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Factors governing survival of black willow (*Salix nigra*) cuttings in a streambank restoration project

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ABSTRACT

A field study was conducted at Little Topashaw Creek in northern Mississippi, aimed at expanding the limited database on the survivorship of *Salix nigra* (black willow) cuttings planted on riparian restoration sites. We tested the hypothesis that sediment moisture availability (deficit, excess) as mediated by sediment texture and depth to the prevailing water table is a major factor governing black willow survival during the initial stage of establishment following transplanting. Replicated plots were established across elevational gradients and a range of soil texture. Each plot contained 16 planted cuttings (2.5 cm diameter × 2.5 m length). Plot depth to water table, soil texture, and soil redox potential were measured. Plant gas exchange, leaf chlorophyll content, growth, and survival were monitored periodically over two growing seasons. Survival was best at low elevation compared to cuttings planted at mid- and high elevations. Poor survival and growth were noted for cuttings that encountered sediment moisture deficits in plots with coarse texture while the best cutting survival was recorded for intermediate sand content plots. Results indicated that plot location on the bank and soil texture are two important factors that influence riverbank restoration success. Therefore, any riparian restoration plan should include careful assessment of these factors prior to undertaking such efforts.

1. Introduction

Streambank erosion is a pervasive problem causing millions of dollars of damage annually to lands and structures and important but not easily quantified detrimental effects on riparian zones, water quality, and downstream habitats (Klapproth and Johnson, 2001). Although traditional erosion control practices have often focused on structures made from stone and other nonliving materials, interest in the use of plant materials, alone and in combination with nonliving materials ("soil bioengineering") for a range of applications, is increasing (e.g., Coppin and Richards, 1990; Gray and Sotir, 1996; Li et al., 2006). Plantings of woody plants such as willow (*Salix* spp.) have been proposed or implemented for managing watershed nutrient and sediment yield (Parkyn et al., 2005), trapping sediments and organic debris (Karle and Densmore, 1994), managing invasions of exotic species into wetlands (Kim et al., 2006), biofuel production from abandoned surface mines (Bungart et al., 2000), and wastewater treatment (Aronsson et al., 2002). Successful application of plants to control erosion and to restore riparian ecosystems is a subset of ecological engineering (Shields et al., 2003a; Kangas, 2004) involving principles of forcing functions (streamflow, watershed hydrology, streambank geomorphology), energy transfer (solar energy is used to produce biomass that dissipates kinetic energy of stream and subsurface flow), self-organization (as succession occurs within the planted zone), and the importance of the ecotone (Mitsch and Jorgensen, 2004).

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Streambanks represent disturbance–prone environments, particularly along unstable streams. Plants face disturbances such as erosion and deposition, mechanical breakage and abrasion, competition, herbivory, and diseases as well as stresses such as soil moisture deficits, reduced soil redox potential (E_h) due to flooding and water table fluctuation. Willows (*Salix* spp.) are among choice species to revegetate and restore eroded streambanks due to the vigorous growth rate and production of a massive root system that can rapidly stabilize streambank sediments (Grissinger and Bowie, 1984; Hupp, 1992; van Splunder et al., 1994; Shields et al., 1995). The reintroduction of *Salix* spp. is also promoting the secondary establishment of other vegetation worldwide (Kleinfelder et al., 1992; Hupp, 1992; van Splunder et al., 1994; Pimentel et al., 1995; Rowntree and Dollar, 1999). In southcentral and central U.S., *Salix nigra* Marshall (black willow) is used frequently as a restoration species, while other *Salix* spp. are widely used elsewhere (Anderson et al., 1978; Conroy and Svejcar, 1991; Svejcar et al., 1992; Hoag, 1993, 1995; Federal Interagency Stream Restoration Working Group, 1998; Anonymous, 2005). *S. nigra* regenerates from root and shoot fragments and is often planted along streambanks as dormant, unrooted cuttings (Bentrup and Hoag, 1998; Cronk and Fennessy, 2001).

Previous revegetation projects using cuttings of *Salix* spp. have reported variable and often disappointingly low survival rates (Hoag, 1993, 1995; Vora et al., 1988; Watson et al., 1997; Shields et al., 1998; Price and Birge, 2005). Clearly, successful ecological engineering in the riparian zone requires a thorough understanding of interactions among plants, hydrology and fluvial geomorphology (Bennett and Simon, 2004). Naturally occurring riparian plant communities exhibit strong sensitivity to physical factors (Mallik and Rasid, 1993), and several environmental factors such as moisture and soil texture have been identified as being critical in determining survival and performance of planted willow cuttings (Pezeshki et al., 1998a; Schaff et al., 2003). These are interrelated factors that exhibit wide temporal and spatial variation along streambanks. Inadequate soil moisture leading to plant desiccation is one of the causes of first year mortality of willow cuttings planted in riparian habitats (Shields et al., 1998; Karrenberg et al., 2002). Such unrooted cuttings are especially vulnerable to low soil moisture conditions early in the growing season due to transpirational water losses until root systems, with their vascular tissues, have developed (Grange and Loach, 1983; Ikeda and Suzaki, 1986).

