Influences of cutting diameter and soil moisture on growth and survival of black willow, *Salix nigra*

E. Greer, S.R. Pezeshki, and F.D. Shields, Jr.

ABSTRACT: Streambank restoration projects utilize large black willow *(Salix nigra)* cuttings otherwise known as posts; however, potential exists that smaller size cuttings alone or in combination may improve success efforts. Furthermore, the effects of soil moisture conditions and the potential interaction between size of the cutting and soil moisture regime have not been tested. Therefore, a greenhouse study was conducted to quantify cutting performance in response to the combined effects of soil moisture and diameter size. Replicated cuttings with basal diameters measuring 1, 5, or 10 cm (0.4, 2, or 4 in) were placed in three soil moisture regimes including well-watered, periodic flooding and drought. Biomass accumulation and partitioning, height, and survival were measured. tinder periodic flooded conditions, 10 cm (4 in) cuttings had greater leaf number and weight (p<.o5), leaf area index (p<.o5), shoot weight (p<.o5), root weight (p‹.05), and height growth (p<.o5) compared to 1 and 5 cm (0.4 and 2 in) cuttings (p<.o5). Survival was best for 1 cm (0.4) cuttings in all three moisture regimes (loo percent) and for 10 cm (4 in) cuttings under flooded conditions (loo percent). Growth and biomass of 10 cm (4 in) cuttings were reduced by drought compared to periodic flooding treatment (p=.02). Based on the data, it appears that planting strategies using i cm (0.4 in) cuttings of black willow in any given moisture regime may lead to increased survival rates. Planting larger cuttings may improve overall restoration success. The technique of planting a combination of these two diameters may help to further stabilize streambanks.

Keywords: Cutting size, erosion control, riparian restoration, streambank stabilization, soil moisture

The dynamic environmental conditions of riparian zones are dependent on precipitation and streamflow, which greatly influence the type of vegetative species that occur (Naiman et al., 1993; Amlin and Rood, 2001; Mitsch and Gosselink, 2000). Riparian vegetation is known to provide nutrients to aquatic and terrestrial biota and regulate light and temperature gradients through water shading (Naiman et al., 1993; Mahoney and Rood, 1998), assist in river-bank stabilization (van Splunder et al., 1994) and establishment of other species (Johnson, 1984;Watson et al., 1997). Although riparian zones are highly valued for water quality and biodiversity, human influences on these areas have been devastating. For example, over the last 200 years, more than 80 percent of riparian zones in North America and Europe have been destroyed (Naiman et al., 1993). Hastened bank erosion arid a decrease in the diversity of native plant species are a few consequences of human impacts on these systems (Hoag, 1995).

Societal response to this degradation has been slow, but efforts are being made to restore these ecosystems. Several restoration techniques have been applied in projects conducted worldwide to re-establish riparian vegetation and stabilize streambanks including many projects in the south central United States (Hoag, 1995; Shields et al., 1995; Watson et al., 1995; Abt et al., 1996). Woody vegetation occurring in natural stands has proven to reduce streambank erosion during stochastic events (Geyer et al., 2000). Due to the extreme nature of these events, which are characteristic of riparian corridors, woody species, such as willow *(Salix spp.)* are often used in restoration efforts (Vora et al., 1988; van Splunder et al., 1994; Hoag, 1995; Shields et al., 1995; Shields, 1998; Schaff et al., 2000; Pezeshki et al., 2002; Pezeshki arid Shields, 2004).

Willows *(Salicaceae spp.)* are pioneer species, inhabiting areas around swamps and bodies of fresh water (McLeod and McPherson, 1973; Karrenberg et al., 2002; Donovan et al., 1988). Black willow *(Salix nigra* Marshall) exhibits traits that are indicative of a flood tolerant species; it survives and even thrives on active floodplains (Karrenberg et al., 2002). The ability to establish rapidly by means of its massive root system, as well as the ability to regenerate from dormant and non-dormant, unrooted cuttings allows black willow to be a cost effective species for riparian restoration (Shields et al., 1995; Shields et al., 1998; Schaff et al., 2000; Pezeshki et al., 2005).

Despite some reported successes, many projects using black willow cuttings have suffered from low survival rates. Factors that have contributed to the low survival are erosion, herbivory, and soil moisture extremes (Pezeshki et al., 1998a; Schaff et al., 2000; Pezeshki, 2003). Soil moisture conditions have proven to have a significant impact on the initial cutting growth and survival, therefore it has been the focus of several research projects. Flood and drought conditions were reported as leading causes of low growth and biomass production in black willow cuttings (Donovan et al., 1988; Pezeshki et al., 1998a; Schaff et al., 2003). The effects of soil conditions on black willow in combination with other planting techniques have received considerable attention but still remain a critical concern in restoration efforts. Several studies have examined interactive effects on cuttings by soil moisture arid other factors such as soil texture and elevation (Pezeshki and Shields, 2004, Pezeshki et al., 2002, Schaff et al., 2003, Shields et al., 1998). However, the influences of initial cutting size and the potential interaction with soil moisture regime have not been explored.

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Many of the restoration efforts using black willow utilize large cuttings otherwise known as "posts". For example, Hoag (1995) used cuttings of various species that were 8 to 20 cm (3 to 8 in) in diameter. Watson et al. (1997) highly recommended the use of larger posts (minimum of 4 cm; 1.6 in) to increase survival in the field, yet sample sizes were small for cuttings less than 4 cm leaving the question open as to what diameter of black willow is most appropriate for planting. In contrast, smaller diameter (2 to 3 cm; 0.8 to 1.2 in) cuttings of willow had higher survival rates than larger diameter cuttings (Vora et al., 1988). It is important to note that larger diameter cuttings have a greater food and water reserve than smaller diameter cuttings of equal length and consequently may have an advantage over smaller diameter cuttings enabling them to develop a more extensive root system early in the establishment period (Hoag, 1993). In contrast, smaller diameter cuttings are younger plant material, and for this reason may grow more vigorously or differentiate more efficiently to form roots and shoots.

In light of these considerations, the present study was conducted to examine the effects of cutting diameter and soil moisture on the survival and performance of black willow. The specific objective was to quantify cutting performance due to the individual and the combined effects of cutting diameter and soil moisture. The main hypothesis of this study is that growth and survival will increase with greater cutting diameter within all moisture treatments. The three questions asked were: 1) Does initial cutting diameter affect subsequent growth and survival of transplanted black willow cuttings? 2) Are there any additive or synergistic effects between cutting diameter and soil moisture conditions where cuttings are transplanted? and 3) If so, what effect does diameter have on the level and nature of the response to soil moisture regime? Such information is critical and may help improve planting techniques that may utilize the most appropriate cutting size based on the predominant soil moisture regimes within a designated restoration site.

Materials and Methods

Black willow cuttings were collected from a localized population on the Loosahatchie River floodplain in western Tennessee in late March 2004. Each cutting, 1.2 m (4 ft) in length, was cut so the basal diameter measured 1 cm, 5 cm, or 10 cm (0.4, 2, or 4 in). Larger diameter cuttings (10 cm; 4 in) were removed from the base of individual parent plants, and when possible 1 and 5 cm (0.4 and 2 in) cuttings were collected from the branches and shoots of these parent plants. The existing branches were removed from the cuttings to conform to common planting practices (USDA-NRCS, 1996). Cuttings were transported to the laboratory and wrapped in wet towels, covered with dark plastic bags, and stored overnight in a cool, dark room. Cuttings were planted in the greenhouse within 24 hours.

Pots 0.6 m (2 ft) high and 15 cm (6 in) in diameter were constructed of PVC pipe and filled with two parts commercial sand and one part field soil (v:v) which was collected from the same area as the cuttings (Falaya Soil Series). Caps were glued to the bottom and a hole was drilled on the side of each pot to allow for control of water regime. A single cutting was planted in each pot so that 55 cm (22 in) of the cutting remained above the soil level. The study was conducted in an air-conditioned greenhouse with an average daily temperature of 25°C (77°F) using natural light. Cuttings were maintained under well-watered conditions for 14 days before initiation of soil moisture treatments to allow for root initiation. Cuttings were fertilized weekly with 200 mL of 20-20-20 Peter's fertilizer mixed with tap water at 1.25 g

Eleven cuttings of each diameter were placed in each of the three water regimes including periodic flooding (PF, one day flooded to 5 cm (2 in) above soil surface, six days drained), control (C, well-watered, well-drained), and drought (DR, please see the following paragraph) for a total of 99 replicates. Flooding occurs in low elevation areas along the stream edge creating saturated soils that can be stressful for plants located here (Shields et al., 1995; Pezeshki et al., 1998b; Schaff et al., 2003). In high-elevated areas along the streambank where depth to the water table is great, drought conditions may occur throughout the growing season. Once a day for the duration of the experiment, approximately 1000 mL of tap water was added to each pot in periodic flooding and control treatments.

To ensure soil drought and monitor drought conditions in drought treatment, predawn leaf water potential OH measurements were conducted on days 24, 31,38, and 43 after treatment initiation using a pressure chamber (PMS Instrument Co., Model 1002). Once predawn 1P$_l$ reached between -5 to -7 bars, cuttings were lightly watered to maintain drought conditions but prevent mortality of cuttings. On each measurement day, three samples from each of the cutting diameters in both control arid drought treatments were randomly selected for data collection totaling nine measurements per soil moisture treatment. Plant predawn Ψ$_l$ in drought treatment was compared to the control treatment to ensure drought conditions were present. To monitor changes in soil oxidation-reduction conditions, soil redox potential was measured in periodic flooding and control treatments at 30 cm (12 in) below the soil surface using platinum-tipped electrodes, a millivoltmeter (Orion, Model 250A), and a calomel reference electrode (Corning, Model 476350). Soil redox potential measurements were conducted on days 23, 30, 37, and 42 after treatment initiation. Soil redox potential was measured on three samples from each of the cutting diameters for a total of nine measurements per soil moisture treatment.

The experiment followed a randomized block design. Cuttings were blocked by water regime and the three different diameter sizes were randomly assigned within each regime. All cuttings were planted on March 29, 2004. Soil moisture treatments were initiated on April 13, 2004. Harvesting was completed on June 29, 2004.

