investigations (e.g., Kesel and Yodis 1992) indicate unassisted recovery may take much longer. Streambank restoration attempts to accelerate recovery by actively establishing riparian vegetation as a first step in rebuilding a forested corridor adjacent to the waterway.

Forested riparian zones perform multiple functions within stream corridor ecosystems including moderating water temperature, providing large wood and other types of carbon inputs, providing habitats for terrestrial and aquatic species and their prey, forming corridors that facilitate movement of organisms, maintaining water quality, and reducing suspended sediment (Daniels and Gilliam 1996, Kleiss 1996, Keim and Schoenholtz 1999). Perhaps most importantly, riparian forests stabilize streambanks (Odgaard 1987, Hupp 1992, Daniels and Gilliam 1996, Montgomery 1997, Cerdà 1999) through the establishment of roots and by shielding banks from erosive currents (Kleinfelder and others 1992). Lateral roots bind with soil and resist lateral movement of the streambank during periods of high streamflow, whereas taproots penetrate deeply and resist soil sliding (Zhou and others 1998).

Black willow (*Salix nigra* Marshall) is a colonizing floodplain species that grows quickly, produces a massive root system, and has been shown to stabilize streamside sediments (Hupp 1992). It is ideal for streambank restoration because it may be propagated easily from cuttings, grows quickly, and provides rapid soil stabilization. Planting willow cuttings thus simulate the initial step in natural riparian reforestation described above. The use of large willow cuttings (posts) to control streambank erosion and to improve natural habitat has been adopted by a number of agencies (Grissinger and Bowie 1984, Shields and others 1995, 1998, Watson and others 1995, 1997). However, survival rates have varied,

KEY WORDS: Bioengineering; Black willow; Erosion control; Riverbank restoration; *Salix nigra*

Published online May 13, 2003.

*Author to whom correspondence should be addressed at The University of Georgia, Savannah River Ecology Laboratory, P.O. Drawer E, Aiken, South Carolina 29802, USA; *email:* sschaff@uga.edu

with rates as low as 40% observed by the end of the first growing season in Mississippi (Shields and others 1995). Explanations for such low success rates have included flooding, drought, vertical location on the bank, and soil texture (Pezeshki and others 1998a, Shields and others 1998).

Greenhouse studies have shown that both flooding and drought adversely affected physiological functions such as stomatal conductance and net photosynthesis, growth, and biomass production of potted willow posts (Pezeshki and others 1998a). The patterns of root development along the posts appeared to be dependent on watering regime; poor root growth was noted on the portion of post located in flooded zones of the soil. A field study by Pezeshki and others (1998b) also implicated both flooding and drought as major contributing factors to growth reduction in willows. However, the latter work dealt with willow post responses to soil conditions during the third growing season following field planting.

Clearly, data are needed to quantify willow responses to in situ conditions immediately following site planting. Such information is critical to our understanding of willow post growth during early stages of establishment. Such data may also lead to development of inexpensive, robust tools to assess the suitability of sites for restoration. Therefore, the present study focused on responses of willow posts to soil conditions during the first and second growing seasons following field planting. The specific objectives were to quantify the relationship between soil texture and moisture regime and early growth and survival of willow posts used for streambank restoration.

Materials and Methods

Experimental plots were located along a reach of Twentymile Creek, Lee County, Mississippi, USA (34°26' 54″>N, 88°33'56''W; Figure 1) in November 1997 prior to willow post planting in March 1998. The watershed of Twentymile Creek consists of cultivated floodplains (primarily cotton and soybeans) and low, steep hills. Streams are underlain by sands and chalky formations. Annual rainfall averages about 1500 mm. Floodplain soils are classified as sandy and silty loams of the Marietta and Robinsonville Series (Garber 1973).

Twentymile Creek has a long history of channelization intended to enhance floodplain drainage for agricultural purposes. Drainage districts formed by local governments and landowners between 1904 and 1911 constructed at least 19.2 km of straightened channels in the Twentymile Creek watershed in order to alleviate flooding. Reaches of the stream downstream from our study site were straightened and enlarged in 1938 and 1966, triggering 1–3 m of incision in the study reach and massive erosion throughout the watershed channel network (Shields and Hoover 1991) in accordance with conceptual models of channel evolution (e.g., Simon 1989). Between 1967 and 1980, erosion increased the channel cross-sectional area by factors of 1.4 to 2.7 and channel width by factors of 1.8–3.0 within the study reach (Neill 1987, in Shields and Hoover 1991). The willow planting project described herein was part of an effort to remediate damages triggered by the channelization.

Three transects were placed perpendicular to the creek and extended from the toe of the creek to the expected edge of the planted area, half way up the streambank (Figure 1). Transects were located to encounter a range of soil and moisture conditions based on visual evaluation of local topography, exposed soils, and stream morphology. Three plots, each measuring about 2 m perpendicular to the stream and 6 m parallel to the stream, were spaced at roughly 2-m intervals along each transect. Plot 1 was located adjacent to the stream, plot 2 halfway up the streambank, and plot 3 at the highest expected planting location.

Piezometers were installed in the middle of each plot to monitor groundwater fluctuation. Piezometers were constructed of PVC pipe with an outside diameter of 5.72 cm and were installed to a depth of 2–3 m using a soil auger. Water measurements were initiated prior to planting in November 1997. Water level at each monitoring well was quantified during each site visit using a Fisher m-Scope WLT water-level indicator (Fisher Research Laboratory, Los Banos, California, USA).

Surface water levels were recorded at 15-min intervals by the US Geological Survey at a gauge (Twentymile Creek near Guntown, Mississippi, USGS gauge number 02430680) that was 0.5–1.8 km upstream from the three study transects. Records for water surface elevation were obtained for the period of observation (March 1998–November 1999), and stage duration curves were developed for each study plot based on the vertical distance between the center of the plot and base flow water surface elevation. These curves allowed computation of the amount of time each plot was flooded during our study.