Although dry sediment conditions are likely to occur at locations away from the prevailing water table, excess soil moisture can be stressful to willow cuttings at locations near the bank toe. During high stages, stream water fills soil pore spaces and dissolved oxygen in pore water is rapidly depleted, leading to oxygen deficiency for plant roots and soil microorganisms (Mitsch and Gosselink, 2000; Pezeshki, 2001). A lack of oxygen in the soil environment leads to a drop in soil redox potential (E_h) and subsequent disruption of normal root functions (Ernst, 1990; Pezeshki, 1994).

The present research was designed to expand the limited database on the survival of willow cuttings planted on riparian restoration sites. We initiated a larger sample size (20 plots, total of 320 cuttings) planted over a wide range of soil texture and elevation relative to water table as compared to previous studies (Pezeshki et al., 1998b; Schaff et al., 2003). In addition, we studied smaller cuttings (2.5 cm diameter × 2.5 m length) than the "posts" used in other studies (7.5 cm diameter × 3 m length). We focused specifically on the relationships between plot elevation above the water table, soil moisture condition of drought and flooding, soil texture and survival and growth of cuttings. We tested the hypothesis that sediment moisture availability (deficit or excess) as mediated by sediment texture and location relative to the prevailing water table is a major factor governing willow cutting survival during the initial stage of establishment following field transplanting.

2. Materials and methods

Field research was conducted at Little Topashaw Creek (LTC), an unstable, incised, fourth-order stream in the Yalobusha River watershed, Chickasaw County, Mississippi, draining about 37 km^2. Geomorphology of the Yalobusha River watershed has been described by Simon and Thomas (2002), while additional detail about the study reach of LTC is provided by Shields et al. (2003b, 2004). Floodplain stratigraphy was characterized by dispersive silt and clay soils overlying sand overlying consolidated cohesive material. Sandy deposits were often found along the bank toe, but sandy soils near the bank toe tended to be finer and denser (higher bulk density) than those at higher locations (Collison et al., 2001). The channel had a single-thread planform with an average sinuosity of 2.1, an average slope of 0.0025, an average width of 35 m, and an average depth of 3.6 m, with eroding bank heights of about 6 m. Channel bed materials were comprised primarily of 0.2–0.3 mm sand. However, cohesive materials occurred as massive outcrops and as gravel-sized aggregates. Data suggest that mean channel width increased by a factor of 4–5 between 1955 and 2000.

Flows in LTC were flashy, with stage fluctuations of 1–2 m in 24 h commonly occurring. Stage records for the period of this study indicated that flows reflected seasonal precipitation patterns: base and mean flows were lower in July–October, and higher in November–June. However, intense, brief thunderstorms can occur during any season with brief but sharp runoff hydrographs. Precipitation and shallow water tables underlying the floodplain 1–5 m landward of the channel top bank adjacent to the study reach were monitored for most of our study period by others (Simon, Personal communications, National Sedimentation Laboratory) as part of a study described by Collison et al. (2001). Resulting data were plotted with our stream stage records in Fig. 1. Water table fluctuations were characterized by strong signals from individual precipitation events superimposed on gradual wet- and dry seasonal trends.

S. nigra Marshall cuttings were harvested from local populations along the Mississippi River in January 2001. The ~4000 willow cuttings planted in holes along the entire 2 km LTC reach were imported from a Mississippi River sandbar, and soaked in a pond for 2–3 weeks. In addition, cuttings selected for planting in 20 experimental plots of this study were harvested from a population within the Yalobusha River watershed about 10 km from the LTC site. Each experimental plot was planted with 8 cuttings that were soaked in a pond for

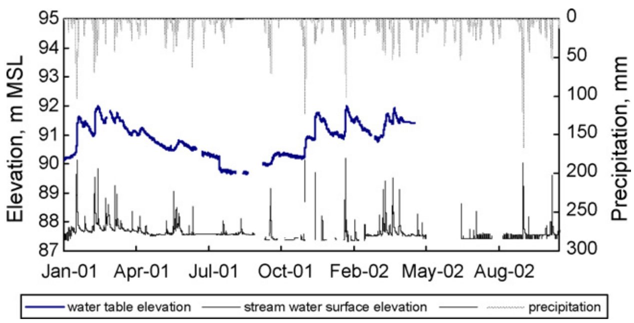

Fig. 1 – Daily precipitation and hourly stream stage and water table elevation for study reach, Little Topashaw Creek, Mississippi. Water table elevation data represent hourly means of tensiometer readings collected at 10-min intervals as described by Collison et al. (2001). The tensiometer was located 4.7 m below the floodplain and 3 m landward of the top bank of our study reach. Floodplain elevation was about 94.5 m MSL; adjacent study plots were at about 90 m MSL.

10–12 days prior to planting, and with other 8 cuttings that were planted to a depth of 1.5 m within 24 h of cutting. Soaked and unsoaked cuttings were planted alternately in a checkerboard fashion. The effects of soaking on cutting performance have been reported by Martin et al. (2005). Ten plots were established on sandbars and 10 on steep, eroding banks for a total of 20 study plots. *S. nigra* cuttings approximately 2.5 cm (1 in) in diameter at the base (due to tapering from the base to the tip, over the 2.5 meter length, the top may have been only 0.2 cm in diameter) and 2.5 m in length with side branches removed were placed in holes with depths of approximately 1.5–1.8 m. Cuttings were planted in 4 rows of 4 cuttings at each of the 20 plots totalling 320 cuttings. The plastic protective stem collars about 30 cm tall were installed for each cutting at planting time to minimize herbivory. The cuttings began bud break by late March. The environment during the initial bud break period was characterized by temperature ranging between average minimum of 5.1 °C and maximum of 19.2 °C. From the initial 20 plots planted prior to the first growing season (2001), 18 plots were used for the 2001 sampling (2 plots destroyed by erosion) and of these initial plots, 12 plots were used for continued study during the second growing season in 2002 due to plot destruction by erosion and other events.

