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RESEARCH ARTICLE

Growth Response of Coyote Willow (*Salix exigua*) Cuttings in Relation to Alluvial Soil Texture and Water Availability

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Abstract

A common approach to re-establishing cottonwood–willow habitat along regulated rivers is through installing dormant, rootless cuttings, yet there is little published information exploring floodplain characteristics that optimize growth of southwestern riparian willows planted in this manner. The goal of this project was to evaluate relationships between growth attributes of *Salix exigua* and soil texture and soil water availability. Monitoring plots were established in five willow swales planted with dormant *S. exigua* cuttings along the banks of the Middle Rio Grande in central New Mexico. Data analysis revealed significantly higher aerial cover, height, and stem density for *S. exigua* plants installed in plots with intermediate levels (15–25%) of fine textured soils distributed through the soil profile. Similar relationships were found in relation to soil water availability. Regression analysis of percent fines and available water at different depth increments provided limited explanation of variability in willow growth attributes at different plots. Findings indicate that *S. exigua* plants established from cuttings can achieve heights and aerial cover values similar to naturally established willow bars if the floodplain soil profile contains intermediate levels of fine textured soils and the maximum depth to groundwater is within 1.5 m of the ground surface. Where sites are dominated by coarse sand, *S. exigua* growth may be improved if maximum depth to groundwater is within 1 m of the ground surface.

Key words: **live stakes, revegetation, riparian restoration, willow habitat.**

Introduction

The decline of naturally regenerating cottonwood (*Populus* spp.) and willow (*Salix* spp.) along regulated rivers in North America is well documented. Their decline is typically attributed to hydrologic and geomorphic alterations caused by flood control, groundwater depletion, and water diversion projects that limit seedling recruitment, growth and survival (Rood & Mahoney 1990; Howe & Knopf 1991; Stromberg 1993; Busch & Smith 1995; Johnson 1998). To improve our knowledge and management of cottonwood–willow habitats, researchers have documented relationships between cottonwood and willow establishment and survival associated with the shape of the river hydrograph (Scott et al. 1993; Mahoney & Rood 1998; Shafroth et al. 2010), fluctuating and declining groundwater tables (Stromberg et al. 1996; Shafroth et al. 2000; Amlin & Rood 2002; Rood et al. 2003), prolonged flood inundation (Amlin & Rood 2001; Kozlowski 2002; Glenz et al. 2006), and fluvial geomorphic processes (Hupp & Osterkamp 1996; Trush et al. 2000).

Information generated from these studies are invaluable to applied scientists, and case studies are emerging which apply and test these relationships towards restoring riparian and aquatic habitats along regulated rivers across the western United States (e.g. McBain & Trush 1997; Rood et al. 2003; Shafroth et al. 2010), Europe (e.g. Hughes & Rood 2003) and Australia (e.g. Arthington & Pusey 2003). Unfortunately, progress towards optimizing flow regimes below large flood control dams to facilitate ecological processes can be exceedingly difficult to achieve, particularly where rivers flow through relatively urbanized corridors.

In the face of such constraints, a common approach to re-establishing Salicaceous species along regulated rivers is through installing dormant, rootless cuttings. This planting technique, also referred to as "live staking" (Gray & Sotir 1996), has been used as a bioengineering technique for hundreds of years throughout Europe and China for stabilizing stream banks, hillslopes, and irrigation ditch banks (Evette et al. 2009; Ying et al. 2011). Along many regulated rivers throughout the world, revegetation using live stakes may be the only viable option for re-establishing native riparian

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vegetation where the interplay between surface water and groundwater required for large scale seedling establishment has been functionally altered.