A single sediment sample was collected from 15, 30, 60, and 90 cm below the surface during piezometer installation and used to characterize the sediment conditions at each of the plots. Sediment samples were homogenized in the laboratory, and three replicate analyses were performed using portions of each sample. Particle size distribution was analyzed by the USDA Agricultural Research Service, Mid South Area, using a

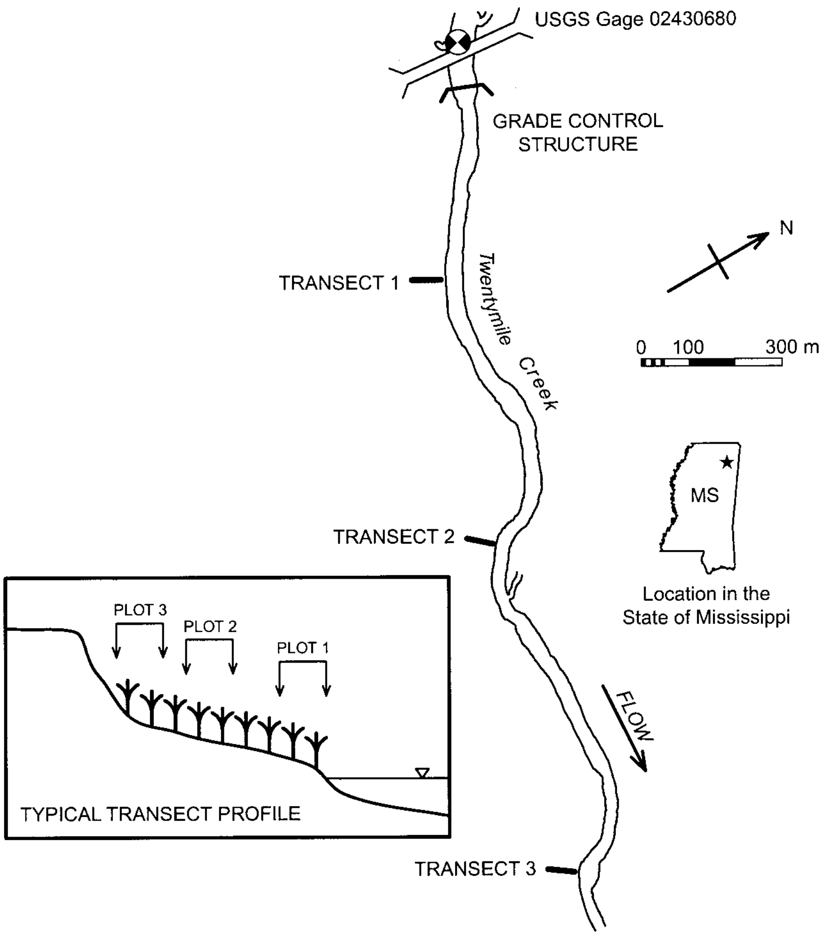

Figure 1. Map showing the location of the Twentymile Creek restoration site in northern Mississippi, USA.

Horiba model LA-910 laser scattering particle size distribution analyzer (Horiba Laboratory Products, Irvine, California, USA). Sediment texture at each depth for each plot is represented by the mean of these three values. Mean values of particle size distribution were used in the statistical and graphical analyses presented below.

In situ sediment measurements were initiated at the same time as water measurements. Sediment redox potential (Eh) was measured at a distance of 15 cm from each piezometer at 15-, 30-, 60-, and 90-cm depths below the surface. Measurements were conducted during each sampling day using platinum tipped redox electrodes, a millivoltmeter (Orion, model 250A, Thermo Orion, Beverly, Massachusetts, USA) and a calomel reference electrode (Corning, model 476350) as described in detail elsewhere (Patrick and DeLaune 1977). Measurements were recorded after the redox probes had been in the ground for 2–3 hours to allow for equilibration of the electrodes.

Sediment water potential (SWP) was measured at 15 and 30 cm below the soil surface during each site visit using Delmhorst model GB-1 gypsum blocks and a model KS-D1 soil moisture tester (Delmhorst Instrument Co., Towaco, New Jersey, USA). Blocks were buried next to each piezometer and provided bimonthly SWP measurements within the range of 0.00 to −1.50 MPa. SWP values presented are the average of the two depth measurements.

Climatic data were obtained from the National Weather Service for the nearest stations with available data for our period of observation (1998–1999). Precipitation data were obtained for Baldwyn, Mississippi, which is ~10 km from the site and air temperatures were obtained for Tupelo, Mississippi, which is ~30 km from the site.

Our study plots and willow posts were selected within a large restoration project that consisted of planting willows in selected zones along 4.2 km of the creek. Black willow posts were harvested from adjacent local populations along the creek in late February and early March 1998, while the posts appeared to be physiologically dormant. Cuttings at least 3 m in length with basal diameter of at least 7.5 cm, with side branches removed, were placed in holes with depths of 1.8–2.4 m. No more than 1.2 m of the post extended above ground. The posts were spaced at 0.9-m centers beginning at the edge of the creek and extending half way up the bank. Each plot contained two rows of six posts planted parallel to the streambank, for a total of 12 posts per plot.

Heavy rain within the watershed raised the level of the stream on the night prior to willow planting at transect 3, resulting in an atypical planting pattern. All posts planted at transect 3 were located a significant distance from the stream along a portion of the streambank with little variation in access to groundwater. This is not the typical planting pattern used for streambank restoration of channelized waterways, nor did it provide congruent growing conditions with the other two experimental transects (transects 1 and 2); therefore, results from this transect will be presented separately as a case study.

A major storm event in January 1999 washed out plots 1 and 2 at transect 1. These plots were relocated approximately 50 m from their original locations before the beginning of the second growing season by simply designating new plots within the area planted at the beginning of the study. The new plots were at similar elevations to the original plots, and the posts in the new plots were similar in size, age, and origin and had been planted at the same time as posts in the original plots. Replacement piezometers were installed and sediment samples were collected using similar techniques described above. In addition, SWP and Eh measurements were conducted according to the protocol described above.

Plant Measurements

Initial shoot production was quantified by counting the number of shoots originating from each post one month after planting. Height was measured at the end of each growing season using a telescoping measurement rod. Measurements were taken from the top of the initial willow post (to avoid inaccuracies resulting from fluctuating soil levels) to the terminal bud of the tallest shoot. Zeros were recorded when no shoots were produced or no growth was measured and included in all data analyses.

Survival was determined at the end of each growing season by visual inspection of each post for living biomass. In addition, at the conclusion of the experiment (October 1999), six of the 12 trees in each plot at transects 1 and 2 were randomly chosen for aboveground biomass determination. Branches were removed from the original post and separated into shoot and leaf components. Branches were weighed using a portable field scale. A representative subsample of branches was transported back to the laboratory to determine the fresh weight-dry weight ratio using basic regression analysis. Leaves were packed in plastic airtight bags and transported to the lab for fresh and dry weight measurements. Specific leaf area (SLA) was measured using 20 randomly selected leaves from each tree and was calculated as the ratio of leaf area per leaf fresh mass.

Data Analysis

The general linear models (GLM) procedure of the Statistical Analysis System (SAS 1990) was used to test for differences in means among soil moisture and texture treatments. Analysis was conducted as a two-factor analysis of variance. Leaf area, leaf mass, and specific leaf area were analyzed using subsamples of leaves from individual trees. Therefore, the sample tree was nested within the sample (transect) for these analyses. Tukey's Studentized range tests were used to identify differences within each treatment. Biomass data was log-transformed prior to analysis to minimize the variation in biomass production based on factors associated with post age or stock quality.

