RIVERBANK RESTORATION IN THE SOUTHERN UNITED STATES: THE EFFECTS OF SOIL TEXTURE AND MOISTURE REGIME ON SURVIVAL AND GROWTH OF WILLOW POSTS

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Abstract—Field studies were conducted to quantify the relationship between soil conditions and growth of black willow posts planted for riverbank erosion control along Harland Creek (HC) and Twentymile Creek (TC) sites in Mississippi. Both sites had a wide range of soil texture and moisture regimes. Soil texture, water level, redox potential (Eh), and willow survival and growth were monitored. At the HC site, growth was lower in posts located at elevational extremes than for posts planted approximately 0.5 m above creek elevation at baseflow. Optimum conditions for growth were provided at moderate elevations characterized by groundwater levels that fluctuated around 50 cm beneath the soil surface. Data from the TC site also indicated a close correlation between soil texture, moisture, and survival of willows. Posts grown in silty-clay soils displayed low survival and growth in comparison to those grown in sandy soils. Locations along the creek characterized by sandy soils, adequate soil moisture, and well-drained conditions resulted in high survival and growth.

INTRODUCTION

Riverbanks and stream reaches in the Southern United States are often subject to accelerated erosion and associated habitat deterioration. However, there are opportunities for both erosion control and improvement of natural habitat. Many techniques are presently used for riverbank restoration including planting vegetation primarily composed of woody species on eroding banks. Willow posts (Salix spp.) have been extensively utilized for such restoration (Roseboom 1993; Shields and others 1995a, 1995b; Watson and others 1997). Large-diameter (> 7.5 cm) willow cuttings with lengths up to 4 m are sometimes used to stabilize rapidly eroding banks. The deeply planted posts provide mechanical control of erosion during the period of initial growth and establishment. A dense array of growing willow posts is intended to modify riparian habitats, fostering natural succession to a diverse riparian plant community and relatively stable banks. Despite reported success on many restoration sites, low survival rates have been reported in certain areas. For instance, survival rates of > 40 percent by the end of the first growing season have been reported for northern Mississippi (Shields and others 1995b). This has been attributed to many factors including post location on the bank, parasites, flooding, drought, and soil texture (Shields and others 1998). Field observations suggest that regimes of excess and deficit soil moisture may be primary factors. Experimental evidence on adverse extreme soil moisture effects have come primarily from a greenhouse study conducted on black willow (Salix nigra Marsh.) cuttings and have shown flooding or drought have significant adverse effects on physiological functioning, growth, and biomass production (Pezeshki and others 1998).

Field observations also suggest the potential effects of soil moisture on the growth of willow cuttings. Willow posts planted on steep banks appeared to do better in middle elevation as compared to those planted close to the river or at higher elevations further from the river (Shields and others 1998). At the two elevational extremes, willows experience quite different situations. At high elevations, periodic soil drought may impose severe water stress to which the posts are likely to be sensitive. In contrast, at low elevations close to the permanent water table, willows are likely to experience frequent root inundation due to soil flooding. In such conditions, willows will be subjected to soil and, thus, root oxygen deficiency as well as to soil chemical changes that result from flooding (Pezeshki 1994). The effects of soil oxidation-reduction conditions (redox potential, Eh) could be significant because reducing soil conditions (low soil Eh) may impose substantial stress on plants including willow, a species considered to be flood tolerant (Hook 1984). Depending on the level of soil Eh in the root zone, significant reductions in root growth can occur in many flood-tolerant woody species (Pezeshki 1991). In addition, substantial alterations in normal root metabolic activities may occur leading to the disruption of various root processes critical to a plant's functioning. Such processes include water and nutrient uptake, production of metabolites, and oxidation of the immediate rhizosphere under flooded conditions (Pezeshki 1994). Partial or complete death of roots may occur leading to insufficient masses of functional roots, and this may create root/shoot imbalances. Such imbalances may initiate a chain of events leading to shoot-water deficits and massive root and shoot death (Kozlowski 1982, 1997; Pezeshki 1991, 1994).