At planting, initial height for all cuttings was determined to be 0 (cutting only; no shoot growth). Height growth was measured from the top of the cutting to the tip of tallest shoot. Leaf chlorophyll content was measured for every cutting at the end of the study using a chlorophyll content meter (Opti-Sciences, model CCM-200). Leaf chlorophyll content was measured on the third leaf from the top of the shoot in order to avoid taking measurements on very young or older leaves. However, due to the death of mature leaves on cuttings in the drought treatment, chlorophyll data was not available for drought plants. Survival was determined at the end of the experiment by visual inspection for living aboveground and belowground biomass. If the aboveground biomass was dead and the cutting had less than five apparent live roots, the cutting was considered to be dead. If the aboveground biomass was alive and the cutting had less than five live roots, the cutting was considered to still be

Table 1. ANOVA results and MANOVA results (F value, df and p value) for the simple effects and interaction between cutting diameter and soil moisture for predawn leaf water potential (ψ_l) (control (C) and drought (DR)) and for biomass parameters (periodic flooding, control, and drought), respectively of black willow cuttings.

Source of variation	df	Predawn leaf water potential (-bars)				Biomass parameters
		F	p	F	p	df
Moisture	1	62.51	<0.001	16, 166	2.56	<0.001
Diameter	2	9.15	<0.001	16, 166	11.94	<0.001
Moisture*Diameter	2	6.22	0.003	32, 308	1.72	0.01

alive at the end the study although in the process of dying.

At the conclusion of the study, cuttings were separated into shoots, leaves, and roots. Shoots and leaves were separated from the cutting and carefully counted. They were then separated and oven-dried at 70°C (158°F) until a constant weight was reached. Roots were counted, removed from the cutting, and carefully washed. Belowground components were also placed in separate bags and dried in an oven to a constant weight. All growth variables were then weighed for biomass. Root/shoot ratios were calculated using the total amount of roots and shoots for each cutting. Leaf area was calculated using a leaf area model presented in Pezeshki et al. (1998a).

Multivariate analysis of variance (MANOVA) of the general linear model was used to test for differences in growth variables between diameter sizes within and across each soil moisture treatment. Analysis for predawn leaf water potential, height growth, and chlorophyll content was conducted as a two-factor analysis of variance (ANOVA). Tukey's Studentized range test was used to identify differences in the pair-wise comparisons. A two-factor chi square analysis was used to determine differences in survival rates. T-test procedures were used to test for significance in soil redox measurements between periodic flooding and control soil moisture treatments. All analyses were performed using the SPSS 11.0 statistical package with an alpha level <0.05.

Results and Discussion

Soil conditions. Soil redox potential levels remained in an aerated range (soil redox potential > + 350) in all periodic flooding pots prior to treatment initiation. Within 24 hr after flooding was initiated, soil redox potential levels in the periodic flooding treatment were reduced (soil redox potential < + 350). This soil reduction was significant from soil redox potential levels in the control treatment, which remained aerated (Mean soil redox potential = 444.9, ± s.d. = 72.6, p <0.001). Soil redox potential levels in the periodic flooding treatment were never severely reduced due to the short duration of the flooding event (ranged between + 230 to + 326 mV). Soil redox potential levels returned to the aerated range after the flooding water was removed. This pattern was consistent throughout the course of the study.

The interaction between cutting size and soil moisture was significant for predawn v_i (Table 1). Predawn v_i of 10 cm cuttings was lower (more negative) compared to 1 and 5 cm (0.4 and 2 in) cuttings in the drought treatment. However, predawn values in the control treatment did not differ significantly across diameter sizes (Figure 1). Predawn v_i values in the drought treatment were on average significantly lower (more negative) than cuttings in the control treatment (-1.3 and -5.0 bars, respectively) confirming drought conditions.

Effects of cutting diameter on biomass components within various moisture treatments. There was a significant interaction between soil moisture and cutting diameter on the biomass components including number of leaves (L), leaf weight (LW), number of shoots (S), shoot weight (SW), number of roots (R), root weight (RW), root:shoot ratio (R:S ratio), and leaf area (LA) (Table 1). Simple main effects analysis was conducted for the interaction between moisture treatments and diameter size. Biomass parameters showed significant differences between the three diameter sizes within each moisture treatment: for treatment control ($F_{(16,46)} = 4.70$, $p<.0.001$); for treatment periodic flooding ($F_{(16,46)} = 7.164$, $p<0.001$); for treatment drought ($F_{(16,46)} = 4.847$, $p<0.001$). The

Figure 1
Mean (± s.d.) predawn leaf water potential (ψ_l) of 1 cm, 5 cm, and 10 cm black willow cuttings in control (C) and drought (DR) moisture treatments. Significant differences, indicated by different letters, are within moisture treatments for cutting diameter sizes.

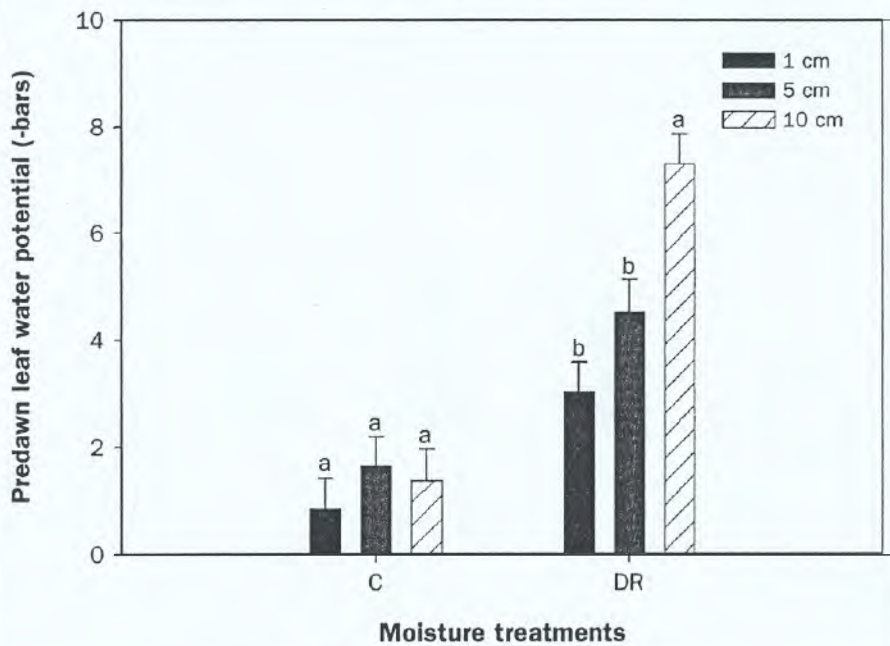
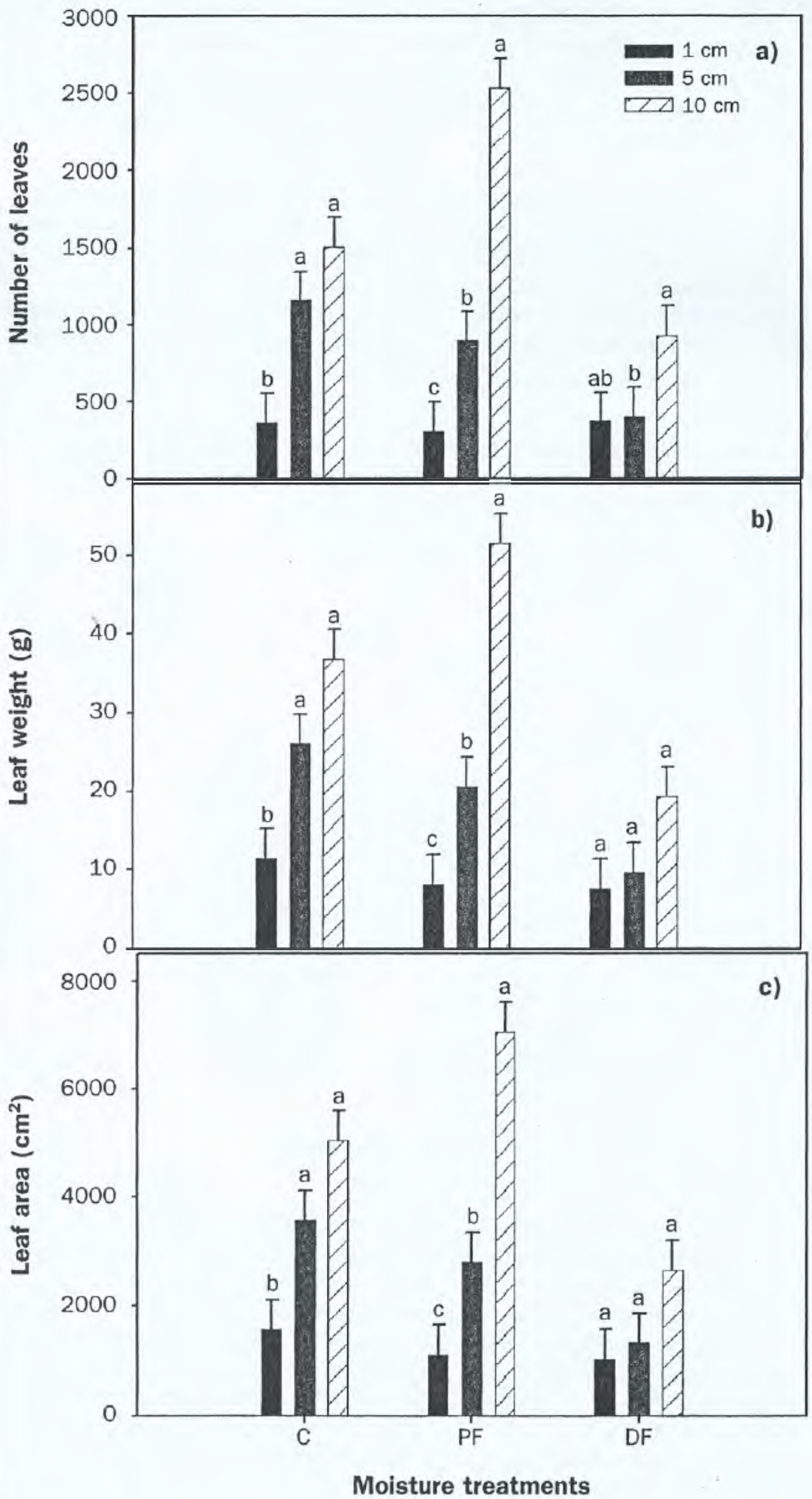


Figure 2
Mean (± s.d.) a) number of leaves, b) leaf weight, and c) leaf area for 1 cm, 5 cm, and 10 cm black willow cuttings in control (C), periodically flooded (PF), and drought (DR) moisture treatments. Significant differences, indicated by different letters, are within moisture treatments for cutting diameter sizes.



results of the pair-wise comparisons indicated that in the control treatment, 5 and 10 cm (2 and 4 in) cuttings did not differ significantly overall for the biomass parameters. Also, in the drought treatment, 1 and 10 cm (0.4 and 4 in) cuttings did not differ significantly for the biomass parameters.