Results

Both years of our study were hot and dry relative to normal conditions (Table 1). Growing season (March–October) dry-bulb monthly mean temperatures were as much as 2.6°C and 1.7°C above normal in 1998 and 1999, respectively, and averaged 1.6° and 0.8°C above normal in 1998 and 1999, respectively. Cumulative total precipitation was 366 mm below normal between March 1998 and October 1999. Measurable precipitation was recorded on only 8 days in July through October 1999, which compares with a normal value of 30 days.

Analysis of gauge records showed that the study plots were flooded only for short periods (Figure 2). Plots were located 0.3–3.0 m above base flow elevation; associated flooding durations ranged from 0.07% to 5% of the time. The median length of flooding was 1.2 days for the lowest plots, while the median time between flooding episodes was 3.0 days. Longest floods occurred in March 1999.

A wide range of sediment textures were present in the experimental plots (Table 2). Sediment samples averaged 71% sand, 22% silt, and 7% clay, but ranged from 0 to 100% sand, 0 to 76% silt, and 0 to 39% clay. Typical grain size distributions for samples dominated by fine-grained and sandy sediments are shown in Figure 3. Sands were fairly uniform, with median sizes between 250 and 350 μm.

Table 1. Monthly mean climatic data recorded by the National Weather Service[a]

Month	Temperature (°C)			Precipitation (mm)		
	Normal dry-bulb	1998 dry-bulb	1999 dry-bulb	Normal	1998	1999
Jan	4	7	8	122	Missing data	236
Feb	7	9	10	118	Missing data	63
Mar	12	11	10	152	128	169
Apr	17	16	19	131	154	111
May	21	23	21	143	62	96
Jun	25	28	26	96	40	165
Jul	27	28	28	108	194	41
Aug	26	27	28	76	96	3
Sep	23	26	24	90	43	9
Oct	17	19	18	86	93	48
Nov	11	13	13	121	38	Missing data
Dec	6	8	8	154	185	Missing data

[a]The term "normal" is defined by World Meteorological Organization (1989).

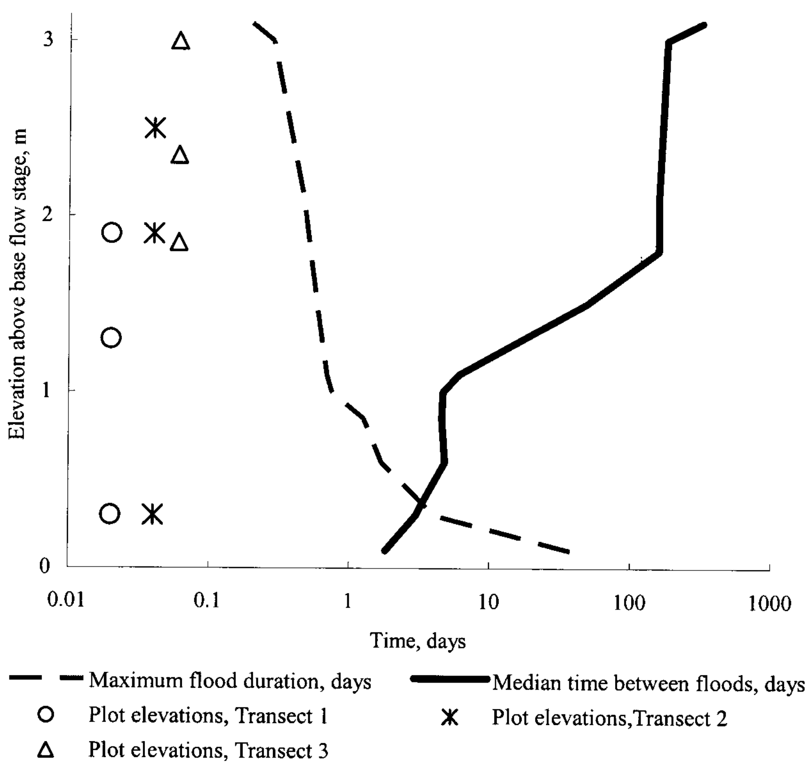

Figure 2. Maximum flooding duration and median interval between flooding for Twentymile Creek near Guntown, Mississippi for the period of March 1998 through November 1999. Willow study plot elevations are relative to base flow stage.

Interactions Between Environmental Variables

Average leaf area and height growth were the only measured response variables for which interactions between plot elevation and texture were significant ($P < 0.10$, Table 3 and Figure 4). The interaction diagrams clearly separate responses between coarse and fine-grained soil texture groups. In addition, the interaction between plot elevation and sediment texture was manifest as differences in leaf expansion and height growth at high elevation. Therefore, we feel the interactions between the main factors can be clearly interpreted and can be presented independently.

Effect of Elevation

Sediment texture and moisture availability differed across plots for each growing season. In 1998, low plots had 35%, medium plots contained 48%, and high plots contained 21% fine material (Table 4). Low elevation

Table 2. Sediment sizes for experimental plots

Transect-plot	Sand (mean ± SD, %)	Silt (mean ± SD, %)	Clay (mean ± SD, %)
1-1 (1998)	77± 4	18± 3	4± 1
1-1 (1999)	68±27	23±19	10± 8
1-2 (1998)	71±10	22± 7	7± 3
1-2 (1999)	88±11	10±10	2± 2
1-3	89± 1	9± 1	3± 0
2-1	52±35	36±24	12±11
2-2	32±18	49±11	19± 7
2-3	69± 7	24± 5	7± 1
3-1	94± 7	5± 6	1± 1
3-2	86± 8	11± 7	3± 1
3-3	18±36	57±25	24±13

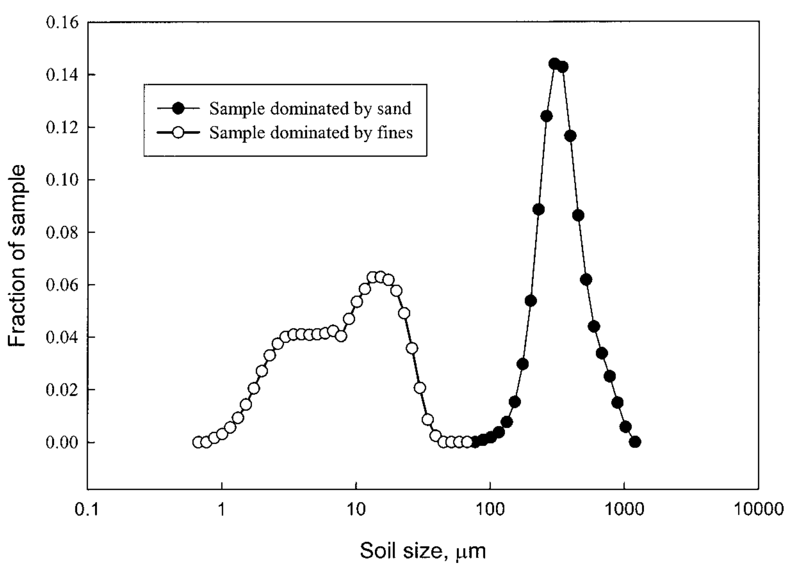

Figure 3. Typical soil size gradations for samples collected from experimental plots, Twentymile Creek.

plots were closest to the water table and had the lowest Eh values (+233 mV, Table 4). These Eh values are considered to represent moderately reduced soil conditions. In contrast, medium and high elevation plots had aerated sediments with Eh values of +483 and +521 mV, respectively (Table 4).