Soil texture is also critical because soil-pore space, moisture-holding capacity, and oxidation-reduction capacity are closely correlated with texture. Poor performance of willow posts planted on streambanks composed of fine soils has been observed in the field (Abt and others 1996). Posts

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also could experience severe drought in coarse soils (sand-gravel) on steep banks during the low-precipitation periods due to low moisture-holding capacity of coarse soils. Thus, both soil-moisture regime and texture are inter-related and may play a critical role in the success of willow posts planted on a restoration site.

Clearly, the poor performance of willow posts involves a complex set of environmental factors to which the posts are responding. The environmental conditions and the associated plant responses change substantially over the course of a typical growing season in the highly dynamic riverbank systems. Therefore, the present studies were designed to quantify the relationship between soil texture and moisture regime and physiological functions, survival, and growth of willow posts under field conditions.

MATERIALS AND METHODS

Field work was conducted on black willow (*Salix nigra* Marsh.) posts planted for streambank restoration at two restoration sites in northern Mississippi, the Harland Creek (HC) restoration site, and the Twentymile Creek (TC) restoration site (fig. 1).

Harland Creek Restoration Site

The HC restoration site was located in Holmes County, MS (fig.1). Black willow posts were harvested from local populations during the dormant season in 1994. The posts were approximately 3 m in length with a minimum diameter of 7.5 cm at the base. Posts were placed in holes 2.4 m deep, thus, approximately 0.6 m of the post remained aboveground. Willow posts were spaced at 0.9 m-centers for four rows of posts. The first row was placed 0.6 m from where the stream channel met the bank at the time of planting. Posts were planted along the bank in February 1994. In 1996, a total of 13 posts were selected along an elevational gradient extending from the upstream and ending at the last downstream post. These posts were located at various distances from the creek. PVC piezometers with a diameter of 3.1 cm were established in proximity of each post. Measurement locations were also established at each piezometer to monitor soil Eh. Water, soil, and plant measurements (described in Methodologies) were continued through the end of the 1996 growing season (November).

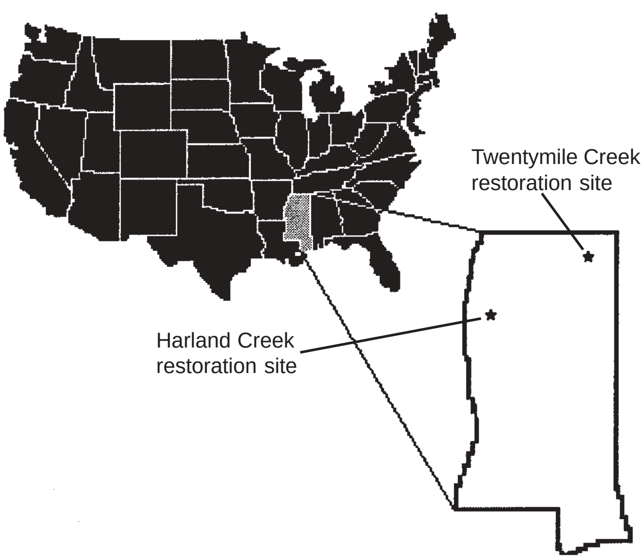

Figure 1—Map of the United States showing locations of the Harland Creek and Twentymile Creek restoration sites in northern Mississippi, USA.

Twentymile Creek Restoration Site

The TC restoration site, located in Lee County, MS (fig. 1), was the subject of intensive data collection. Black willow posts were planted according to the methodology described above in February 1998. At this site, four transects were established along the creek. Each transect was placed perpendicular to the creek and extended from the toe of the creek to the edge of the planting zone, approximately half way up the bank. Three plots were located within each transect: one at each end of the elevational extremes and one in the middle elevation. Piezometers were installed in the middle of each plot to monitor the water level below the soil surface. Each plot consisted of 12 posts. The posts were grouped into 2 rows each consisting of 6 plants, parallel to the stream for a total of 12 posts per plot. Soil and plant measurements were initiated in the spring of 1998 and continued through the end of the growing season.