In periodic flooding treatment, leaves, leaf weight, and leaf area were greatest for 10 cm (4 in) cuttings compared to 1 and 5 cm (0.4 and 2 in) cuttings. In addition, leaves, leaf weight, and leaf area were significantly greater in 5 cm (2 in) cuttings compared to 1 cm (0.4 in) cuttings in this treatment. In control treatment, leaves, leaf weight, and leaf area were greater in 5 and 10 cm (2 and 4 in) cuttings compared to 1 cm (0.4 in). In drought treatment, leaf weight, and leaf area did not differ significantly among cutting diameters. However, leaves were greater in 10 cm (4 in) cuttings compared to 5 cm (2 in) cuttings. Leaf numbers and weight of 1 cm (0.4 in) cuttings were comparable to that of 5 cm (2 in) cuttings in the drought treatment (Figure 2a, b, c).

Numbers of shoots and shoot weight were greatest for 10 cm (4 in) cuttings in periodic flooding treatment compared to 1 and 5 cm (0.4 and 2 in) cuttings. Although number of shoots was not significantly different among cutting sizes in control treatment (Figure 3a), shoot weight was greater in 10 cm (4 in) cuttings compared to 1 cm (0.4 in) cuttings (Figure 3b). Shoot weight for 5 cm (2 in) cuttings did not differ significantly from shoot weight of 1 or 10 cm (0.4 and 4 in) cuttings in this treatment. In drought treatment, number of shoots and shoot weight were greatest in 10 cm (4 in) cuttings compared to 5 cm (2 in) cuttings (Figure 3a, b).

Numbers of roots were greatest for 1 and 10 cm (0.4 and 4 in) cuttings compared to 5 cm (2 in) cuttings in periodic flooding treatment (Figure 4a). Root weight was greatest for 10 cm (4 in) cuttings in this treatment compared to .1 and 5 cm (0.4 and 2 in) cuttings (Figure 4b). However, number of roots:number of shoots ratio was greatest for 1 cm (0.4 in) cuttings compared to the other cutting sizes (Figure 4c). In control treatment, number of roots and number of roots:number of shoots ratio were greater for 1 cm (0.4 in) cuttings compared to 5 cm (2 in) cuttings, but root weight did not differ between cutting sizes. In drought treatment, number of roots and number of roots: number of shoots ratio were greater for 1 and

10 cm (0.4 and 4 in) cuttings compared to 5 cm (2 in) cuttings. Root weight was greater in 1 cm (0.4 in) cuttings compared to 5 cm (2 in) cuttings while root weight of 10 cm (4 in) cuttings was comparable to root weight of 1 and 5 cm (0.4 and 2 in) cuttings (Figure 4a, b, c).

Effects of cutting diameter on biomass components across moisture treatments. The biomass parameters also showed significant differences for the 1 and 10 cm (0.4 and 4 in) but not the 5 cm (2 in) diameter size cuttings across soil moisture treatments (for 1 cm (0.4 in): $F_{(14,42)} = 3.358$, p = 0.001; for 5 cm (2 in): $F_{(14,42)} = 0.527$, p = 0.361; for 10 cm (4 in): $F_{(14,42)} = 2.828$, p = 0.001). The results of the pair-wise comparisons showed that for 1 cm (0.4 in) size cuttings, biomass parameters did not differ for cuttings grown in periodic flooding and drought treatments in comparison to those grown in control treatment, but they differed significantly from each other. The results also indicated that 5 cm (2 in) cuttings did not differ on the biomass parameters across moisture treatments. In contrast, for 10 cm (4 in) cuttings, biomass parameters for cuttings grown in drought treatment did not differ from control treatment.

For 1 and 5 cm (0.4 and 2 in) cutting sizes, most biomass parameters did not differ across moisture treatments (Figures 5, 6, and 7a). However, root weight for 1 cm (0.4 in) cuttings was greater in drought compared to periodic flooding treatment (Figure 7b). Root: shoot ratio for 1 cm (0.4 in) cuttings was greater in drought treatment compared to periodic flooding treatment (Figure 7c).

For 10 cm (4 in) cuttings leaves, leaf weight and leaf area were greatest in periodic flooding treatment compared to both control and drought treatments (Figure 5). In addition, the number of shoots was greater in periodic flooding treatment compared to control (Figure 6a). Shoot weight for 10 cm (4 in) cuttings was greater in periodic flooding compared to control and drought treatments (Figure 6b). Root numbers were greater for 10 cm (4 in) cuttings in periodic flooding treatment compared to control, but root weight was greater in periodic flooding compared to drought treatment (Figure 7a).

Chlorophyll content, height growth, and survival. Height growth data showed a significant interaction between cutting size and moisture treatment (Table 2). Height growth was significantly different among cutting sizes only in periodic flooding treatment; it was greater in 10 cm (4 in) cuttings at the end of the study compared to 1 and 5 cm (0.4 and 2 in) cuttings. Cutting sizes did not differ significantly in height growth in control or drought treatments (Figure 8).

Height growth did not differ across moisture treatments for 1 cm (0.4 in) cuttings but did differ for 5 and 10 cm (2 and 4 in) cuttings (Figure 9). Height growth was greatest for 5 cm (2 in) cuttings in periodic flooding treatment compared to drought, where growth did not differ significantly between control and drought or between control and periodic flooding treatments. Height growth was greatest in periodic flooding treatment for 10 cm (4 in) cuttings compared to control and drought treatments, and growth was greater in control compared to drought treatment (Figure 9).

Analysis of leaf chlorophyll content data showed no interaction between cutting diameter and moisture treatment. Chlorophyll

Figure 3
Mean (± s.d.) a) number of shoots and b) shoot weight of 1 cm, 5 cm, and 10 cm diameter black willow cuttings in control (C), periodically flooded (PF), and drought (DR) moisture treatments. Significant differences, indicated by different letters, are within moisture treatments for cutting diameter sizes.