Relocation of two plots following the storm event in January 1999 (see above) shifted the overall soil texture for the low and middle elevation plots to 40% silt and clay (Table 4). Low elevation plots were closest to the water table (0.52 m), resulting in reduced sediment Eh conditions (+183 mV, Table 4). The middle and high elevation plots were farther from ground water (1.31 and 2.11 m, respectively) and had sediment Eh values indicative of aerated soils (+385 and +407 mV, respectively). Periodic sediment water potential measurements indicated no evidence of soil water deficits across the elevational gradient during 1998 (Table 4). However, SWP was lower (more negative) at high elevation plots during 1999, indicating a soil water deficit.

In 1999, height growth was greater in middle plots compared to high elevation plots (Table 4). Low elevation plots consistently produced the most total biomass (P = 0.0608) and shoot biomass (P = 0.0671) while high elevation plots yielded the least (Figure 5). Similarly, leaf biomass in low elevation plots was greater than high elevation plots (P = 0.0335). Leaf size showed no changes as average leaf size (leaf area per leaf, P = 0.2972) or average leaf mass (mass per leaf, P = 0.1158) and specific leaf area (P = 0.9252) remained similar across the elevational gradient (Table 4).

During the 1998 growing season survival rates were 67%, 50%, and 46% for high, middle, and low elevation plots, respectively (Table 4). Interestingly,

Table 3. Two factor analysis of variance on willow post growth parameters measured at Twentymile Creek restoration site[a]

Source of variation	*df*	*F*	*P*
Height growth 1998			
Texture (T)	1	36.2	< 0.0001
Elevation (E)	2	2.24	0.1145
T × E	2	2.77	0.0699
Error	66	6617.6[b]	
Height growth 1999			
Texture (T)	1	73.68	< 0.0001
Elevation (E)	2	2.27	0.1169
T × E	2	2.95	0.0647
Error	38	8973.8[b]	
Avg. leaf area			
Texture (T)	1	55.68	< 0.0001
Elevation (E)	2	1.27	0.2972
T × E	2	3.42	0.0474
Error	627	2.68[b]	
Avg. leaf weight			
Texture (T)	1	33.48	< 0.0001
Elevation (E)	2	2.34	0.1158
T × E	2	1.79	0.1866
Error	627	0.0017[b]	
Specific leaf area			
Texture (T)	1	5.46	0.0271
Elevation (E)	2	0.08	0.9252
T × E	2	2.08	0.1442
Error	627	313.4[b]	
No. initial shoots			
Texture (T)	1	51.78	< 0.0001
Elevation (E)	2	1.9	0.1583
T × E	2	0.14	0.8701
Error	66	483.1[b]	
% posts with shoots			
Texture (T)	1	11.28	0.0013
Elevation (E)	2	0.42	0.6603
T × E	2	0.42	0.6603
Error	66	0.0998[b]	
% survival			
Texture (T)	1	19.99	< 0.0001
Elevation (E)	2	1.45	0.2413
T × E	2	0.07	0.9332
Error	66	0.2008[b]	

[a]The two edaphic factors considered were soil texture and planting elevation along the streambank.
[b]Mean squares value.

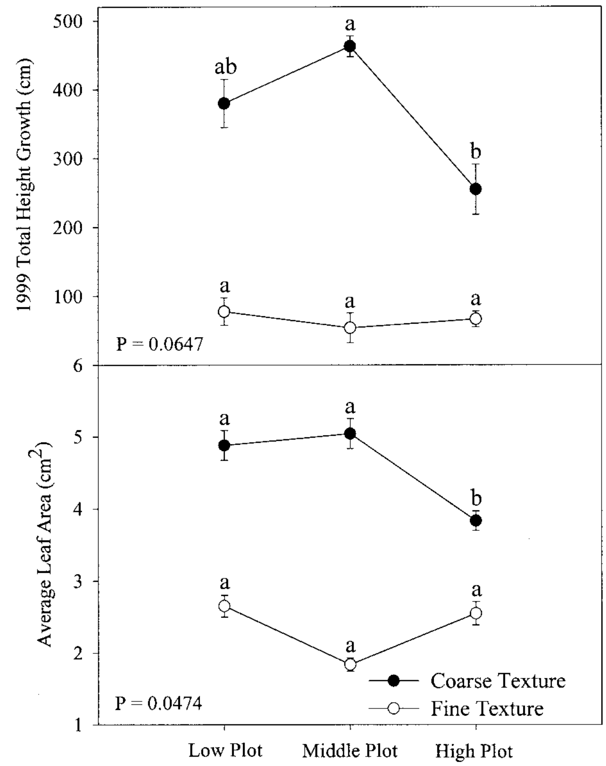

Figure 4. Diagrammatic representation of interactions between soil texture and plot elevation for total height growth (cm) and average leaf area (cm ^{2}) for the 1999 growing season. Differences in means for each parameter at different plot elevations are indicated by different lower case letters.

posts that survived 1998 and those additional posts selected for the 1999 growing season survived through the end of our study, even though there was evidence of water deficits in high elevation plots during that year (Table 4).

Effect of Sediment Particle Size

Initial growth responses were negatively affected by the amount of silt and clay present in sediment. For instance, in 1998 there were 25% fewer posts with live shoots one month after planting ($P = 0.0013$) and 60% fewer shoots per post ($P < 0.0001$, Table 5) in transect 2 as compared to transect 1. Additionally, this trend of poor growth held throughout the duration of the study with substantial reductions in height growth during both 1998 ($P = 0.0001$) and 1999 ($P = 0.0001$, Table 5) growing seasons.

Above-ground biomass production was also low in fine-textured sediments. Shoot biomass, leaf biomass, and total above-ground biomass were 15-, 10-, and 14-fold greater for posts grown in coarse versus fine-grained sediments ($P = 0.0001$ for all biomass components, Figure 6). Field observations indicated substantial changes in leaf morphology associated with sediment texture. Analysis of leaf morphological variables supported these observations as average leaf size, average leaf mass, and specific leaf area were all lower in fine textured plots ($P = 0.0001$, $P = 0.0001$, and $P = 0.0417$, respectively, Table 5).