2.1. *Soil texture*

Soil particle size distribution at each plot was evaluated in December 2000 (prior to planting), February 2001, and June 2002. Samples were collected at 15, 30, and 60 cm depths below the soil surface for four locations in each plot; corners of a 2 m^2 area centered on the middle of each plot. Soil samples (240 total) were collected for analysis in 2000 and 2001. In 2002, 144 samples were collected from 12 plots for analysis. A laser scattering, particle size distribution analyzer (Horiba, Model LA-910) was used for analysis of the December 2000 and February 2001 samples whereas standard sieve analyses were used for the 2002 samples.

2.2. *Soil redox potential, water potential, and depth to water table*

Soil redox potential (E_h) was measured to quantify the level of reduction in the soil at study plots. Platinum-tipped redox electrodes (Patrick and DeLaune, 1977) were inserted at 15, 30, and 60 cm depths below the soil surface near the center of each study plot, 15 cm from the monitoring wells. After 2–3 h to allow for equilibration to environmental conditions, a millivoltmeter (Model 250A, Thermo Orion, Beverly, MA, USA) and calomel reference electrode (Corning, Model 476350, Orion Research, Inc., Boston, MA) were used to take measurements. Measurements were corrected for the Calomel reference electrode as outlined by Patrick and DeLaune (1977). A total of 162 and 216 measurements were made from study plots during the 2001 and 2002 growing seasons, respectively (May–September).

Soil water potential (SWP) was measured as an indicator of water availability at 15, 30, and 60 cm depths below the soil surface at six study plots. Electrodes housed within gypsum blocks (Model GB-1, Delmhorst, Towaco, NJ, USA) were buried next to each monitoring well and left in place. A soil moisture tester (Delmhorst, Model KS-D1, Delmhorst, Towaco, NJ, USA) was used to measure soil water potential within the range of 0.0 to −1.5 MPa. A total of 144 and 90 measurements were made during the 2001 and 2002 growing seasons, respectively.

Wells were dug in the center of each study plot prior to planting and fitted with pipes to monitor fluctuations in shallow ground water level. Pipes were constructed of PVC pipe with an outside diameter of 5.72 cm and perforated for 65 cm from the bottom of the pipe to allow water to flow through. A cloth sewer pipe "sock" covered the outside of each pipe to prevent fine grain soil particles from seeping into the well. Depth to the water table from the soil surface was measured using a water-level indicator (Fisher m-Scope WLT Water Level Indicator, Fisher Research Laboratory, Los Banos, CA) lowered into monitoring wells. Depth to the water table was measured on a biweekly schedule during the study period of May–September of 2001 and 2002.

2.3. *Precipitation*

Daily precipitation data were collected at Little Topashaw Creek and compared to normal monthly precipitation from a nearby permanent station (30-year average, Grenada Dam, National Atmospheric and Oceanographic Administration).

2.4. *Plant responses*

Six plots were selected for monitoring *S. nigra* gas exchange functioning and leaf chlorophyll content (LCC) measurements. These plots were selected to represent a range of elevation relative to water table and soil texture. *S. nigra* gas exchange measurements were conducted between 11:00 and 14:00 h when photosynthetic photon flux density (PPFD) was close to maximum on sunny or cloudy days, avoiding partly cloudy conditions. Gas exchange measurements were taken using a portable photosynthesis system (CIRAS1, PP Systems, MA, USA). Mature, intact leaves located on branches in the upper one third of the canopy were utilized for the measurements.

Measured variables included net photosynthesis (P_n) and stomatal conductance (g_s). LCC measurements were conducted using a chlorophyll content meter (Model CCM-200, Opti-Sciences, Tyngsboro, MA, USA). On each sampling date, six replicates were sampled for LCC and gas exchange measurements at each of the six designated plots for a total of 36 measurements. Measurements were conducted every 2–3 weeks from June to September 2001 and repeated over the 2002 growing season.

Survival was determined at the end of the first (October 2001) and second (October 2002) growing seasons. Final height was measured on all living sample cuttings at the end of 2001 and 2002 growing seasons. Despite installation of stem collars at planting time, some sporadic herbivory activities (presumably due to beaver, *Castor canadensis*) were observed throughout our studies that were not accounted for in the reported height growth data.

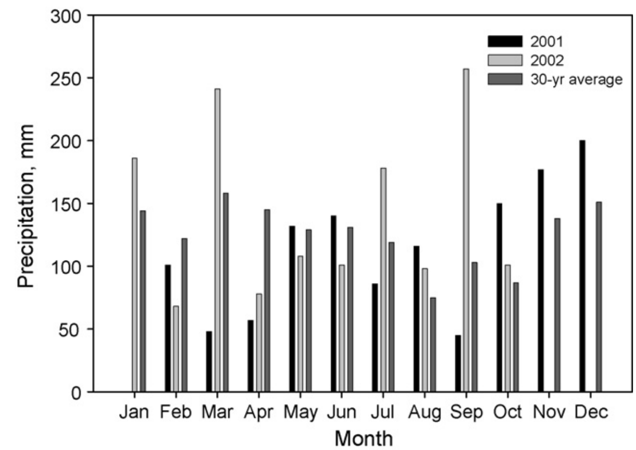

Fig. 2 – Monthly precipitation at Little Topashaw Creek in 2001, 2002, and 30-year average monthly precipitation.