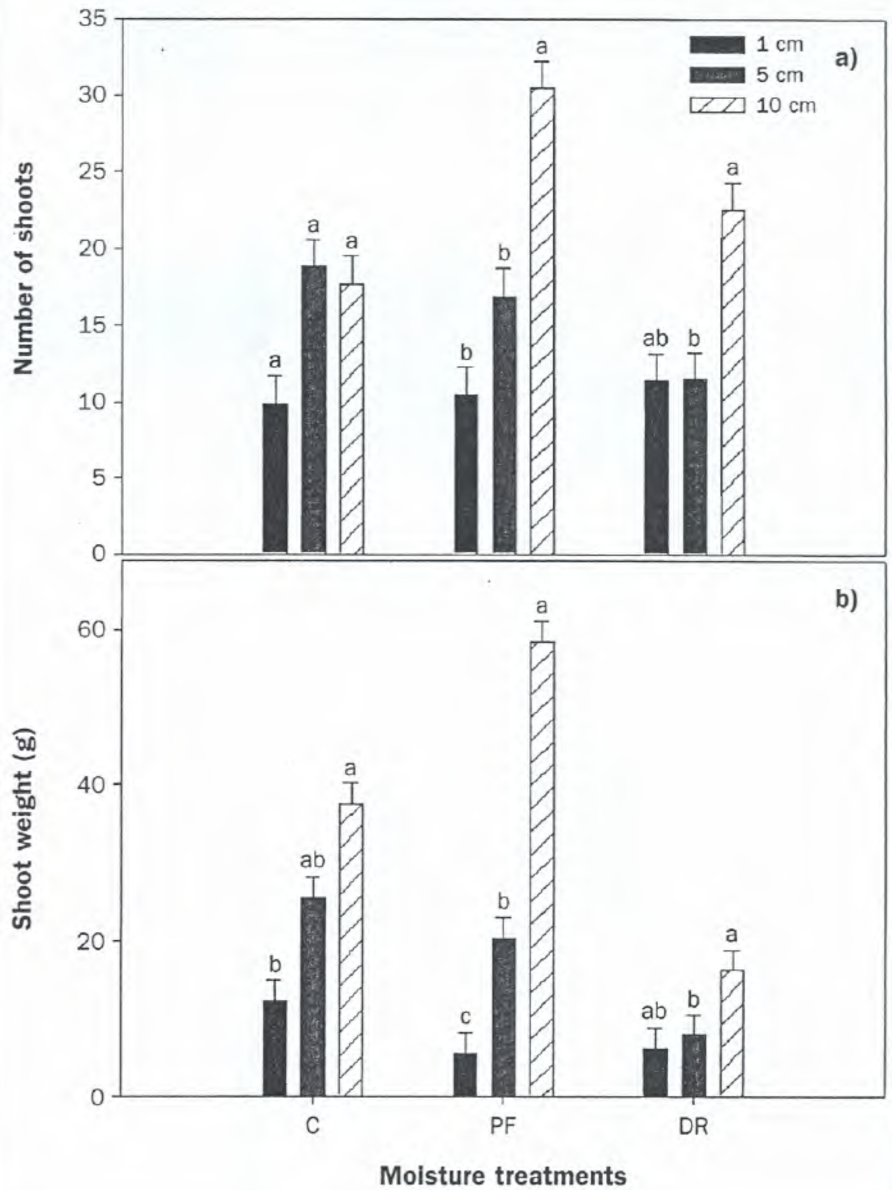
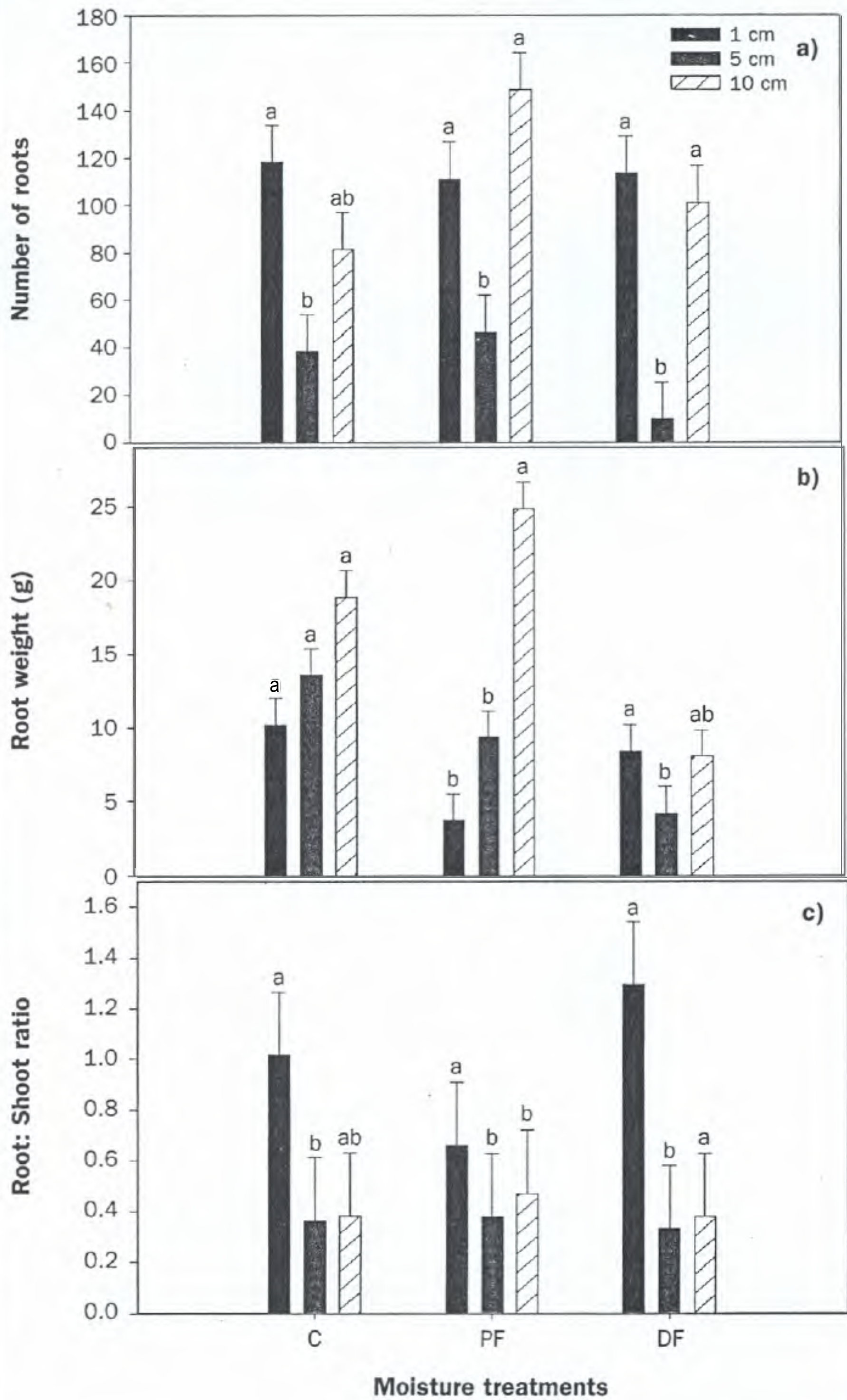


Figure 4
Mean (± s.d.) a) number of roots, b) root weight, and c) root: shoot ratio for 1 cm, 5 cm, and 10 cm black willow cuttings in control (C), periodically flooded (PF), and drought (DR) moisture treatments. Significant differences, indicated by different letters, are within moisture treatments for cutting diameter sizes.



content was not significantly different between cutting diameters but was significantly affected by moisture treatment (Table 2). At the end of the study; cuttings in periodic flooding treatment had significantly lower chlorophyll content compared to cuttings in the control treatment (C = 5.87, PF = 3.68). This finding indicates that there was some chlorophyll degeneration in willow leaves as a result of periodic flooding.

Survival rate of 1 cm (0.4 in) cuttings was 100 percent in all moisture treatments. However, survival of cuttings differed significantly only in the periodic flooding treatment (Table 3). Survival of 5 cm (2 in) cuttings was lower compared to 1 and 10 cm (0.4 and 4 in) cuttings in this moisture treatment. Survival rates did not differ significantly across moisture treatments for any of the cutting diameters.

Effects of cutting diameter on growth and biomass components within various moisture treatments. The biomass data indicated the influence of initial cutting diameter on growth and survival of black willow grown under varying soil moisture conditions. Growth and a number of biomass parameters were greater for 10 cm (4 in) cuttings in the periodic flooding treatment compared to 1 and 5 cm (0.4 and 2 in) cuttings (Figures 2, 3, 4, and 8).

Reports of short-term flooding effects on flood- tolerant species, including black willow, have been conflicting. Several studies have shown a decrease in growth and some biomass components as a result of inundation (Donovan et al., 1988; Pezeshki and Anderson, 1997; Pezeshki et al., 1998ab). However, McLeod and McPherson (1973) noted an increase in growth of black willow in saturated soils. The confusion is primarily due to the difference in duration of flooding among these studies as well as lack of quantification of soil redox conditions that prevail in inundated soils. It imposes a wide range of soil redox potential with significant implications for wetland plant survival, growth, and root functioning (for a review see Pezeshki 2001 and the references cited therein). Nonetheless, a wide range of soil moisture conditions including flooded (low soil redox potential), partially flooded, and periodic drought, characterize riparian systems where black willow is found (Shields et al., 1995; Schaff et al., 2003).

In addition to soil moisture conditions, diameter size may be an important factor for survival and growth of cuttings (posts) planted for riverbank restoration projects. For instance, height growth also increased with increasing cutting diameter in a *Populus alba* hybrid (Hansen and Tolstead, 1981). This is expected since larger diameter cuttings have greater storage of carbohydrate and water reserves compared to smaller cuttings (Hoag, 1993). These reserves may aid larger cuttings in rapidly producing biomass and establishing a root system.

In the present study, soil condition was not reduced severely in the periodic flooding treatment due to the short- term duration of flooding imposed (soil redox potential ranged between + 230 to + 326 mV). The one day of flooding event was then followed by six days of drainage where adequate soil moisture combined with aerated soil conditions were present (soil redox potential ranged between + 530 to + 555 mV). With these alternating soil conditions, the large store of reserves as a result of large cutting size may have contributed to the greater height growth and biomass accumulation of 10 cm (4 in) cuttings in the periodic flooding treatment compared to 1 and 5 cm (0.4 and 2 in) cuttings (Figures 2, 3, 4, and 8).

Flooding also affects belowground components dramatically. First, production of aerenchyma tissue and adventitious roots is initiated by flooding in flood- tolerant species such as black willow. These characteristics play an important role in oxygen transport allowing these species to survive in periodically saturated soils (Pezeshki et al., 1998a; Schaff et al., 2003). Moreover, aerenchyma tissue and adventitious rooting contribute to the high nutrient-uptake efficiency of flood-tolerant species (Kozlowski, 1997). Second, flooding affects root production and biomass of riparian plants. Initially, root growth is reduced by soil inundation in most woody plants, which consequently decreases root/shoot ratios (Kozlowski, 1997). For instance, root mass of tamarack *(Larix laricina)* seedlings was reduced due to flooding compared to non-flooded seedlings (Islam and MacDonald, 2004). Additionally, root biomass of black willow decreased in response to continuously flooded conditions (Pezeshki et al., 1998a).

In the present study under periodic flooding treatment, although 5 and 10 cm (2 and 4 in) cuttings had greater aboveground biomass accumulation, the smaller cuttings produced more roots than 5 cm (2 in) cuttings and a greater root/shoot ratio compared

Figure 5

Mean (± s.d.) a) number of leaves, b) leaf weight, and c) leaf area for 1 cm, 5 cm, and 10 cm black willow cuttings in control (C), periodically flooded (PF), and drought (DR) moisture treatments. Significant differences, indicated by different letters, are across moisture treatments for cutting diameter sizes.