METHODOLOGIES

The frequency and duration of flooding of both sites was analyzed using stage data collected at 15-minute intervals from nearby U.S. Geological Survey gauging stations. The TC transects were about 0.4 to 1.7 km downstream from the gauge, whereas the HC site was about 6.3 km upstream from the gauge. The applicability of the HC gauge data to our site was verified by comparing the signal from the U.S. Geological Survey gauge with a temporary gauge located about 1 km upstream from our site. Stages were transformed into height above baseflow elevation for assessing impacts at each site.

At both sites, soil samples were collected from 15, 30, 60, and 90 cm below the soil surface during piezometer installation. These samples were used to characterize the soil texture for each post location using standard methods (Brady 1974). For the HC site, the percentage of sand, silt, and clay are approximate as determined by the “feel method.” For the TC site, soil particle size distribution was determined by the “feel method” and by the USDA Agricultural Research Service, Midsouth Area, using a laser scattering particle size distribution analyzer (Horiba, Model LA-910).

At each site, soil redox potential (Eh) was measured at a distance of 15 cm from each well at 15-, 30-, 60-, and 90-cm depths below the soil surface using platinum-tipped redox electrodes, a millivoltmeter (Orion, Model 250A), and a calomel reference electrode (Corning, Model 476350). Measurements were recorded after the redox probes had been in the ground at least for 2 hours to allow for equilibration of the electrodes. Measurements of Eh were replicated (two measurements at each depth) per sampling location per sampling date. The water level at each monitoring well was quantified using a measuring tape.

Plant measurements at each site included selected physiological measurements and growth responses. Gas exchange measurements (leaf conductance and net carbon fixation) were conducted approximately twice each month using a portable photosynthesis system (CIRAS1, PP Systems, England). Measurements were conducted on mature, intact, attached leaves located on the upper one-third of the branches on each post between the hours of 11:00 and 14:00 during each site visit. The environmental factors of air temperature, leaf temperature, and photosynthetic photon flux density (PPFD) were recorded followed by measurements of net photosynthesis (Pn) and stomatal conductance (gw) on each sample leaf. Replicated sample leaves were used for the measurements during each field visit.

The growth of posts at the HC site was quantified by biomass sampling at the end of the growing season. Posts were destructively sampled and dry weight of biomass components was determined (Shields and others 1998). Growth of posts at the TC site was determined by measurement of height on study posts at the end of the 1998 growing season. No destructive samples were conducted on these posts because the posts were to be utilized in a longer study. The general linear models (GLM) procedure of the Statistical Analysis System was used to test for differences in means among different posts planted at various elevations relative to the creek. Regressions for the relationships between post survival, height growth, and soil texture were calculated using the SAS System (Statistical Analysis Systems 1994).

RESULTS

Harland Creek Restoration Site

Posts were planted at the HC site in February 1994, and we conducted measurements during the 1996 growing season. Rainfall and runoff patterns during the period 1994–96 were within limits typical of the period of record. However, in 1994 precipitation and streamflow were well above average during late summer. During our study, inundation of the posts was brief and infrequent. The median duration of flooding ranged from about 26 hours for the lowest posts to 15 hours for the highest posts. Median times between flooding ranged from more than 8 to more than 13 days, depending on elevation.

At the HC site, study posts were grouped into four distinct groups based on soil characteristics, relative elevation from the creek, and the distance to ground water (table 1). Posts in the upper part of the bank (group I) where soil texture was sandy gravel experienced little or no soil flooding as was evidenced by soil Eh data (> 350 mV). However, due to location and soil texture, the posts were likely to have encountered drought. Net carbon fixation indicated a significantly lower mean as compared to the posts that were located in the middle slopes (group II, percent III). No biomass sampling was done for this group, but gas exchange data suggest that these posts were stressed. Groups II and III consisted of posts located in the middle-bank elevation as verified by elevation and depth to water table (table 1). These posts had the highest measured net carbon assimilation rates among the study groups. The two groups showed no significant differences in gas exchange responses, but the mean (root and shoot) biomass per post was significantly greater in group II than group III (table 1). The difference in the observed responses between the two groups was attributed to the difference in soil texture that was more favorable for group II (less cohesive, higher Eh) than group III (more cohesive, lower Eh). Group IV posts were located at low elevations in sand-gravel soil. The water table was higher for this group as compared for the middle-bank groups; thus, soil Eh was in the reducing range. However, it was not significantly greater in intensity compared to the middle-bank groups. This finding was primarily attributed to the sand-gravel soil texture, which had little capacity for intense reduction. Examination of root