2.5. *Data analysis*

We stratified our data into three groups based on soil texture and plot elevation. Plot elevations relative to the creek baseflow varied widely, and mean depth to water table ranged between 0.2 and 2.6 m. In 2001, there were five plots we classified as "low elevation" (vertical distance to baseflow water surface <0.7 m), six were "middle elevation" (0.7–1.1 m), and seven were at "high elevations" (>1.1 m). In 2002, three plots were low elevation, three were in the middle elevation category and six were at high elevations. Soil particle size analysis revealed that banks were comprised of varying amounts of silts and sands, typical of streambanks in this region (Grissinger et al., 1982): 6 of the 18 plots studied in 2001 were coarse-textured (>80% sand), 10 were intermediate (60–80% sand), and 2 were fine-textured (<60% sand). In 2002, 7 of the 12 study plots were coarse-textured, 3 were intermediate, and 2 were fine-textured.

One-way ANOVA (SPSS Version 11.5) was used to test for differences in means of plant response variables between study plots at low, middle, and high elevation as well as between those with coarse, intermediate and fine soil texture for 2001 and 2002 (see Tables 1 and 2 for details). In addition, soil texture data were included as a co-variable in the ANOVA of elevation and elevation data were included as a co-variable in the ANOVA of soil texture. Tukey tests were used to determine significant differences between groups following ANOVA.

Attempts to run two-way ANOVA were unsuccessful because certain soil texture-elevation combinations were missing or were represented by only one plot. Instead, stepwise multivariate regression analyses were used to test the interactive effects of depth to water, sand content, E_h at three depths (15, 30, and 60 cm) on P_n, g_s, LCC, height, and survival for both years.

3. Results

Depth to water table and E_h at 60 cm depth had significant influence on survival thus were included in the regression equation (survival = 56.54 − 19.74(depth to water) + 0.06E_h60). These two factors explained 20% of variance in survival ($R^2 = 0.20$, $F = 3.38$, $p = 0.049$). A *t*-test of depth to water and E_h at 60 cm showed that relationship between depth to water and survival was significant (*p* of depth to water = 0.016, *p* of E_h at 60 = 0.061). In addition, depth to water explained 37% of variance in g_s ($R^2 = 0.37$, $F = 5.33$, $p = 0.046$) and the equation was $g_s = 230.53 - 44.82$(depth to water). Results of *t*-test showed that the relationship between depth to water and g_s was also significant ($p = 0.046$). There were no apparent correlations between those environmental factors and P_n, LCC, or height. Therefore, our data indicated that survival rate and g_s in black willow were both promoted by low plot elevation. However, there were no correlations between those environmental factors and P_n, LCC, or height.

Soil water potential data did not reveal any severe drought conditions (soil water potential more negative than −1 MPa) in the soil at 15, 30, or 60 cm depths (data not shown). However, coarse-textured plots at high elevation represented the potential likelihood for low water availability periods as SWP measurements approached −0.15 MPa or lower (more negative). In addition, precipitation data showed the potential for several brief drought periods at the study site and particularly at most of the high- and mid-elevation sandy plots (see the following section).

Total precipitation during the first growing season (1308 mm) was 194 mm below the 30 year average (1502 mm; Fig. 2). There was no precipitation for 14 days after the cuttings were planted (February 1–15, 2001). March was also a low precipitation month with no rainfall for 22 consecutive days. The total precipitation during the 2002 growing season, 1793 mm, was above normal, but it was concentrated in 4 out of the 7 months of the growing season (Fig. 2). Therefore, there were brief potential drought periods in coarse-textured plots at high elevation during April–June 2002. Overall, the precipitation patterns for the 2001 and 2002 growing seasons indicated the occurrence of short-term low soil moisture conditions at LTC.

Flooding (stream water level at or above soil surface) frequency and duration varied widely depending on plot elevation. In general, flood events tended to be brief (Fig. 1). Average

Table 1 – Environmental and biological data (mean ± S.E. and sample sizes) for the 2001 and 2002 growing seasons measured at study plots at Little Topashaw Creek with different vertical elevations and soil textures