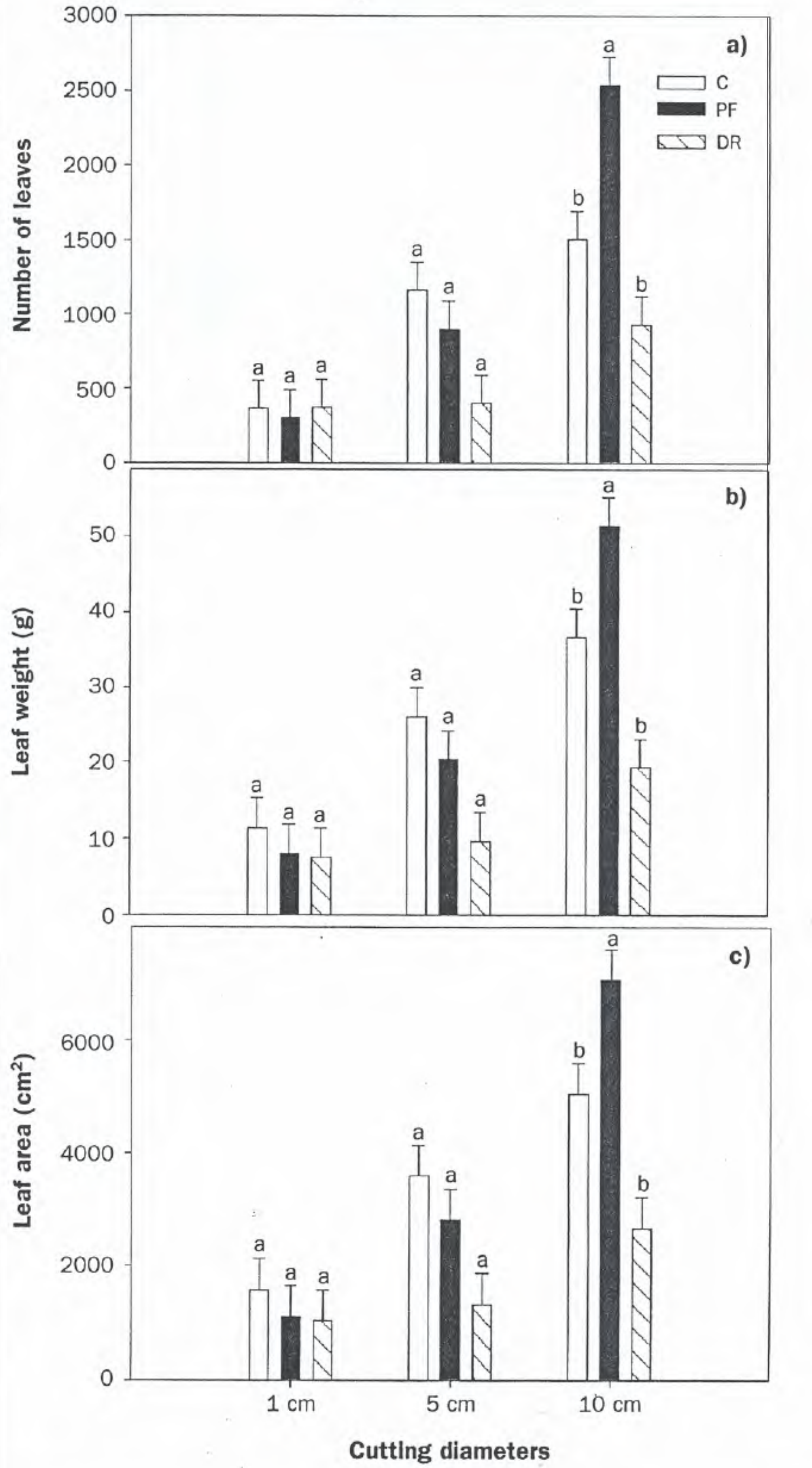
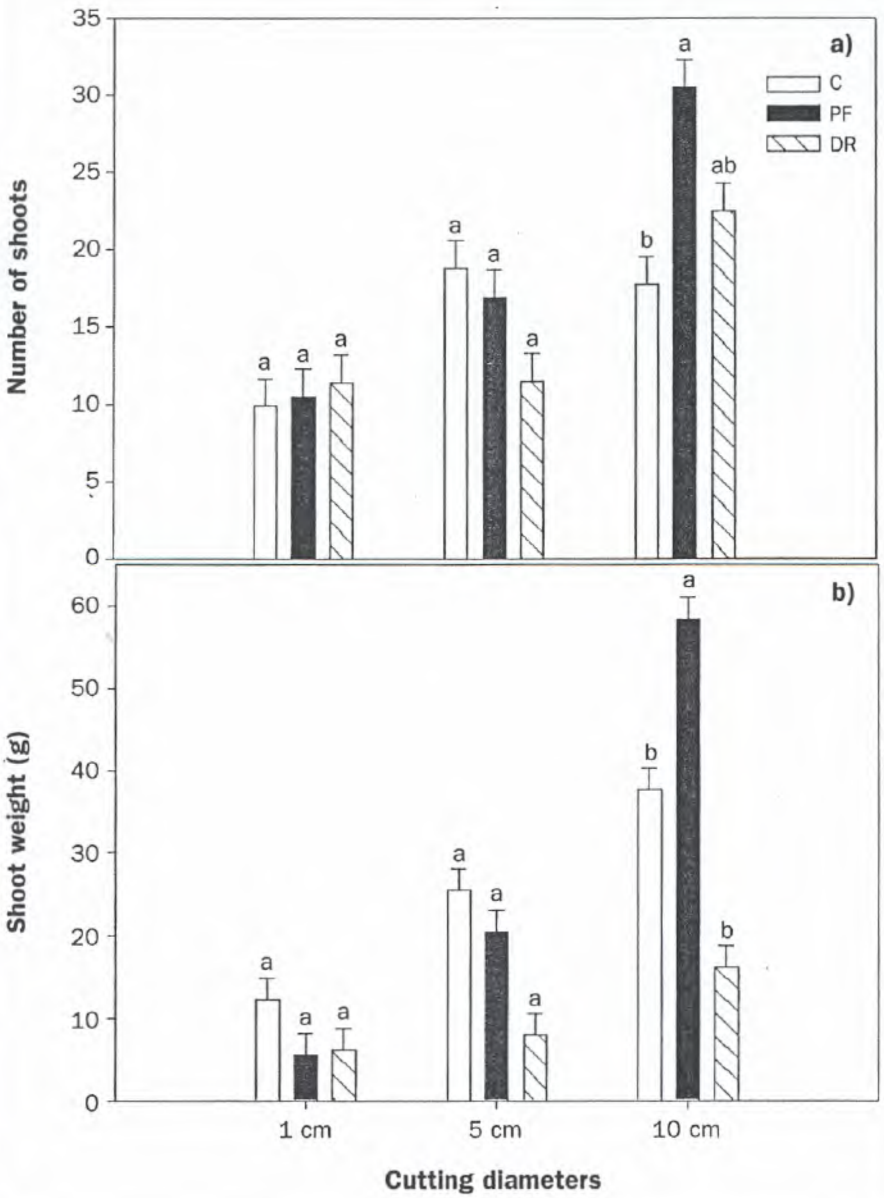


Figure 6

Mean (± s.d.) a) number of shoots and b) shoot weight of 1 cm, 5 cm, and 10 cm diameter black willow cuttings in control (C), periodically flooded (PF), and drought (DR) moisture treatments. Significant differences, indicated by different letters, are across moisture treatments for cutting diameter sizes.



to the other cutting diameter sizes even though root weight was the least for 1 cm (0.4 in) diameter cuttings (Figure 4). Establishing a root system is important in streambank restoration. Root production and proliferation can improve soil strength and thus, retard bank collapse (Shields et al., 1995). For example, production of larger, stronger roots in trees reduced the extent of streambank erosion on the Kansas River during a large flood (Geyer et al., 2000). In the present study, root response of 1 and 10 cm (0.4 and 4 in) cuttings to the periodic flooding treatment showed that these cutting diameter sizes could help provide bank support in low elevation zones in the field where they are likely to be subjected to periodic flooding.

Under control treatment, aboveground biomass accumulation of 5 and 10 cm cuttings was greater compared to 1 cm (0.4 in) cuttings (Figures 2 and 3). However, root numbers arid biomass of 1 cm (0.4 in) cuttings were comparable to that of 10 cm (4 in) cuttings (Figure 4), and height growth of the three cutting diameter sizes was similar (Figure 8). This finding is in agreement with the previous reported performance of black willow cuttings in the field. For example, height growth was enhanced in cuttings 7.8 cm (3 in) in diameter located along a streambank in mid-elevation plots (Schaff et al., 2003). Moist, well-drained soils typically provide an optimum environment for root growth for some species (Donovan et al., 1988) as well as enhance aboveground growth in black willow (Pezeshki et al., 1998a).

The predawn vi data showed that, while not significantly different, v_i of 5 and 10 cm (2 and 4 in) cuttings was more negative than 1 cm (0.4 in) cuttings in the control treatment. The nature of growth medium (sandy coarse sediments) characterized by fast drainage along with more leaf surface area in 10 cm (4 in) cuttings may have resulted in less soil water availability and excess water loss. Aeration of the soil and the high percentage of sand may have led to decreased water absorption and in turn increased internal moisture stress of the larger cuttings leading to mid-day depression of photosynthesis. Such internal water deficit, which can occur even in moist soils, can negatively affect plant processes such as photosynthesis and growth (Dickson and Broyer, 1972). The potential adverse effects on photosynthetic activity as a result of internal moisture stress may have led to the observed reduced height growth of 10 cm (4 in) cuttings in the control treatment (Figure 9). Further investigation into physiological responses of varying cutting diameters across a range of soil moisture conditions is needed to quantify these differences and understand the mechanisms responsible for the observed responses.

The biomass and predawn vi data indicated sensitivity of 5 and 10 cm (2 and 4 in) cuttings to the drought treatment. For instance, vi of 10 cm (4 in) cuttings was significantly more negative than 1 cm (0.4 in) cuttings indicating greater leaf and root water deficits of the larger cuttings (Figure 1). The development of greater internal water deficits was further confirmed by biomass data (Figures 2, 3, and 4).

Drought conditions have been shown to adversely affect growth and biomass of woody species (Dionigi et al., 1985; Pezeshki et al., 1998ab; Mahoney and Rood, 1992; Ogaya et al., 2002). For example, seedlings of *Salix spp.* had lower biomass in declining water table treatments compared to seedlings in saturated treatments (Horton and Clark, 2001). Reduced leaf biomass production is a common response to drought for black willow (Pezeshki et al., 1998a; Schaff et at, 2003). This response could lead to reductions in carbohydrates and sugars due to a smaller photosynthetic surface area. This may help explain the observed reduction in aboveground biomass accumulation of the larger diameter cuttings in the drought treatment (Figure 5).

Drought also negatively affected belowground biomass accumulation of willow cuttings. Numbers of roots for 5 cm (2 in) cuttings was severely affected by drought compared to 1 and 10 cm (0.4 and 4 in) cuttings, and only two 5 cm (2 in) cuttings produced more than 20 roots in this treatment. In contrast, the 1 cm (0.4 in) cuttings produced 63 or more roots, and the 10 cm (4 in) cuttings produced 29 or more roots per cutting. Reduced root initiation and elongation as a result of drought has been noted in black willow (Pezeshki et al., 1998a). The high root production and root/ shoot ratio of 1 cm (0.4 in) cuttings may allow this cutting diameter size to maintain contact with a declining water table in the field thus, partially avoiding drought. Such efficient establishment of roots can help increase survival of riparian plants as well as the potential for continuous contact with the declining water table occurring during drought events (Mahoney and Rood, 1998). Based on the response of the larger diameter cuttings to drought, the hypothesis that larger diameter cuttings would be most successful in all moisture treatments is rejected.