Table 1—Field data of post location, soil texture, depth to water table, soil Eh, net carbon fixation, root dry biomass, and shoot dry biomass for posts studied at Harland Creek restoration site, Mississippi

	Post location on the streambank			
Variable	Lower bank group IV	Medium group III	Medium group II	Upper bank group I
Soil texture	Sand-gravel	Sand-silt-clay	Sand-silt	Sand-gravel
Water depth (m)	0.33 c	0.58 b	0.54 b	1.13 a
Soil Eh (mV)	202 b	107 b	172 b	384 a
Net carbon fixation (μmol CO_2 m^{-2} leaf s^{-1})	8 b	10 a	11 a	7 b
Root dry mass (g)	100	29 b	192 a	NA
Shoot dry mass (g)	24	173 b	1029 a	NA

NA = missing data.
Different letters within each column indicate statistically significant differences ($p< 0.05$).

distribution patterns showed that for posts located at low elevations characterized by low soil Eh conditions, 100 percent of roots excavated were located between a depth of 0 to 15 cm. Posts at medium elevation showed substantially different root-growth patterns depending on the soil texture. Group II located on sand-silt soil had significantly higher root biomass than group III located on soils that contained some clay (fig. 2). In addition, roots were more uniformly distributed at various depths in soil profile in group II whereas roots were confined to the top 15 cm of the soil in group III. Overall, conditions for growth of willow posts at HC site were best at moderate elevations characterized by sand-silt soil texture and water levels that fluctuated close to the soil surface allowing for adequate soil moisture but frequent drainage. In contrast, posts located at higher elevations relative to the baseflow stage suffered from soil moisture deficits whereas posts located at the bank toe were hampered by flooded soils and low soil Eh conditions.

Twentymile Creek Restoration Site

At the TC site, the study plots on each transect were located along an elevational gradient. At each transect, the low-elevation plot was flooded frequently due to proximity to the creek, which rose whenever light to moderate rains fell. The middle plot flooded at a moderate frequency but required moderate to heavy rainfall throughout the watershed whereas the high-elevation plot was located at the top of the planting zone and was never flooded. Rainfall and runoff patterns during the 1998 growing season were typical of the period of record. Plots located 0.3 m above baseflow were flooded about 10 percent of the time during March through July (later data not available at this writing), whereas those at intermediate elevations (+ 1.0 to 1.5 m above base stage) were flooded only about 1 percent of the time, and those at highest elevations (>3 m above base stage) were not flooded during this period. Flooding episodes lasted only 2 to 39 hours, and median times between flooding ranged from 8 to 26 days, depending on elevation.

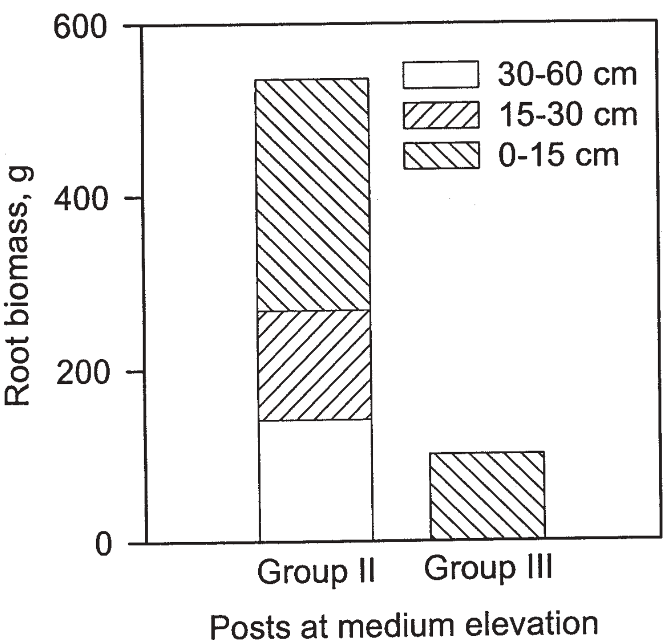

Figure 2—Total root biomass distribution for willow posts in soil profile at three depths: 0 to 15 cm, 15 to 30 cm, 30 to 60 cm, for posts harvested at Harland Creek site, Mississippi. Data for group II represent the mean for two posts while data of group III represent the mean for four posts.