	Elevation			Soil texture		
	Low	Middle	High	Fine	Intermediate	Coarse
2001						
Depth to water (m)	0.49 (±0.10)/25	0.83 (±0.05)/30	1.64 (±0.20)/35	0.48 (±0.31)/10	0.97 (±0.14)/50	1.46 (±0.35)/30
Sand (%)	57.00 (±11.19)/60	80.50 (±5.88)/72	73.57 (±3.18)/84	33.50 (±4.25)/24	70.36 (±1.68)/120	88.40 (±1.60)/72
E_h 15 (mV)	491 (±44.33)/15	562 (±34.62)/18	601 (±23.91)/21	528 (±20.95)/6	550 (±30.21)/30	585 (±18.21)/18
E_h 30 (mV)	392 (±71.42)/15	546 (±49.72)/18	597 (±21.07)/21	436 (±32.39)/6	511 (±44.43)/30	586 (±27.21)/18
E_h 60 (mV)	269 (±53.00)/15	329 (±65.90)/18	575 (±43.98)/21	229 (±46.50)/6	392 (±59.12)/30	514 (±64.93)/18
P_n (μmol m^{-2} s^{-1})	35.20 (±3.87) a/30	34.30 (±1.25)a/60	32.00 (±2.23)a/60	34.60 (±2.29)a/30	33.50 (±2.61)a/60	33.10 (±1.51)a/60
g_s (mmol m^{-2} s^{-1})	153.20 (±27.41)a/30	177.00 (±14.79)a/60	143.40 (±15.43)a/60	172.20 (±17.05)a/30	150.60 (±14.39)a/60	160.30 (±19.99)a/60
LCC (cci)	8.56 (±0.35)a/48	8.01 (±0.20)a/95	8.14 (±0.22)a/143	7.81 (±0.25)a/47	8.17 (±0.23)a/143	8.34 (±0.22)a/96
2002						
Depth to water (m)	0.47 (±0.03)/15	0.83 (±0.89)/15	1.90 (±0.19)/30	1.90 (±0.30)/10	0.57 (±0.67)/15	1.40 (±0.29)/35
Sand (%)	79.00 (±4.73)/36	82.33 (±2.67)/36	75.33 (±8.11)/72	50.00 (±2.00)/24	75.33 (±1.67)/36	87.14 (±1.12)/84
E_h 15 (mV)	531 (±33.14)/18	529 (±76.63)/18	591 (±22.58)/36	613 (±22.50)/12	579 (±31.63)/18	537 (±34.81)/42
E_h 30 (mV)	467 (±16.17)/18	575 (±48.17)/18	578 (±25.61)a/36	605 (±70.00)/12	498 (±14.50)/18	555 (±29.58)/42
E_h 60 (mV)	264 (±39.25)/18	627 (±11.35)/18	571 (±25.07)/36	589 (±43.00)/12	376 (±125.44)/18	541 (±49.56)/42
P_n (μmol m^{-2} s^{-1})	14.16 (±0.63)a/49	14.00 (±0.79)a/20	14.29 (±0.52)a/63	13.33 (±0.60)a/19	14.23 (±0.97)a/22	14.37 (±0.45)a/91
g_s (mmol m^{-2} s^{-1})	228.53 (±13.31)a/49	216.15 (±20.66)a/20	160.44 (±10.23)b/63	174.53 (±15.71)b/19	271.77 (±18.77)a/22	179.49 (±9.38)b/91
LCC (cci)	8.93 (±0.32)a/92	8.96 (±0.41)a/46	8.87 (±0.25)a/138	10.05 (±0.42)a/46	9.48 (±0.44)b/46	8.47 (±0.21)c/184

Significant differences in plant measurements across vertical locations or soil texture categories are shown using different letters. E_h, soil redox potential at 15, 30, or 60 cm depths; P_n, net photosynthesis; g_s, stomatal conductance; LCC, leaf chlorophyll content.

Table 2 – ANOVA table for the effects of elevation and texture on net photosynthesis (P_n, μmol m^{-2} s^{-1}), stomatal conductance (g_s, mmol m^{-2} s^{-1}), leaf chlorophyll content (LCC, cci), height (cm), and survival (%) for study plots at Little Topashaw Creek in 2001 and 2002

	Elevation								Soil texture							
	2001				2002				2001				2002			
	d.f.	MS	F	p	d.f.	MS	F	p	d.f.	MS	F	p	d.f.	MS	F	p
P_n	2	21.630	0.537	0.592	2	0.718	0.041	0.960	2	3.780	0.090	0.914	2	8.582	0.496	0.610
g_s	2	2920.400	1.144	0.337	2	69585.675	9.091	<0.001	2	796.350	0.290	0.751	2	79709.156	10.631	<0.001
LCC	2	4.926	0.853	0.427	2	0.183	0.020	0.980	2	4.522	0.783	0.458	2	55.039	6.461	0.002
Height	2	32114.600	8.466	<0.001	2	7768.028	5.526	0.005	2	27953.473	7.235	0.001	2	11759.936	8.805	<0.001
Survival	2	0.069	1.238	0.318	2	0.147	4.949	0.036	2	0.195	5.051	0.021	2	0.106	2.717	0.119

frequency of flooding (%of time) as well as minimum, median, and maximum length of each flooding event were 32%, 0.5, 6.6, and 56.6 h for low elevation plots, 12%, 1.0, 7.0, and 52.1 h at middle elevation plots, and 7%, 0.8, 2.5, and 12.5 h at high elevation plots, respectively.

3.1. *Effects of elevation*

Elevation and sediment texture differed widely across plots. For instance, in 2001, low elevation plots had an average of 57% sand, middle, and high elevation plots contained much coarser texture with 81% sand and 74% sand, respectively. For 2002, average sand content ranged between 75 and 82% across elevation (Table 1).

The relationship between soil E_h and depth to the water table showed a consistent trend of increasing E_h with increasing water table depth at 15, 30, and 60 cm below the soil surface, indicating that plots characterized by deeper water table were likely to have oxidized soil conditions characteristic of drained soils. Low elevation plots had shallow water table and had E_h values in the reduced range at the 60 cm depth (Table 1). However, in these plots soil E_h remained in the oxic range in the upper part of the sediment profile. A similar E_h pattern was found for the mid elevation plots while the E_h for high elevation plots remained in the oxic range at all depths. The E_h data for 2002 showed a similar pattern except that mid elevation plots had E_h in oxic range for all the measured depths. The flooding frequency and duration data supported these findings.