At least a moderate level of survival of willow cuttings is essential for the success of a restoration project. Shields et al. (1995) suggested a 50 percent survival rate of willow cuttings after two years was necessary for good cover of streanibanks, whereas Watson et al. (1995) suggested a minimum of 34 percent survival for bank stabilization. Whatever the optimal survival rate may be, survival has been reported to increase with cutting diameter (Hansen and Tolsted, 1981) while flooding and drought have been known to reduce survival in willows (Abt et al., 1996; Shields et al., 1998; Pezeshki et al., 1998a; Gage and Cooper, 2004). Although survival rates of the three cutting diameters did not differ significandy in control and drought treatments, survival of 5 and 10 cm (2 and 4 in) cuttings was lower compared to 1 cm (0.4 in) cuttings

Figure 7

Mean (± s.d.) a) number of roots, b) root weight, and c) root: shoot ratio for 1 cm, 5 cm, and 10 cm black willow cuttings in control (C), periodically flooded (PF), and drought (DR) moisture treatments. Significant differences, indicated by different letters, are within moisture treatments for cutting diameter sizes.

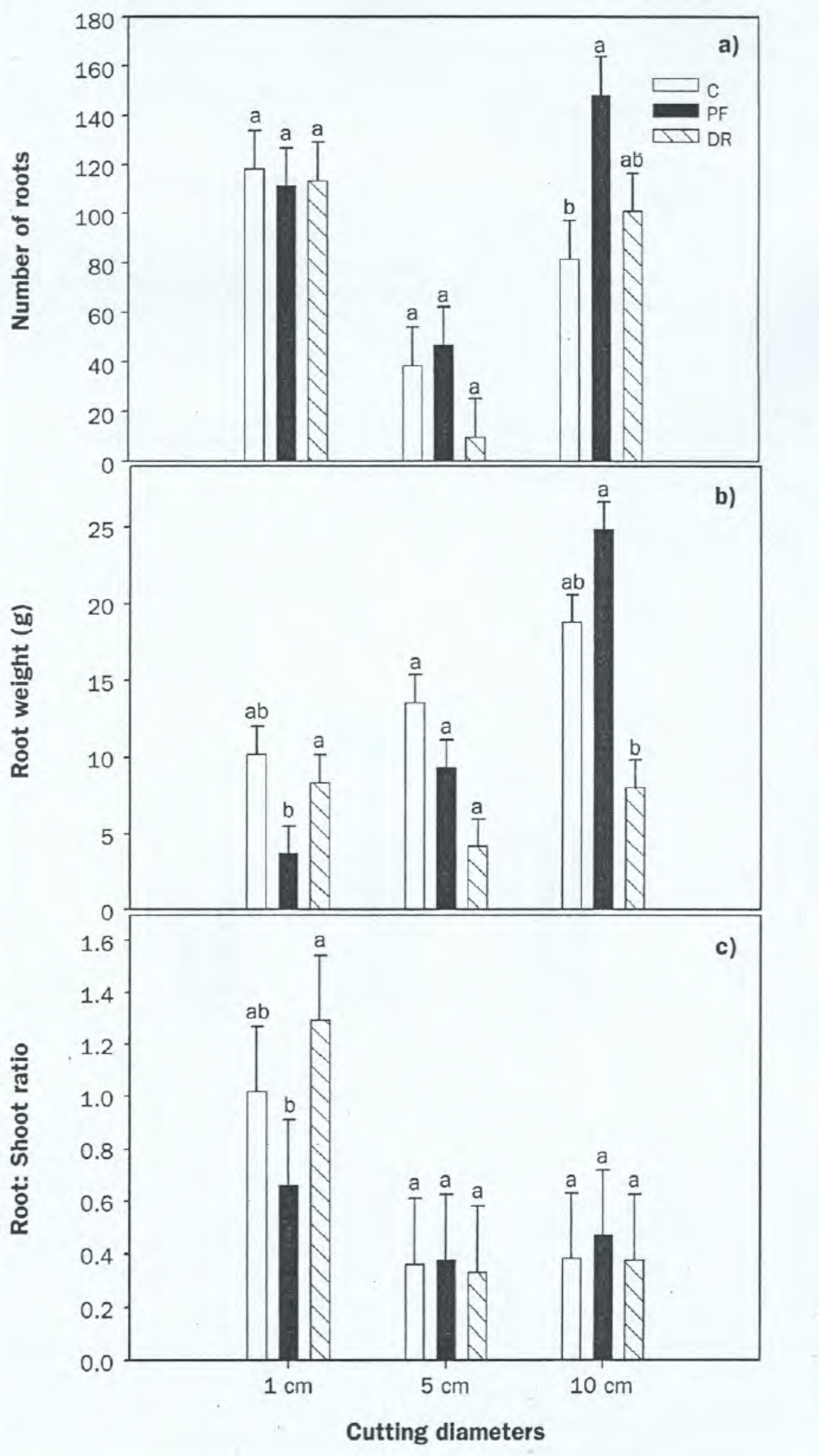


Table 2. ANOVA table (F value, df and p value) for the simple effects and interaction between cutting diameter and soil moisture for leaf chlorophyll content (LCC) and height growth of black willow cuttings.

		Height growth (cm)			**LCC** (ccl units)	
Source of variation	df	F	p	df	F	p
Moisture	2	19.89	<0.001	1	11.66	0.001
Diameter	2	9.04	<0.001	2	0.750	0.477
Moisture*Diameter	4	3.45	0.01	3	0.561	0.561

(Table 3). It is likely that the root initiation capability of 1 cm (0.4 in) diameter cuttings contributed to its high percentage of survival in all moisture treatments.

Effects of cutting diameter on growth and biomass components across moisture treatments. The biomass data also indicated the influence of cutting diameter on growth and biomass accumulation across moisture treatments. When subjected to increased soil moisture availability, members of the Salicaceae family have displayed enhanced shoot growth (Hansen and Phipps, 1983). Other studies have shown that black willow reduces biomass production in response to flooding (Donovan et al., 1988; Pezeshki et al., 1998a). However, in the present study, periodic flooding appeared to enhance height growth and aboveground biomass accumulation of 10 cm (4 in) cuttings compared to control and drought treatments (Figure 5, 6, 9). Also, drought reduced height growth of 10 cm (4 in) cuttings by 71 and 33 percent compared to periodic flooding and control treatments, respectively. These results are consistent with previous reports of reduced height growth in response to drought for black willow (Dionigi et al., 1985; Pezeshki et al., 1998a). Drought also reduced shoot growth in a *Populus* species (Mahoney and Rood, 1992). The effects of periodic flooding and drought on 10 cm (4 in) cuttings are also seen in the belowground production.

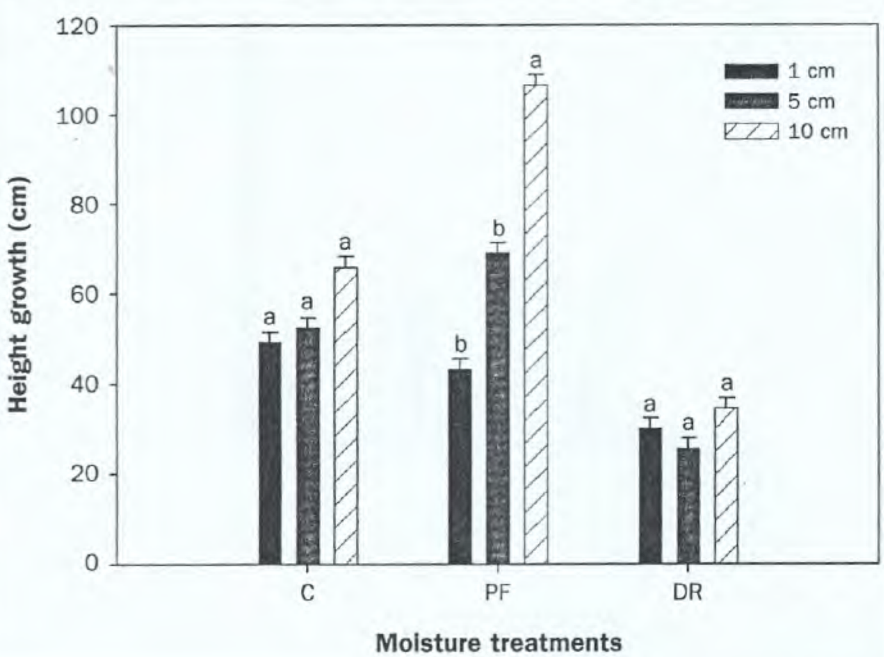


Figure 8
Mean (± s.d) height growth of 1 cm, 5 cm, and 10 cm black willow cuttings under control (C), periodically flooded (PF), and drought (DR) moisture treatments. Significant differences within moisture treatments for cutting diameter sizes are indicated by different letters.

Root numbers and biomass data reflected the influence of soil moisture on willow cuttings. Root production of 10 cm (4 in) cuttings was enhanced due to periodic flooding compared to cuttings in the control treatment, and soil drought significantly reduced root weight compared to periodic flooding (Figure 7a, b). Root biomass of black willow decreased in response to drought (Pezeshki et al., 1998a) as was noted in the present study. For instance, 10 cm (4 in) cuttings had a water potential decrease from an average of -1.3 bars (in control cuttings) to -7.3 bars (in drought cuttings). Plant water stress can limit growth and development by disrupting plant activities such as transpiration and photosynthesis (Mahoney and Rood, 1992; Pezeshki et al., 1998a). Flood tolerance is a trade off for drought intolerance in black willow. Because growth and biomass accumulation of 10 cm (4 in) cuttings was reduced by drought compared to periodic flooding, planting this cutting diameter in high-elevation zones in the field will likely decrease success of the project. The enhanced growth and biomass of 10 cm (4 in) cuttings in the periodic flooding treatment indicates that this diameter size is more suitable for planting in low- to mid-elevation areas in the field. In general, these findings are in agreement with the results of several other studies that evaluated the effects of cutting diameter size on growth and survival of other woody species (Table 4).