The soils in each of the elevational categories were fairly similar in texture ranging between 76 to 62 percent coarse sandy materials (table 2). The low-elevation plots were closest to the water table (0.3 m) and had moderately reduced soils due to the saturated conditions (Eh +230 mV). In contrast, the medium- and high-elevation plots had aerated soils with Eh values of +480 and +520 mV, respectively (table 2).

Height growth, survival rates, and gas-exchange measurements showed no significant differences across the elevational groups. However, posts in the medium-elevation plots grew 98.4 cm on average, 196 percent more than the 50.2-cm average for low-elevation plots and 154 percent more than the 63.8 cm recorded for the high-elevation plots. The high-elevation plots had the highest survival rate at 67 percent followed by the middle plots at 50 percent and the low plots at 46 percent (table 2). However, differences in growth and survival were not statistically significant.

The soil texture effects were apparent when plots of the same elevation were compared between reach 1 and reach 3. The amount of fine-grained soil (silt and clay) in reach 3 plots was double that of reach 1 plots at all elevations. The depth to the water table showed no significant difference across the lowest plots; however, there were slight differences (0.5 and 0.3 m, respectively) between the middle- and high-elevation plots (table 3). This difference may be biologically insignificant, however, because this is well below the root establishment zone. Similarly, the only

Table 2—Field data of post location, soil texture, depth to water table, soil Eh, height growth, survival, and net carbon fixation for willow posts studied at the Twentymile Creek restoration site, Mississippi

	Post location on the streambank		
Variable	Lower bank	Medium	Upper bank
Soil texture (percent coarse)	70	62	76
Water depth (m)	0.3 a	1.4 b	1.7 c
Soil Eh (mV)	230 a	480 b	520 c
Height growth (cm)	50.2 a	98.4 a	63.8 a
Survival (percent)	46 a	50 a	67 a
Net carbon fixation (µmol CO_2 m^{-2} leaf s^{-1})	11.7 a	12.3 a	10.3 a

Means in each row followed by the same letter are not significantly different across groups at the p< 0.05 level.

Table 3—Field data comparing the effects of soil texture on net carbon fixation when plot elevation (thus, depth to water table and soil redox potential) is held constant. Data represents mean values taken over the first growing season for depth to water table, soil Eh, and net carbon fixation for willow posts studied at Twentymile Creek restoration site, Mississippi

		Silt + clay	Sand	H_2O depth	Soil Eh	Pn
		- - - - Percent - - -		*m*	*mV*	*µmol CO_2 m^{-2} leaf s^{-1}*
Low plots	Reach 1	23	77	0.26 a	146 a	12.4 a
	Reach 3	48	52	.31 a	259 b	11.0 a
Middle plots	Reach 1	29	71	1.2 a	378 a	13.9 a
	Reach 3	67	33	1.7 b	376 a	9.7 a
High plots	Reach 1	11	89	1.8 a	553 a	11.7 a
	Reach 3	30	70	1.5 b	491 b	7.0 b

Means in each column for each elevation followed by the same letter are not significantly different across groups at the p< 0.05 level.

plots to have biologically significant differences in soil Eh were the low plots. The low plot in reach 1 had a significantly lower Eh value than in reach 3, even though there was only a 3-cm difference in the depth to the water table, and the majority of the soil was sand, which characteristically has a lower capacity for reduction. Nevertheless, both plots were in the anaerobic range (below + 350 mV). All of the middle and high plots had Eh values indicative of aerated soils (above + 350 mV) (table 3).