In 2001, LCC, P_n, and g_s were comparable across the elevational gradient (Tables 1–3). In 2002, responses were similar except that g_s was lower for high elevation plots indicating partial stomatal closure (Tables 1–3), which is usually associated with plant water deficits.

At the end of the 2001 growing season, height was significantly greater for low elevation plots (Fig. 3A and Table 2). However, by the end of 2002, plants in high elevation plots were taller than those in low and middle elevation (Fig. 3A and Table 2). Average survival of *S. nigra* cuttings at the end of the first growing season was 70% at low elevation, 48% at mid elevation, and 61% at high elevation. At the end of the second growing season, survival was significantly greater (86%) at low elevation plots, than at mid elevation plots (49%), and at high elevation plots (50%; Fig. 3B and Table 2).

Table 3 – Effect of elevation (with soil texture as covariate) and effect of soil texture (with elevation as covariate) on plant performance in 2001 and 2002 at Little Topashaw Creek

	2001		2002	
	Effect of elevation (soil texture as covariate)	Effect of soil texture (elevation as covariate)	Effect of elevation (soil texture as covariate)	Effect of soil texture (elevation as covariate)
LCC (cci)	$p = 0.3133$	$p = 0.5255$	$p = 0.4649$	$p = 0.0017$; fine soil, a; intermediate, ab; coarse soil, b
g_s (mmol m^{-2} s^{-1})	$p = 0.3509$	$p = 0.5968$	$p < 0.0001$; low elevation, a; middle elevation, a; high elevation, b	$p = 0.0244$; fine soil, b; intermediate, a; coarse soil, b
P_n (μmol m^{-2} s^{-1})	$p = 0.6867$	$p = 0.9371$	$p = 0.7901$	$p = 0.6607$
Height (cm)	$p = 0.0015$; low elevation, a; middle elevation, b; high elevation, b	$p = 0.0525$	$p = 0.0063$; low elevation, b; middle elevation, ab; high elevation, a	$p = 0.0056$; fine soil, a; intermediate, b; coarse soil, a
Survival (%)	$p = 0.4067$	$p = 0.0393$; fine soil, ab; intermediate, a; coarse soil, b	$p = 0.1150$	$p = 0.8190$

Whenever p is less than 0.05, significance was indicated by different letters. Mean ± S.E. was not shown here because it is the same as those already provided in Table 2. P_n, net photosynthesis; g_s, stomatal conductance; LCC, leaf chlorophyll content.

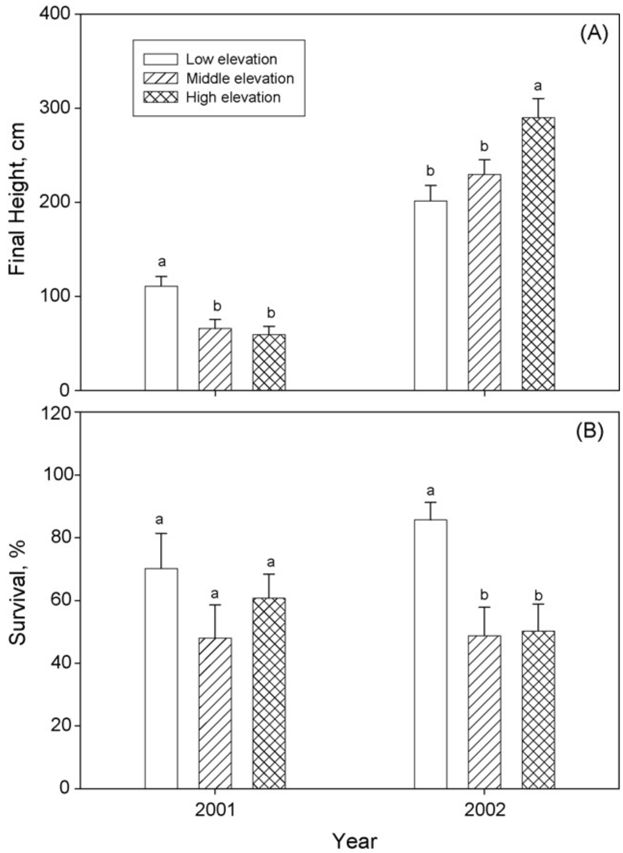

Fig. 3 – Height (A) and survival (B) of black willows in plots at low elevation, middle elevation, and high elevation in 2001 and 2002. Bars represent mean ± S.E. Height values represent the mean for 25–50 measurements while survival values represent the mean for 3–7 plots. For each year, significant differences across vertical elevations are shown using different letters.