In contrast to the results for belowground biomass of 10 cm (4 in) cuttings, root biomass of 1 cm (0.4 in) cuttings was greater in control and drought treatments compared to the periodic flooding treatment (Figure 7b). Donovan et al. (1988) also noted a decrease in root biomass of black willow cuttings in flooded conditions. While soil reduction was not considered to be severe in this study, it is likely that soil redox potential conditions may have been stressful enough for this cutting diameter to adversely affect root biomass. The apparent increase in root biomass in the drought treatment can be explained by the predawn data. The 1 cm (0.4 in) cuttings, with an average water potential of -3.0 bars, did not appear to have experienced water stress unlike the larger cuttings. The lower water demand of 1 cm (0.4 in) cuttings due to a relatively low aboveground biomass accumulation and leaf area may have allowed water to remain available in the soil for a longer period of time thus, providing a less stressful environment for root development.

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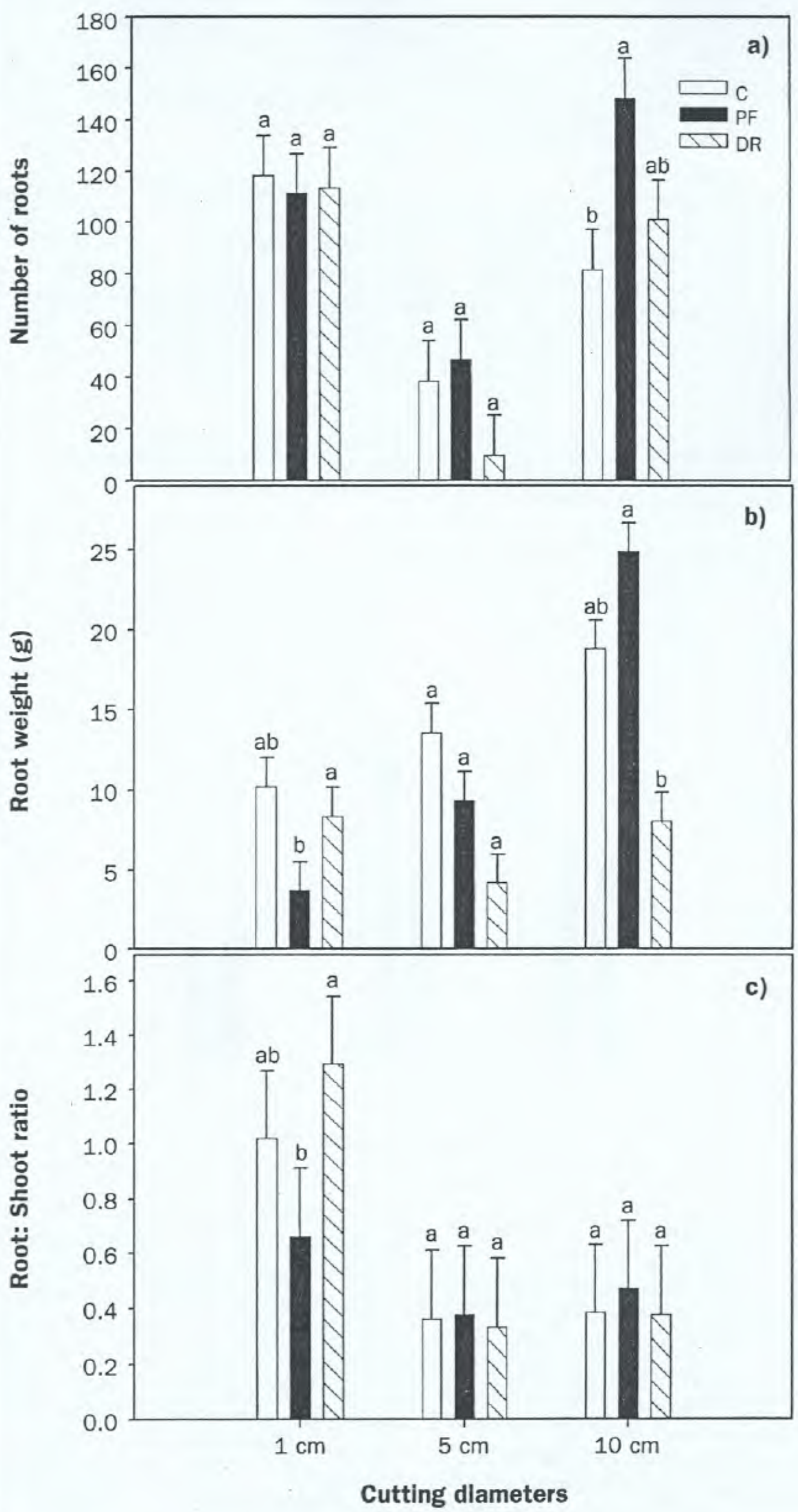

Figure 9
Mean (± s.d) height growth of 1 cm, 5 cm, and 10 cm black willow cuttings under control (C), periodically flooded (PF), and drought (DR) moisture treatments. Significant differences across moisture treatments for cutting diameter sizes are indicated by different letters.

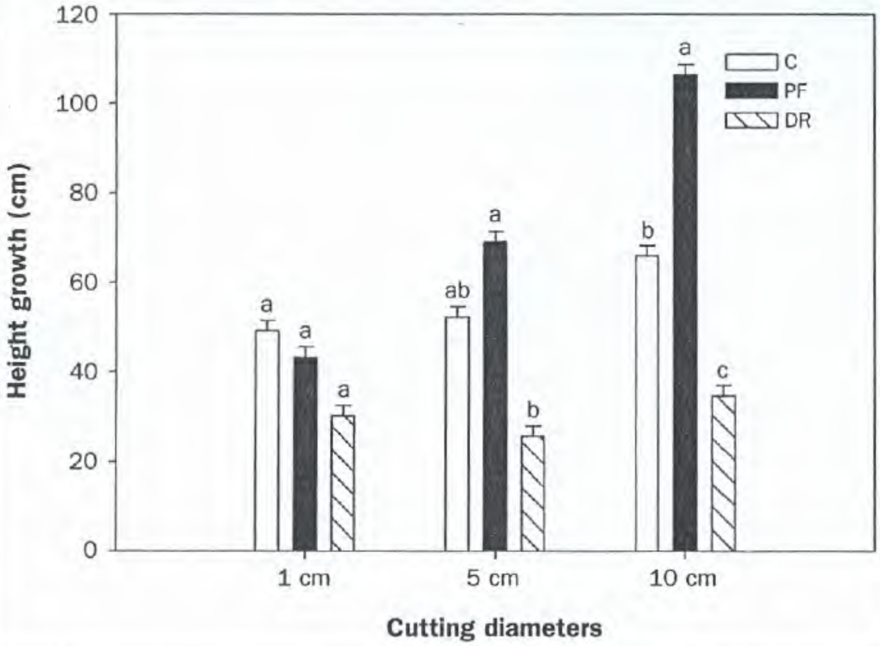

Table 3. Percent of surviving (p value) 1 cm, 5 cm, and 10 cm black willow cuttings within periodic flooding, control, and drought moisture treatments.

	Moisture Treatment			
	Periodic Flooding	Control	Drought	
Diameter	Percent survival			p
1 cm	100%	100%	100%	—
5 cm	73%	73%	64%	0.86
10 cm	100%	73%	73%	0.16
p	0.03	0.16	0.09	

Table 4. Field and greenhouse studies that evaluated the effects of cutting diameter size on growth and survival of various woody species.

Species	Cutting diameter (cm)	Location	Diameter effects	Reference
Populus alba Hybrid	0.5-2.0	Greenhouse/ Field	height growth, Survival	Hansen and Tolsted (1981)
Salix nigra	0.9-4.5	Field	Survival	Vora et al. (1988)
Salix spp., *Populus* spp., *Cornus* spp.	8-20	Field	Establishment success	Hoag (1995)
Salix nigra	2-16	Field	Survival	Watson et al. (1997)
Salix nigra	1, 5, 10	Greenhouse	Growth, Survival	present study

The good root growth of 1 cm (0.4 in) cuttings may allow these cuttings to remain in contact with the declining water table and inadvertently avoid water stress and possibly death in the field.

Flooding and streambank erosion are among the primary factors that govern black willow mortality in restoration projects. In these projects, willow cuttings are planted for the purpose of stabilizing eroding steambanks by providing physical stability required by pioneer species. The lowest elevation zone is subjected to the most stress due to stream velocities and frequent flooding. High water velocities tend to rip plants from the ground before they have a chance to establish a root system (Hoag and Landis, 2001). The technique of planting a combination of 1 and 10 cm (0.4 and 4 in) cuttings may help to improve success in these areas. The larger diameter cuttings could potentially reduce stream velocities allowing time for 1 cm (0.4 in) cuttings to become established. Both 1 and 10 cm (0.4 and 4 in) cuttings will decrease streambank erosion through rapid establishment of the root matrix and increase success of the planting with enhanced cutting survival.

In mid-elevation areas where soil moisture may be adequate, planting a combination of 1, 5 and 10 cm (0.4, 2, and 4 in) cuttings would be appropriate. Although survival rates of 5 and 10 cm (2 and 4 in) cuttings in the control treatment of this study were not 100 percent like 1 cm (0.4 in) cuttings, in the field, dead material can still serve a function for sediment trapping and establishment of other artificially planted or naturally occurring plants. The high root production of the . three diameter sizes may help stabilize the bank and slow down or even prevent lower elevation plots from being buried. In high elevation areas, where the probability of drought is likely, planting 1 cm (0.4 in) cuttings would likely improve survival rates and thus success of the project.

Summary and Conclusion

This study showed the importance of initial cutting diameter size, the relationship between diameter size and soil moisture, and subsequent effects on growth and survival of black willow cuttings. In periodically flooded conditions, 10 cm (4 in) diameter cuttings thrived, producing greater biomass and height growth than the other diameter sizes. Also in this treatment, 1 cm (0.4 in) diameter cuttings had a comparable root production and survival rate compared to that of the larger diameter cuttings. In the control treatment, belowground growth of 1 cm (0.4 in) diameter cuttings was similar to growth of 10 cm (4 in) diameter cuttings, and height growth of the three diameter sizes was not significantly different. In the drought treatment, the measured biomass parameters and height growth of 1 cm (0.4 in) diameter cuttings was comparable to that of the larger diameter cuttings. Cost data for planting willow cuttings are rare. Live stake (< 4 cm) plantings are usually denser arrays than larger caliber cuttings and require more hand labor. Data compiled by McCullah et al. (2005) indicate that unit costs for stake plantings are about 1.5 times as great as for posts or poles.