Gas exchange data showed a consistent pattern of response to soil texture. Net photosynthetic rates were consistently higher in sandy soils; however, rates were significantly higher only in high-elevation plots. In these plots, average carbon fixation was 40 percent higher in coarse-grained sandy soils than in fine soils (table 3). The middle plots showed moderately significant results (p = 0.0545) with an average increase in carbon fixation of over 30 percent. Average height growth per post followed similar trends (fig. 3). The low-elevation plots failed to show a significant difference in growth; however, posts grown in sandy soils were considerably taller than posts grown in silt and clay soils (139 cm and 77 cm, respectively). Posts grown in coarse soils showed a significantly greater amount of growth at both the middle- and high-elevation plots. Posts grown in sandy soils in the middle-elevation plots showed a threefold increase in growth (246 cm compared to 74 cm) and a fourfold increase at the high-elevation plots (131 cm compared to 31 cm) (fig. 3). Post survival showed the most consistent significant effects of soil texture as posts grown in sandy soils had greater survival in all plots. Posts planted in predominantly sandy soils had mean survival rates of 67 percent, 75 percent, and 92 percent, for low-, middle-, and high-elevation plots, respectively. In contrast, posts in fine-grained soil (silty/clay soils) had significantly lower survival rates of 25 percent, 25 percent, and 42 percent, for the same respective plot elevations (fig. 3). The relationship between willow survival and soil conditions indicated that

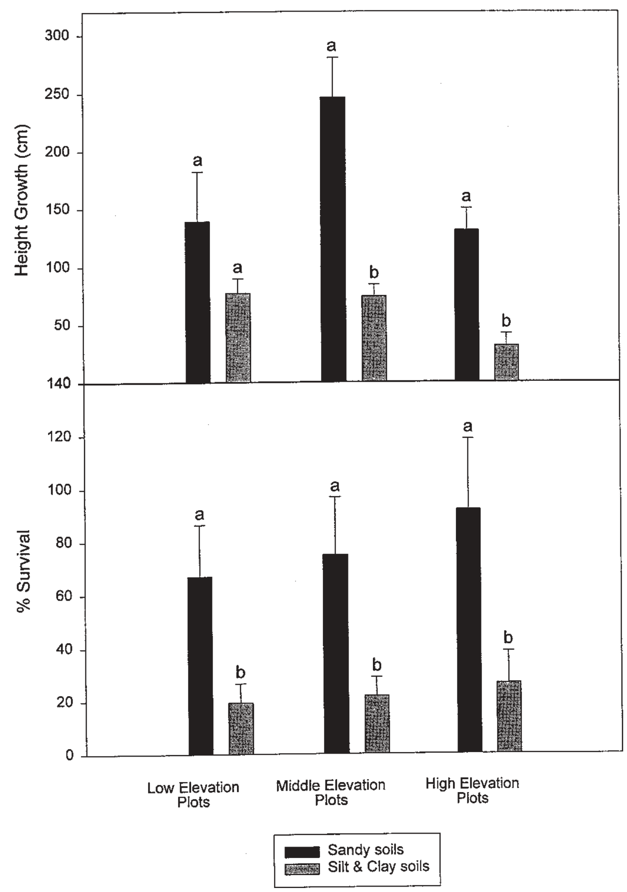

Figure 3—Survival and height growth of willow posts planted on fine vs. coarse soils at the Twentymile Creek site, Mississippi. Data represents the mean height growth per post (cm) and percent survival per plot for posts grown at similar elevation with varying soil textures. Sandy soils were consistently observed at reach 1 in comparison to the silt and clay soils observed at reach 3 (for specific proportions of each soil texture see table 3). Means for each elevation with similar letters represent no significant difference at the p <0.05 level.

posts appear to have low-survival rates in soils containing a high percentage of fine particles (silt plus clay) within the upper soil layer of 0 to 30 cm in depth. Height growth was also sensitive to a high percentage of fine particles.