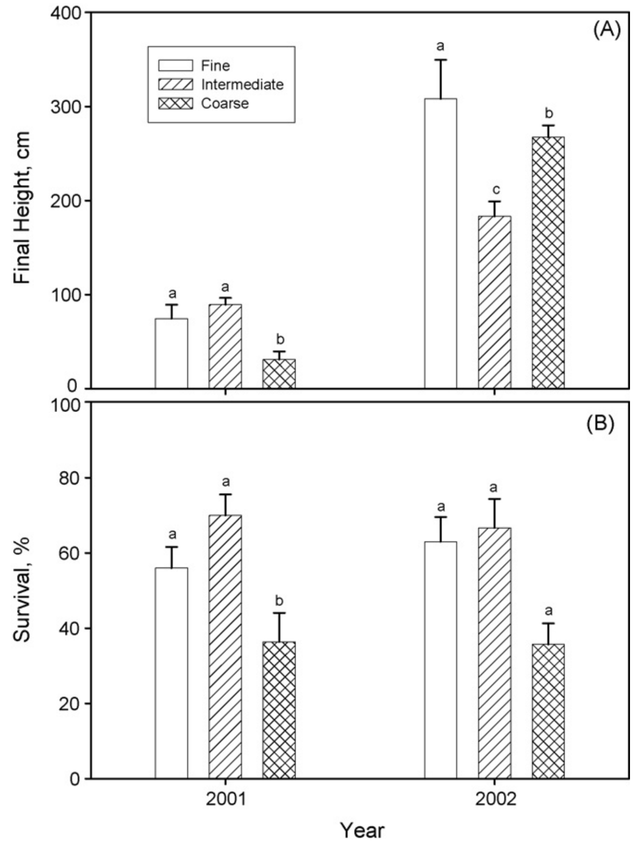

Fig. 4 – Height (A) and survival (B) of black willows in plots with fine, intermediate and coarse texture in 2001 and 2002. Bars represent mean ± S.E. Height values represent the mean for 13–64 measurements while survival values represent the mean for 2–10 plots. For each year, significant differences across soil textures are shown using different letters.

3.2. *Effects of sediment texture*

In 2001, plots with finer soils had a mean water table depth of about 0.5 m. In comparison, depth to water table for intermediate- and coarse textured plots were higher with approximately 1.0 and 1.5 m, respectively. In 2002, intermediate sand plots were closer to the water table (0.6 m) as compared to fine (1.9 m) and coarse texture plots (1.4 m; Table 1). Soil E_h values in the reduced (anoxic) range at the depth of 60 cm were noted for fine texture plots in 2001 (Table 1). However, in these plots, the E_h at 15 and 30 cm was in the oxic range. For intermediate and coarse textured plots, E_h data showed oxic conditions at all depths. The E_h data for 2002 were within the oxic range for all soil texture groups and thus, no evidence of soil reduction at any of the measured depths.

LCC in 2002 was greater in plants grown in fine-textured as compared to plants grown in intermediate and coarse-textured plots (Tables 1 and 2). Photosynthetic measurements in 2002 showed no trends with respect to elevation or soil texture (Table 1). However, g_s showed a decrease in response to fine and coarse soil texture conditions during 2002 (Table 1). The decrease in g_s was moderate and apparently did not lead to significant decreases in P_n.

Across soil texture groups, end of season plant height was greater for plants located in fine and intermediate sand plots as compared to coarse-textured plots at the end of 2001 growing season. For the 2002, height was greater for cuttings located in fine textured plots as compared to intermediate and coarse textured plots (Fig. 4A and Table 2). Survival at the end of the first growing season was 56% for fine-textured plots, 70% for intermediate plots, and 36% for coarse-textured plots. At the end of the 2002 growing season, survival at plots with fine, intermediate, and coarse soil textures was 63, 67, and 36%, respectively (Fig. 4B and Table 2). Additional analyses (Table 3) using soil texture as co-variable with elevation and elevation as co-variable with soil texture produced similar results as reported in Table 2.

4. Discussion

Clearly, both elevation (above water table) and soil texture were important factors that influenced soil moisture availability to plants at our study site. The environmental conditions at LTC indicated occurrence of low soil moisture at high elevation plots or plots with coarse soil texture. In contrast, the expected reduction in sediment E_h due to soil flooding at low elevation plots was not detected above 60 cm. However, roots of black willow normally do not reach that deep, at least early in the establishment period. Therefore, it is not likely that the cuttings in these plots were affected by the reduced E_h conditions.

4.1. *Effects of elevation*

At high elevations, periods of drought occurred during our study. Physiological responses of cuttings to low soil moisture availability included reduced g_s for high elevation plots confirming partial stomatal closure (Table 1); a typical response to water deficits noted in a previous greenhouse study on this species (Pezeshki et al., 1998a) as well as other woody species (Scott et al., 1999). Elevation relative to the prevailing water table is important for recently planted cuttings because it increases plant dependence on the precipitation during the period required for roots to grow long enough to reach moist soils. Such dependence increases vulnerability to periodic drought. For instance, water table decline and the associated water stress has been cited as one of the most common causes of mortality in *Salix* and *Populus* species in the field (Mahoney and Rood, 1992; Karrenberg et al., 2002). Responses of *Populus* spp. to abrupt or sustained water table decline of ≥1 m included leaf desiccation and branch dieback, with 88% mortality after three years. Some of them were capable of surviving gradual water table declines ≤0.5 m with reduced branch growth (Scott et al., 1999).