Willow posts planted in fine-grained sediments had lower survival rates by the end of the first grow-

Table 4. Environmental and biological data for plots located along an elevation gradient[a]

	Vertical location		
	Low elevation	Middle elevation	High elevation
1998 results			
% silt + clay	35	48	21
Depth to water (m)	0.3 (0.03)c	1.4 (0.05)b	1.7 (0.08)a
Eh (mV)	233 (15.2)c	483 (4.5)b	521 (12.6)a
SWP (MPa)	−0.015 (0.003)a	−0.021 (0.004)a	−0.023 (0.004)a
% posts with shoots	91 (6)a	88 (7)a	83 (8)a
No. initial shoots	47.5 (6.0)a	43.0 (6.2)a	35.3 (5.4)a
Height growth (cm)	120.5 (31.2)a	214.7 (34.7)a	109.4 (18.7)a
% survival	46 (10)a	50 (10)a	67 (10)a
1999 results			
% silt + clay	40	40	21
Depth to water (m)	0.52 (0.03)c	1.31 (0.05)b	2.11 (0.06)a
Eh (mV)	183 (13.1)b	385 (10.1)a	407 (6.5)a
SWP (MPa)	−0.012 (0.001)b	−0.101 (0.016)b	−0.534 (0.057)a
Height growth (cm)	290.9 (42.5)ab	345.8 (52.6)a	225.8 (36.6)b
Average leaf area (cm^2)	3.87 (0.15)a	3.58 (0.16)a	3.25 (0.11)a
Average leaf weight (g)	0.087 (0.004)a	0.073 (0.003)a	0.069 (0.002)a
Specific leaf area (cm^2/g)	48.6 (1.66)a	50.5 (1.45)a	49.4 (0.68)a
% survival	100	100	100

[a]*Elevation treatments:* low elevation included plot 1 from each transect, medium elevation included plot 2 and high elevation plot 3. Standard error is shown following the mean in ().

Definitions: Depth to water was measured as the depth to the water table, Eh is soil redox potential, SWP is soil water potential, and the percentage of posts with shoots and No. (number) of initial shoots were growth parameters measured one month after planting. Means in each row followed by the same letter are not different.

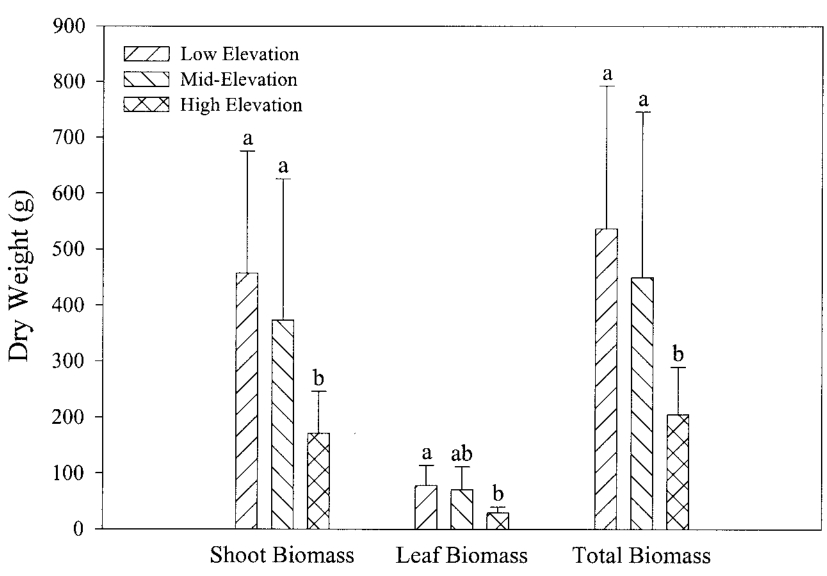

Figure 5. Above-ground biomass production and biomass components for plots grouped according to elevation at the Twentymile Creek restoration site, Mississippi. Elevation treatments combine data from transect 1 and transect 2, where plot 1 in each transect was grouped to form the low elevation treatment, plot 2 forms the mid-elevation, and plot 3 forms the high elevation treatment. For each measured parameter, bars denoted with similar lower case letters represent no difference across elevation groupings.

ing season compared to posts planted in coarse sediments (31% vs 78%, $P < 0.0001$, Table 5). However, all of the trees that survived the first growing season were alive at the end of the study, indicating less sensitivity of willow post survival to sediment texture and other edaphic factors once the posts became established on the bank.

Case Study: Transect 3

The stream bank at transect 3 sloped gradually from the top of the bank to toe in contrast to the relatively steep slopes observed at transects 1 and 2. As noted above, plots at transect 3 spanned a narrower range of elevation than the other two transects. As a result, transect 3 posts were subjected to different growing

Table 5. Soil, water, and willow growth characteristics for plots grouped into different soil textures

	1998 results		1999 results	
	Coarse sediments	Fine sediments	Coarse sediments	Fine sediments
% silt + clay	21	48	18	48
% sand	79	52	82	52
Depth to water (m)	1.2 (0.09)a	1.1 (0.12)a	1.4 (0.08)a	1.2 (0.05)b
Eh (mV)	423 (22.1)a	443 (15.0)b	322 (9.6)a	328 (13.2)a
SWP (MPa)	−0.022 (0.005)a	−0.018 (0.004)a	−0.285 (0.046)a	−0.173 (0.025)b
% posts with shoots	100% (0.0)a	75% (0.07)b	NA	NA
No. initial shoots	60.6 (4.1)a	23.3 (3.2)b	NA	NA
Height growth (cm)	129 (19)a	13 (5)b	363 (23)a	67 (12)b
Average leaf area (cm^2)	NA	NA	4.58 (0.11)a	2.35 (0.08)b
Average leaf weight (g)	NA	NA	0.094 (0.003)a	0.055 (0.002)b
Specific leaf area (cm^2/g)	NA	NA	52.9 (1.26)a	45.5 (0.68)b
% survival	78 (7)a	31 (8)b	100	100

[a]Coarse sediment plots were located in transect 1 and fine sediment plots were located in transect 2. Comparison of means is shown between textures within each year and is followed by standard error in (). See Table 4 for a description of table parameters. Means in each column followed by the same lower case letter are not different.

conditions. Sediments at this transect had the greatest contrast in texture, ranging from 6% to 82% fines (Table 6). The response of the plants to the range of edaphic conditions lends additional insight into the effects of sediment texture on willow posts grown at sites with a deeper water table but little topographic relief.

The average depth to the water table at all plots was greater than 1.5 m during both the 1998 and 1999 growing seasons. The middle elevation plot had the deepest water table each year, followed by the high and low elevation plots (Table 6). Differences were detected for sediment Eh during the 1999 growing season ($P <$ 0.0001), but these values were all above +350 mV, indicating nonsaturated, oxic conditions (Table 6).