The effects of moisture treatments were clearly seen in the 10 cm (4 in) diameter cuttings. Periodic flooding enhanced biomass accumulation of 10 cm (4 in) diameter cuttings compared to control and drought treatments whereas drought reduced height growth compared to control and periodic flooding treatments. Drought had no signifi cant effects on height growth of 1 cm (0.4 in) cuttings compared to periodic flooding or control. Flooding, compared to control and drought treatments, reduced root biomass of 1 cm (0.4 in) cuttings.

Planting techniques for streambank restoration focusing on cutting diameter sizes needs further evaluation. Greenhouse studies like this one allow for complete control of treatments (moisture regime) giving the researcher the opportunity to understand the nature of the responses in a controlled environment; however, the field environment is characterized by the synergistic effects of environmental stresses on plantings. Additional research in field settings might prove helpful in transferring these results into practice. Planting these cutting diameter sizes in high, medium, and low elevation plots and assessing cutting size-soil moisture interactions under field conditions would be beneficial in determining which diameter size of willow is most appropriate for use in future planting projects. In addition, measuring plant physiological functions such as photosynthesis or transpiration, which was beyond the scope of this study, will help with the detailed evaluation of plant performance. These measurements may provide further insights into the reasons for the differences noted between cutting diameter sizes within and across the moisture treatments. Until such information is researched and become available, restoration efforts can be improved if cutting diameter and site soil moisture regimes are considered prior to planting.

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References Cited

Abt, S.R., C.C. Watson, J.P Burgi, D.L. Derrick, and J.H. Batka. 1996. Willow posts construction and evaluation on Harland Creek, Mississippi. Pp. 1114-1123. In: Proceedings of the Sixth Federal Interagency Sedimentation Conference. Sixth Federal Interagency Advisory Committee on Water Data, Washington, D.C.

Amlin N.A. and S.B. Rood. 2001. Inundation tolerances of riparian willows and cottonwoods. Journal of the American Water Resources Association 37:1710-1720.

Dickson R.E. and T.C. Broyer. 1972. Effects of aeration, water supply, and nitrogen source on growth and development of tupelo guru and bald cypress. Ecology 53:626-634.

Dionigi, C.P, I.A. Mendelssohn, and V.I. Sullivan. 1985. Effects of soil waterlogging on the energy status and distribution of Salix nigra and S. exigua (Salicaceae) in the Atchafalaya River. American Journal of Botany 72:109-119.

Donovan, L.A., K.W. McLeod, K.C. Sherrod, and N.J. Stumpff. 1988. Response of woody swamp seedlings to flooding and increased water temperatures. Part I. Growth, biomass, and survivorship. American Journal of Botany 75:1181-1190.

Gage E.A. and D.J. Cooper. 2004. Constraints on willow seedling survival in a Rocky Mountain montane floodplain. Wetlands 24:908-911.

Geyer,W.A., T. Neppl, L. Brooks, and J. Carlisle. 2000. Woody vegetation protects streambank stability during the 1993 flood of central Kansas. Journal of Soil and Water Conservation 55(4):483-486.

Hansen, E.A. and D.N.Tolsted. 1981. Effect of cutting diameter and stern or branch position on establishment of a difficult-to-root clone of a Populus alba hybrid. Canadian Journal of Forest Research 11:723-727.

Hansen, E.A. and H.M. Phipps. 1983. Effect of soil moisture tension and preplant treatments on early growth of hybrid Populus hardwood cuttings. Canadian Journal of Forest Research 13:458-464.

Hoag, J.C. 1993. How to plant willows and cottonwoods for riparian rehabilitation. Pp. 1-6. *In:* Technical Notes for the USDA Natural Resources Conservation Service J. Gibbs, F Reckendorf, D. Ogle, S. Lambert, J. Briggs, G. Young, D. Darris, J. Cornwell, E Fink, G. Kuhn, F. Bailey, L. Zollinger, arid L. St. John (eds.) Plant Materials Center, Boise, Idaho.

Hoag, J.C. 1995. Using dormant pole cuttings to revegetate riparian areas. Paper presented at The Fifth International Rangeland Congress, Salt Lake City, Utah. 2 pp.

Hoag, J.C. and T.D. Landis. 2001. Riparian zone restoration: Field requirements and nursery opportunities. Native Plants Journal 2:30-35.

Horton, J.L. and J.L. Clark. 2001. Water table decline alters growth and survival of Salix gooddingii and Tamarix chinensis seedlings. Forest Ecology and Management 140:239-247.

Islam, M.A. and S.E. MacDonald. 2004. Ecophysiological adaptation of black spruce (Picea mariana) and tamarack (Larix laricina) seedlings to flooding.Trees 18:35-42.

Johnson, F.L. 1984. Vegetational changes in a black willow forest over a 23-year period. Proceedings of Oklahoma Academy of Sciences 64:11-13.

Karrenberg, S., P.J. Edwards and J. Kollmann. 2002. The life history of Salicaceae living in the active zone of floodplains. Freshwater Biology 47:733-748.

Kozlowski, T.T. 1997. Responses of woody plants to flooding and salinity.Tree Physiology Monograph 1:1-17.

Mahoney, J.M. and S.B. Rood. 1992. Response of a hybrid poplar to water table decline in different substrates. Forest Ecology and Management 54:141-156.

Mahoney, J.M. and S.B. Rood. 1998. Streamflow requirements for cottonwood seedling recruitment and intergrative model. Wetlands 18:634-645.

McCullah, J., D.H. Gray, and F.D. Shields, Jr. 2005. Environmentally-sensitive channel- and bank-protection measures. NCHRP Report No. 544 Project No. 24-19, Transportation Research Board, Washington, D.C.

McLeod, K.W. and J.K. McPherson. 1973. Factors limiting the distribution of Salix nigra. Bulletin of the Torrey Botanical Club 100:102-110.

Mitsch, W.J. and J.G. Gosselink. 2000. Wetlands. 3rd edition. John Wiley and Sons, Inc, New York, New York.

Nainian, R.J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3(2):209-212.

Ogaya, R., J. Penuelas, J. Martinez-Vilalta, M. Mangiron. 2003. Effect of drought on diameter increment of Quercus ilex, Phillyrea latifolia, and Arbutus unedo in a holm oak forest of NE Spain. Forest Ecology and Management 180:175-184.

Pezeshki, S.R. and PH. Anderson. 1997. Responses of three bottomland species with different flood tolerance capabilities to various flooding regimes. Wetland and Ecology and Management 4:245-256.

Pezeshki, SR., P.H. Anderson, and ED. Shields, Jr. 1998a. Effects of soil moisture regimes on growth and survival of black willow (Salix nigra) posts (cuttings). Wetlands 18:460-470.

Pezeshki, S.R., ED. Shields, Jr., and PH. Anderson. 1998b. The relationships between soil conditions and growth of willow posts on streambank. Pp. 447-452. *in:* Proceedings of the International Water Resources Engineering Conference. Abt, S.R., J. Young-Pezeshk, and C.C. Watson (eds.) American Society of Civil Engineers, Reston,Virginia.

Pezeshki, S.R.2001.Wetland plant responses to soil flooding. Environmental and Experimental Botany 49:299-312.

Pezeshki, S.R., S.D. Schaff, and ED. Shields, Jr. 2002. Riverbank restoration in southern United States: The effects of soil texture and moisture regime on survival and growth of willow posts. Pp. 146-152. *It::* Proceedings of the conference on sustainabiliry of wetland and water resources. M.M. Holland, M.L. Warren, Jr. and J.A. Stanturf (eds). U.S. Department of Agriculture Forest Service, Southern Research Station, General Technical Report No. SRS-50. U.S. Forest Service, Washington, D.C.

Pezeshki, S.R. 2003. Improving success of willow cuttings planted in damaged riparian zones: Little Tcpashaw Creek study. Preliminary report (Project No. 58-6408-1-098.). U.S. Department of Agriculture Agricultural Research Service National Sedimentation Laboratory, Oxford, Mississippi.

Pezeshki, S.R. and F.D. Shields, Jr. 2004. Riparian ecosystem restoration using willow cuttings: Studies in southern U.S. Pp. 1-7. hi: Proceedings for American Water Resources Association 2004 Summer Specialty Conference on Riparian Ecosystems and Buffers: Multi-scale structure, function, and management. R. Lowrance (ed.) American Water Resources Association, Nliddleburg,Virginia.

Pezeliski, S.R., C.E. Brown, J.M. Elcan, and E.D. Shields, Jr. 2005. Responses of non-dormant black willow (Salix nigra) cuttings to pre-planting soaking and soil moisture. Restoration Ecology 13:1-7.

Schaff, S.D. and S.R. Pezeshki. 2000. Soils influence survival and growth of willow posts at streambank restoration project (Mississippi). Ecological Restoration 18:56-57.

Schaff, S.D., S.R. Pezeshki, and E.D. Shields, Jr. 2003. Effects of soil conditions on survival and growth of black willow cuttings. Environmental Management 31:748-763.

Shields, ED., Jr., A.J. Bowie, and C.M. Cooper. 1995. Control of streambank erosion due to bed degradation with vegetation and structure. Water Resources Bulletin 31:475-489.

Shields, ED. Jr., S.R. Pezeshki, and PH. Anderson. 1998. Probable causes for willow post mortality. Pp 157-162. In: Water Resources Engineering '98 Proceedings. American Society of Civil Engineers, Reston,Virginia.

U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS). 1996. Streambank and shoreline protection. Part 650. Chapter 16. Engineering field handbook. U.S. Department of Agriculture, Washington, D.C.

Van Splunder, I., H. Coops, and M. Schoor. 1994.Tackling the bank erosion problem: Reintroduction of willow on riverbanks. Water Science and Technology 29:379-381.

Vora, R.S., R.W. Schumacher, and C.L., Miller. 1988. Propagating black willow from cuttings in the Lower Rio Grande Valley,Texas. Tree Planter's Notes 39:30-32.

Watson, C.C., D. Gessler, and S.R. Abt. 1995. Inspection of selected bank stabilization sites. Internal report: U.S. Army Corp of Engineers,Vicksburg, Mississippi.

Watson, C.C., S.R. Abt, and D. Derrick. 1997. Willow posts bank stabilization. Journal of the American Water Resources Association 33:293-300.