DISCUSSION

The results from both restoration sites demonstrated the complexity of soil-plant interactions in highly dynamic creek banks such as the HC and the TC restoration sites that are characterized by steep slopes, a wide range of soil moisture conditions, and various soil textures. Willow posts displayed a great level of sensitivity to drought and flooding (low soil Eh conditions). For instance, on the HC site, soil Eh for posts in group I was above + 350 mV, thus, in the aerated range, suggesting that these posts were not exposed to flooding or soil saturation during any of the measurement days (table 1). Nevertheless, this group had the lowest gas exchange rates relative to other groups. This finding was attributed to periodic drought encountered by this group due to elevation and the poor water-holding capacity of the soil (sand-gravel). Similar results were obtained in a greenhouse study where posts under drought treatment had low photosynthetic rates (Pezeshki and others 1998). In contrast, posts in group IV were at the lowest elevations to the creek relative to other groups. Here, water levels were high (close to the soil surface) creating reducing soil conditions indicated by low Eh values (+202 mV). This group had significantly lower gas exchange rates relative to other groups (II and III). In a greenhouse study, willow posts subjected to a continuously flooded condition had significantly lower net photosynthesis compared to control (Pezeshki and others 1998). Reducing soil Eh can adversely affect photosynthetic rates in species considered to be flood tolerant (Pezeshki 1994). Field root biomass data indicated that reductions in soil Eh had a negative impact on root biomass. Root development is slowed in areas of low soil Eh conditions because of the lack of oxygen, which is needed to carry out normal root respiration. In a greenhouse study, little or no root growth was found for black willow posts at locations that remained subjected to continuous flooding and soil Eh around - 200 mV (Pezeshki and others 1998). This lack of roots indicated that willow posts either failed to initiate roots or that such roots, if initiated, died in response to the continued, intense soil-reducing conditions. Other studies have shown that root biomass in black willow was significantly decreased as flooding depth and duration increased (Donovan and others 1988).

Black willow is a flood-tolerant species; thus, it possesses physiological/morphological adaptations allowing oxygen transport to the root zone. However, as soil Eh decreases, the chemical and biological demand for oxygen within the soil rises. Thus, the oxygen-delivery system may be overwhelmed by such increasing demand that is concomitant with increased internal demand for oxygen (Pezeshki 1994). The lower gas exchange rates found in posts under drought and flooding on HC site partially explain the observations on changes in vigor and survival of willow posts due to elevation reported by Abt and others (1996). These observations agreed that posts planted along an elevational gradient from the creek differed in survival rates. Posts located close to the creek at similar elevations to the creek and exposed to prolonged, frequent flooding had mortality rates of 80 percent. The posts at the highest elevations and greatest distance from the creek, which were likely to experience droughty conditions, had mortality rates of about 91 percent. However, higher survival rates of 39 to 58 percent were associated with the posts located in the area between these zones (Abt and others 1996).

The TC data further indicated the significant influence of soil texture on willow performance. Net carbon fixation substantially decreased for posts grown at middle to high elevations in coarse-grained sandy soils (table 3). Soil texture also had a substantial impact on height growth and survival as they were both significantly greater in coarse sandy soils than in fine silt and clay soils (fig. 3). Regression analysis indicated a significant negative correlation ($r = -0.68$ $p = 0.0438$) between the percentage of fine particles (silt + clay at 15- and 30-cm depths) and survival. Height growth was also significantly correlated ($r = -0.69$ $p = 0.0412$) to the average percentage of fine particles (at 15- and 30-cm depths) showing low growth at soils that contained a high percentage of fine particles (silt + clay).

CONCLUSIONS

At both restoration sites, soil texture and moisture regime were important factors affecting survival, physiological functions, and growth of willow posts. For instance, much of the variations in survival and growth were due to soil texture represented by the percentage of fine particles (silt + clay) in the upper 30 cm of the soil. High survival and growth in willow posts required ample soil moisture (but nonwaterlogging conditions) and adequate drainage in the upper soil layer, approximately the top 45 to 60 cm of the soil. In addition, under favorable soil-moisture conditions, posts perform better in soils characterized by coarse-textured rather than fine-grained soils. From a restoration perspective, use of willow posts for riverbank restoration projects is intended to help stabilize the banks while improving habitat quality. Thus, the use of willow posts remains a low-cost restoration strategy; however, a proposed planting site must be evaluated prior to the undertaking of large-scale restoration. Many factors must be considered including soil texture, moisture regime, slope, distance to the creek, and soil oxidation-reduction conditions in order to improve the prospect for high survival and growth of willow posts.

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