Initially, sediment texture did not affect the growth of posts; i.e., no differences were detected for the percentage of posts that produced shoots or the number of initial shoots per post (Table 6). In addition, there were no differences in height growth or survival through the end of the 1998 growing season. However, after two growing seasons, posts grown in fine-grained sediments had grown about 40% less ($P < 0.0001$) than those grown in coarse-grained sediments (Table 6) as was noted for other study transects (Table 5). Although the pattern of height growth at transect 3 was consistent with observations on the effect of increased silt + clay content in the sediment noted at other transects, there was a substantial difference in the severity of the effects. Plots with fine sediments in transects 1 and 2 averaged 48% silt + clay content, leading to an 82% reduction in height growth relative to plots with coarser sediments (67 vs 363 cm, Table 5). In contrast, the sediments in the high elevation plot at transect 3 averaged 82% silt + clay, but this plot exhibited only a 44% reduction in height growth (346 vs 614 cm, Table 6). Thus, the high elevation plot at transect 3 had twice as much fine-grained sediment yet had half the height reduction. This response suggested that cuttings may have exploited zones of favorable rooting habitat (sandy layers) despite high overall average sediment silt/clay content. To investigate this idea, sediment texture profiles (consisting of samples from 15, 30, 60 and 90 cm below the surface) for each plot were reexamined, and the layer containing maximum sand content was designated the "best available layer" for root formation and development. The high elevation plot at transect 3, unlike many of the other plots dominated by fine-textured sediments, contained a sandy layer within the top 90 cm. The 1999 mean height growth per post shows a positive relationship with the percent sand found in the "best available layer" ($r^2 = 0.5442$, $P = 0.0233$, Figure 7).

Discussion

The results above demonstrate the complexity of sediment–plant interactions along highly dynamic creek banks characterized by steep slopes, fluctuating water tables, and variable edaphic conditions. Several of these characteristics have been reported to influence willow growth and survival along riverbanks and under laboratory conditions (Pezeshki and others 1998b, Shields and others 1998, Amlin and Rood 2002). In the present study, there were clear patterns of poor height growth due to saturated sediment conditions characteristic of low elevation plots as well as evidence showing the sensitivity of black willow to sediment moisture

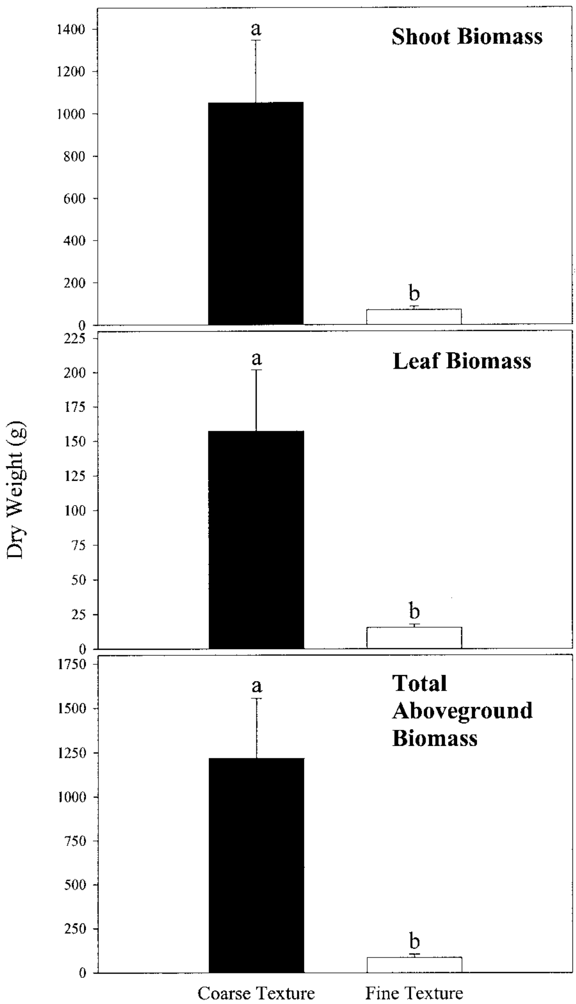

Figure 6. Comparisons of shoot, leaf, and (C) total aboveground biomass grouped based on differences in soil texture, where transect 1 represented the coarse textured and transect 2 the fine textured plots. Bars with different letters indicate differences in biomass.

deficit at high elevation plots. Sediment texture appeared to have a greater influence on willow growth and survival than soil moisture availability, although these two factors are interconnected.

Elevation/Sediment Moisture

Conditions at the Twentymile Creek site indicated the establishment of a moisture gradient along bank elevation; i.e., plots at higher elevation experienced reductions in moisture availability, particularly during the 1999 growing season (Table 4). Willow posts grown in these plots exhibited slowing of height growth in comparison to posts grown in mid-elevation plots (Table 4). These results are consistent with previous reports of drought responses in black willow (Dionigi and others 1985, McLeod and others 1986, Pezeshki and others 1998a) as well as other members of the Salicaceae family (Segelquist and others 1993, van Splunder and others 1996, Amlin and Rood 2002). At the Twentymile Creek site, the greatest survival rates for the 1998 growing season were observed at high elevation plots (67%) where posts were the most likely to encounter sediment moisture deficits. However, periodic sediment water potential measurements indicated little evidence for a drought, as sediment water potential averaged −0.023 MPa in high elevation plots, indicating ample moisture (Table 4). It is important to note that sediment texture and SWP are interrelated as availability of water to plants at a given SWP is governed by sediment texture as well as plant's ability for osmotic adjustment. Drainage of coarse sediments is faster, creating problems for plant water uptake, while more negative internal root water potential is needed to extract water from fine sediments. The plant–sediment interactions need additional investigation that consider assessment of root surface area, plant osmotic adjustment, and water uptake in a range of sediment moisture/texture conditions.

An important observation related to survival is that all of the trees that survived the first growing season were alive at the end of the study, indicating less sensitivity of willow posts to edaphic factors once the posts became established. This finding is in agreement with the reported performance of three willow species planted on riverbank sites in the Netherlands; all the study species showed low mortality after the first year following planting (van Splunder and others 1994).

Members of the Salicaceae family, including black willow, display enhanced shoot growth when exposed to increased soil moisture availability (Hansen and Phipps 1983, Phipps and others 1983). In the present study, the benefits of favorable sediment moisture are clearly indicated for mid-elevation plots, where ample soil moisture combined with aerated soil conditions (high Eh) enhanced height growth.