Although high elevation plots at LTC, particularly coarse-textured plots, suffered from periodic low precipitation, low elevation plots likely provided ample water as was evidenced by reduced soil E_h conditions at 60 cm depth (Table 1). However, soil E_h range of +200 to +350 mV is not likely to have caused any measurable stress (see also Schaff et al., 2003). In our study, cuttings generally survived better at low elevations above the water table as compared with middle and high elevations (Table 1 and Fig. 3). High mineral content and low organic matter in alluvial sediments likely contributed to the mildly reduced conditions observed at low elevation plots (Schaff et al., 2003).

The interpretation of height growth should be made in view of the sporadic observed herbivory by beaver at our study site. We had initially installed stem collars to protect against herbivory. However, some sporadic herbivory activities were noted across the study area. Although we have not addressed herbivory effects herein, greenhouse studies (Li et al., 2005) indicated increased net photosynthesis under both light and heavy herbivory treatments, but these treatments were acute rather than chronic events. Others have noted adverse effects of herbivores on restoration plantings (McLeod, 2000; Mayer et al., 2000).

4.2. *Effects of sediment texture*

Our data indicated that both fine and coarse soil texture components contributed to lower survival rates (Fig. 4), with g_s showing the same trend (Table 1). Plots with highest survival had moderate soil texture allowing for an aerated soil condition that also maintained some water-holding capacity. In contrast, fine-textured sediments led to poor plant performance due to compaction and the associated low aeration. Sandy soils, on the other hand, have larger pore spaces but lower water-holding capacity, increasing the risk for periodic drought stress for plants on streambanks (Fig. 4).

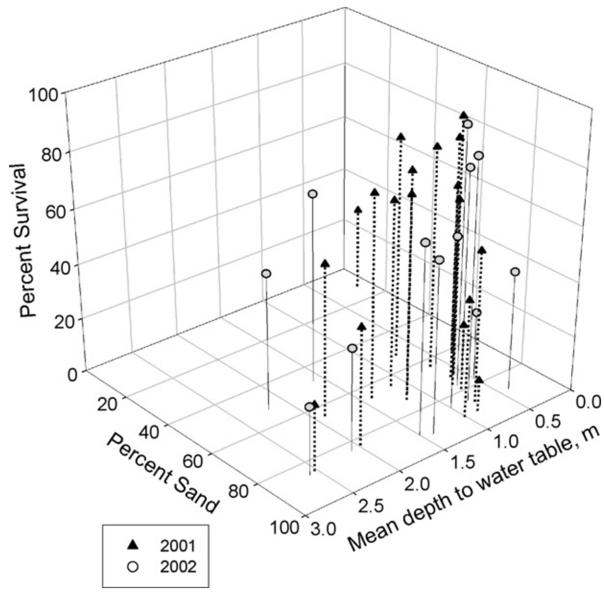

Fig. 5 – Survival of black willow cuttings in Little Topashaw Creek study plots in response to soil texture (percent sand) and plot elevation above water table at the end of the first (2001) and second (2002) growing seasons.

Even though we could not test the interactive effects of sediment texture and elevation on plant responses, it is important to note that texture does interact with depth to water (water availability) in two ways: fine substrates are required to improve water-holding capacity in situations where water availability is low such as at high elevation. In contrast, coarse sediments are required to improve drainage, reduce compaction and permit aeration when water availability is high such as at low elevation. In the present study, it was observed that the average depth to water table for both fine- and coarse-textured plots were rather high (1.9 and 1.4 m) in 2002 (Table 1). But the height and survival in plots with fine texture were relatively high as compared with intermediate sand plots with an average depth to water table of only 0.57 m (Table 1 and Figs. 4 and 5). On the other hand, plots with high sand content performed poorly (Table 2 and Fig. 5). The interaction between texture and elevation may also explain the lack of variability in P_n between the three texture groups in 2002 (Table 1).

Approximately 85% of the plants that lived through 2001 survived through 2002. Contributing factors to low mortality rates of cuttings during the 2002 growing season included higher precipitation in 2002 than 2001 but also cuttings had one growing season (2001) to develop root systems. In 2001, the cuttings had to establish root systems and thus were vulnerable to low precipitation. The established root systems can act as a buffer providing an internal reservoir of water and nutrient supply for plants during periods of less favorable environmental conditions. In addition, an established root system is also likely to be better able to extract water and nutrients from a wider and/or deeper area to support plant growth.

5. Conclusions

Our data indicated that survival and growth of willow cuttings during the first two growing seasons were influenced by elevation relative to water table as well as sediment texture. Survival and growth were generally best for study plots at low elevations and for those with intermediate sand content. About 85% of cuttings that survived the first growing season were alive by the end of the second growing season, highlighting the importance of early survival, which depends on factors that may be evaluated prior to planting.

Determination of an appropriate planting zone based on the depth to the prevailing water table and sediment texture is important. For instance, locations close to the creek can be avoided to minimize loss of plantings due to soil flooding and erosion impacts (Watson et al., 1997). Upper banks containing high sand sediments can also be avoided to reduce mortality of transplanted cuttings due to soil moisture deficits. Obviously, such determinations require basic data on the sediment and hydrologic attributes of a target site. Therefore, any riparian restoration effort should include assessment of these factors prior to implementing restoration plantings. Additional factors may also be important. The long-term survival of the ~4000 cuttings in the LTC project, evaluated in 2004, was less than ~10% (Shields, unpublished data). Thus, even if factors such as soil texture and elevation are properly accounted for in project planning, the probability of long-term success will still depend on other factors such as channel stability, competition from exotics, chronic herbivory and additional factors.

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