As previously mentioned, there was no evidence of soil moisture deficits in high elevation plots in 1998. However, established posts in these plots were subjected to increasingly dry conditions as the 1999 growing season progressed (Table 4). SWP steadily decreased from approximately −0.10 MPa in May to −1.5 MPa in September (data not shown), leading to poor leaf biomass production (Figures F4 and 54 and 5). This response also represents a loss in photosynthetic surface area and a corresponding loss in carbohydrate and sugar production that may, in part, explain the

Table 6. Edaphic conditions and willow post responses at transect 3, Twentymile Creek restoration site, Mississippi[a]

	Transect 3		
	Low elevation	Middle elevation	High elevation
1998 results			
% silt + clay	6	14	82
Depth to water (m)	1.6 (0.13)c	2.4 (0.13)a	2.1 (0.00)b
Eh (mV)	517 (13.4)a	485 (13.7)a	516 (9.8)a
SWP (MPa)	−0.032 (0.008)a	−0.034 (0.008)a	−0.118 (0.063)a
% posts with shoots	100 (0)a	92 (8)a	100 (0)a
No. initial shoots	46.3 (5.3)a	28.5 (5.1)a	50.6 (8.2)a
Height growth (cm)	285.0 (54.5)a	214.6 (49.5)a	173.8 (39.0)a
% survival	75 (13)a	67 (14)a	75 (13)a
1999 results			
% silt + clay	6	14	82
Depth to water (m)	2.17 (0.01)c	2.61 (0.02)a	2.45 (0.02)b
Eh (mV)	391 (13.5)b	407 (10.4)b	495 (12.6)a
SWP (MPa)	−0.288 (0.065)b	−0.577 (0.082)b	−0.208 (0.034)a
Height growth (cm)	614.2 (27.0)a	558.3 (23.6)a	346.0 (49.2)b
% survival	100	100	100

[a]See Table 4 for a description of table parameters. Standard error is shown following mean in ().
Means in each column followed by the same lower case letter are not different.

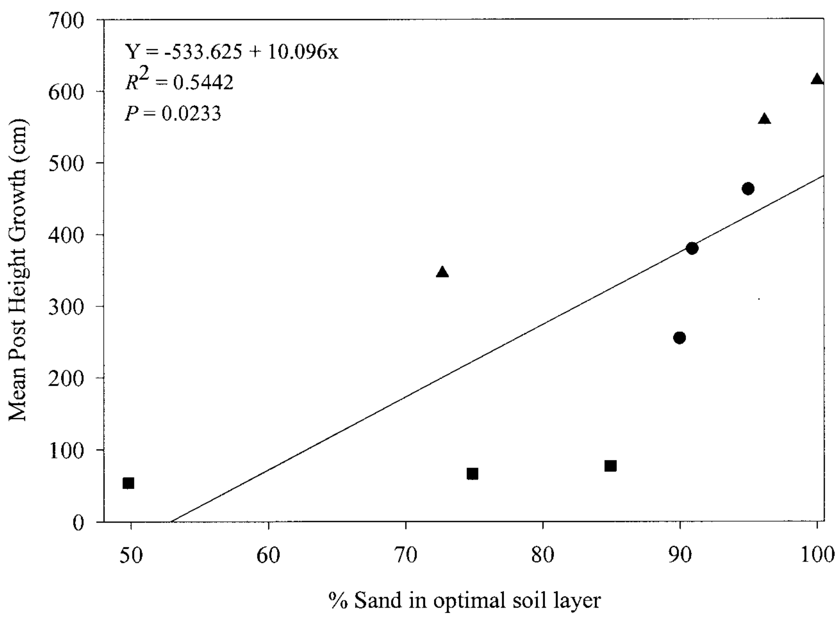

Figure 7. elationship between willow post height growth and the maximum percentage of sand in any layer of the soil profile at each of the nine study plots at Twentymile Creek. ●, transect 1 plots; ■, transect 2 plots; ▲, transect 3 plots.

reduction in height growth and aboveground biomass production noted for high elevation plots (Figures 4 and 5).

The opposite end of the sediment moisture gradient, at the stream edge, exposes willow posts to extended periods of saturated sediment conditions. Soil Eh values measured in low elevation plots indicated reducing sediment conditions (Eh below +350 mV) (Table 4). Previous studies have shown that growth and biomass production of black willow may decrease under these conditions (McLeod and others 1986, Donovan and others 1988, Pezeshki and others 1998a). However, black willow is a flood-tolerant species (Hook 1984) and is better adapted to flooding than to drought (Dionigi and others 1985). For example, in flooded soils, black willow has the capability to oxidize its rhizosphere (Dionigi and others 1985). Rhizosphere oxidation has been linked to the development of aerenchymal tissue, which serves as a conduit for oxygen transport from the aerial portions of the shoot to the root system allowing normal root metabolic activity (Armstrong and others 1991, Pezeshki 1991, 2001). This process leads to radial oxygen loss, i.e., oxygen leaks through the tip and the actively growing root zone into the immediate rhizosphere, and confers a positive benefit to tree performance (Talbot and others 1987, Armstrong and others 1991, Pezeshki 2001).

In the present study, there were no differences in height growth or above-ground biomass production of posts located at low elevation in comparison to mid-elevation plots (Table 4 and Figure 4). A simple explanation for this result is that continuous or extended sediment flooding may not have been present in low elevation plots throughout the 1999 growing season, as it was a drier than normal summer (Table 1). Nevertheless, fluctuating river stage levels created saturated sediments but such conditions typically lasted for short periods and were unlikely to impose severe stress on willows. For instance, on several sample days soil Eh indicative of aerated conditions was measured within the top 15 cm of the sediment surface in low elevation plots, while on other measurement days moderately reducing sediment conditions were found. Another possible explanation is that patterns of root growth, although not measured in this study, may have provided the necessary advantages to exploit aerated root zones early in the growing season, allowing the willows to avoid saturated sediments. Rein and others (1991) showed that early root growth was promoted when cuttings of woody species were grown under high soil moisture availability. However, excess soil moisture may lead to reduced Eh conditions. Such conditions affect root metabolism (Armstrong and others 1991), stunt root growth (Pezeshki and others 1998a), and may result in root death (Stepniewski and others 1991). Adventitious root development relies on the metabolism of stored sugars and carbohydrates in the woody tissue of the cutting (Hassig 1986, Tschaplinski and Blake 1989). Therefore, cuttings may initially avoid the detrimental metabolic constraints produced by low sediment Eh by utilizing stored energy to produce roots that penetrate adjacent, unsaturated sediment zones. These roots would then be in ideal conditions (moist, aerated soils) for tree growth. At the Twentymile Creek site, posts were planted along steep banks and adjacent to, rather than within, the part of the stream channel subjected to continuous inundation. Therefore, in most study plots aerated sediment zones were close enough to plants to be easily accessible to rapidly developing roots.

Sediment Texture

Clearly, soil texture had a much more substantial impact on willow post vigor than planting elevation. Posts grown in sandy sediments had greater height growth, above-ground biomass production, average leaf area, and survival compared to posts grown in fine sediments (Table 5, Figure 6). This is somewhat contradictory to published reports on the impact of soil particle size on members of the Salicaceae. In general, most findings report the greater water holding capacity afforded by fine textured sediment is beneficial for growth, especially under circumstances where moisture availability may be limited (Mahoney and Rood 1992, Hughes and others 2000). Besides shielding roots from severe dessication, fine textured sediment (silt) has been shown to promote the effectiveness of willow posts for bioengineering by increasing the production of fine roots (in comparison to gravel), and thus the root net that binds bank sediments together (Oplatka and Sutherland 1995). However, most sediment texture comparisons involved differences between sand and gravel or a layer of silt overlying gravel. Sediments at the Twentymile Creek site were much more extreme and encompassed a much larger range of soil textures (Table 2).

Roots of *Salix* prefer to grow in the saturated groundwater zone and will rapidly elongate to maintain contact with free water (Amlin and Rood 2002). Many studies document the importance of rapid root growth for the survival and growth of riparian trees (Mahoney and Rood 1992, Segelquist and others 1993, van Splunder and others 1996, Kranjcec and others 1998, Scott and others 1999, Horton and Clark 2001, Amlin and Rood 2002). However, the thick, fine-textured sediment measured in transect 2 at the Twentymile Creek site likely prevented rapid root elongation resulting in reduced willow health. Responses similar to those we observed have been linked to increased soil bulk density (defined as the mass of dry soil per unit bulk volume that includes the soil air space) (see Kozlowski 1999). Jones (1983) showed that as the percentage of silt + clay in soils increased, the bulk density required to significantly reduce root growth decreased. Reductions in root growth can initiate a shift in above-ground productivity (Pezeshki and Santos 1998). In this study, willow posts grew substantially less (80%–90%) when planted in soils with double the amount of silt + clay (Table 5). Height growth in other woody species were reported to be reduced approximately 50%–75% due to increased soil bulk density (Corns 1988, Tuttle and others 1988, Nambiar and Sands 1992), suggesting black willow is much more sensitive to changes in sediment texture. This difference in sensitivity may be a reflection of specific adaptations of black willow for sandy, moist riverbanks.

Poor above-ground biomass and leaf growth were found for posts grown in fine-textured sediments (Table 5, Figure 6). Again, we believe this is due to the inhibition of root expansion by fine-textured sediments. Restricted root growth has been shown to result in reduced shoot biomass in riparian trees (Pezeshki and Santos 1998). Plants must maintain equilibrium between water absorption structures (roots) and water loss structures (leaves) in order to maintain a sustainable water balance. At the Twentymile Creek site, willow posts dropped leaves and reduced their specific leaf area, presumably to maintain this balance in fine-textured sediments. Other *Salix* species have been shown to reduce the ratio between leaf mass and leaf area as a mechanism for coping with water stress (van Splunder and others 1996). Similarly, leaf biomass production (measured as crown volume) was shown to decline when roots of poplars were subjected to poor edaphic conditions (Scott and others 1999). The loss of leaf surface area also represents a loss of photosynthetic potential and may partially explain the subsequent reduction in tree height and productivity as reported for other woody species (Conlin and van den Driessche 1996).

Perhaps most important to streambank restoration efforts, there was a difference of 47% in willow post survival between soil texture classes by the end of the first growing season (Table 5). Increased soil bulk density has been linked to mortality in other woody species, including members of the Salicaceae (Tuttle and others 1988, Stone and Elioff 1998). Niiyama (1990) suggested that soil texture play a role in species abundance in *Salix* communities, and Stromberg and others (1991) further suggest that willow survival in riparian forests is strongly correlated with site quality. This is strong evidence that a suite of streambank characteristics, which must include soil texture and/or bulk density, should be evaluated prior to the onset of restoration in order to ensure success.

Case Study: Transect 3

While trends in growth responses at transect 3 support the effect of sediment texture on tree growth, there was a clear difference in the severity of the impact at this transect (Tables 5 and 6). This difference was interpreted as qualitative, suggesting variations in edaphic conditions existed within planting locations. A review of the sediment texture analyses confirmed variations in the sediment profile and showed a positive relationship between the maximum percentage of sand found within any soil layer at a given plot and willow post height growth (Figure 7). This indicates that willow posts exploited zones or layers within the sediment profile that were more suitable for root development and function. This agrees with findings by Sands and others (1979), who showed that roots were unevenly distributed in soils varying in soil strength; weaker soils allowed greater root exploitation than did stronger soils. Thus, willow post growth and productivity may not be limited if suitable sediment layer(s) occur within the active rooting zone.

Alternatively, differences in properties between fine textured sediments may offer an explanation to the observed variations in sediment texture effects. For example, Sands and others (1979) found that root growth stopped at high soil strengths (defined as the resistance to root penetration). Therefore, even though plots containing fine soils in transect 3 had a much higher percentage of silt + clay than did other fine textured plots, soil strength may have been below the critical value for root growth. Specific parameters associated with soil texture, such as bulk density and soil strength, were not measured in this study but may offer more insight into the suitability of sites for restoration activities. Little and others (1982) showed that mean shear strength for northwest Mississippi streambanks comprised of post settlement alluvium was only about half as great as those comprised of much older fine-grained alluvium. Such differences may have occurred between plots in this study. Clearly, future research efforts need to determine the relationship between soil texture and bulk density and/or soil strength in order to fully understand their effects on willow post growth.

Conclusions

This study identified the importance of sediment texture and moisture availability for willow post growth, biomass production, and survival on a riverbank site during the early stages of plant establishment. Willow located high up on the bank grew slower than those located at the lower elevations. More importantly, willows grew faster in sand than in finer sediments. Poor plant growth and above-ground biomass production were found in posts subjected to sediment moisture deficits. However, sediment texture emerged as the dominant factor governing willow growth and survival. Coarse-grained sediment (sand) was more conducive to willow growth, biomass production, and survival than was fine-grained sediment (silt/clay). Our results demonstrated that sediment texture and moisture conditions can determine success during the most critical stage of restoration, i.e., the first growing season.

Therefore, it is critical that site conditions be factored into the selection of project locations prior to the initiation of willow planting restoration projects. In addition, erosion of willow posts is a primary cause of planting failure. Thus, site erosion potential may be critical for project success. The question then remains as to how close to the bank toe the posts should be planted to avoid the destructive effects of erosion while minimizing the chance of posts suffering from soil moisture deficit. Since posts are relatively cheap, those planted at lower elevations may be regarded as sacrificial elements that provide limited erosion protection for posts planted higher on the bank during the period of establishment. Aside from site hydrology and hydraulics, factors such as sediment texture are relatively easy and inexpensive to measure and should be evaluated before initiation of streambank restoration projects. Efficiency of restoration finances and efforts may be enhanced if project sites are selected that are predominantly sandy and/or characterized by sandy layers within the root zone and provide adequate access to soil moisture.

Acknowledgments

This work was supported in part by a grant from the U S Department of Agriculture, National Sedimentation Laboratory, Cooperative Agreement #58-6408-6-029. Mention of trade names is for information purposes only and does not constitute endorsement. The authors would like to thank P. B. Rodrigue, R. E. Lizotte, Jr., S. Rood, and two anonymous reviewers for their comments on an earlier draft of this manuscript.

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