Unfortunately scant amounts of peer-reviewed research are available that explore relationships between revegetation site conditions and growth responses of riparian cuttings. The few published studies identified (Pezeshki et al. 1998; Schaff et al. 2003; Francis et al. 2005; Pezeshki et al. 2007) documented significant relationships between riparian plant growth and survival associated with seasonal groundwater depths, soil moisture availability, and alluvium stratigraphy. These studies, however, primarily evaluated Black willow (*Salix nigra*) or other riparian species not used in revegetation projects in the southwestern United States or northern Mexico. While the Natural Resources Conservation Service's Los Lunas Plant Materials Center has developed numerous publications describing different planting techniques, including techniques for installing dormant cuttings of various southwestern riparian species (http://plant-materials.nrcs.usda.gov/nmpmc/publications.html#PU), none of these documents examine or specifically address relationships between riparian plant growth or survival and soil texture or soil moisture attributes (D. Dreesen, 2012, NRCS Plant Materials Center, Los Lunas, NM, personal communication). Given the ongoing attention to riparian revegetation throughout the southwestern United States and the lower Colorado river delta of northern Mexico (e.g. Briggs and Cornelius 1998; Carrillo-Guerrero 2002; Hinojosa-Huerta et al. 2005), expanding applied research on these relationships would be immensely helpful towards improving project predictability and meeting wildlife habitat restoration objectives.

This article explores relationships between growth attributes of Coyote willow (*Salix exigua*) cuttings and soil texture and moisture five years after planting along the Middle Rio Grande, New Mexico. *S. exigua* was selected due to its broad geographic distribution along riparian corridors in western North America and northern Mexico's Colorado River delta, and because it is commonly used for riparian revegetation project in these regions. We hypothesize that growth of *S. exigua* plants established from cuttings will be significantly related to both soil texture and available moisture. We further hypothesize that *S. exigua* growth will be significantly influenced by percent of fine textured soil immediately above the seasonal water table due to its ability to extend the height of the soil capillary fringe.

Methods

Study Area

The study was implemented within the Albuquerque city limits along the Middle Rio Grande (MRG) floodplain in central New Mexico. The MRG watershed drains approximately 64,150 km^2 including slopes of the Sangre de Cristo, Jemez, Sandia, Manzano, and Magdelena mountain ranges. The climate is semi-arid with 22 cm of average annual precipitation, much of which falls during mid-summer convective monsoon rainstorms. Snowmelt runoff between April and June contributes substantially to total annual discharge, although variability in annual flow is significant in response to climatic factors such as El Nino cycles and extended drought or wet periods (COE 2006). Mean air temperature is 3.7°C between December and February and 25°C between June and August. Summer daytime air temperatures typically exceed 32°C (WRCC Station 290234).

Historic and contemporary hydrology and fluvial geomorphology of the MRG are well documented (Bullard & Wells 1992; Lagasse 1994; MEI 2002; Richard & Julien 2003), and the river segment through Albuquerque can be summarily characterized as converted from a historically braided channel to a single channel due to bed load reductions from upstream dams. Flows below Cochiti Dam, which are currently capped at 198 cubic meters per second (cms), rarely exceed the bank-full discharge of 170 cms near Albuquerque (MEI 2006). Shallow groundwater wells near the study site indicate average water table depths range between 130 cm and 230 cm below the ground surface (http://www.bosqueschool.org/bemp.htm).

Study plots were established in five *Salix exigua* stands (swales) constructed in March/April 2005. Swale construction utilized bulldozers to scrape woody debris from the floodplain surface and to lower the floodplain elevation, where necessary, to reduce the distance between the bottom elevation of the swale and the groundwater table. Dimensions of constructed willow swales were variable, but ranged between 16 and 50-m wide and 90 and 145-m long (Table 1). The long edge of each swale was oriented parallel to the river channel. Distances from the active river channel edge varied between 8 and 95 m (Table 1).

The floodplain surface at four of the swales—Rio Bravo Southwest, South (RBSW-SS); Rio Bravo Southeast, North (RBSE-NS); Rio Bravo Southeast, South (RBSE-SS); and Interstate 40 (I-40)—was lowered an average of 30–45 cm so that estimated maximum depth to groundwater during river base-flow was no greater than approximately 1.5 m below ground level. The surface elevation of the fifth swale at Rio Bravo Southwest, North Trenches (RBSW-NT) was not lowered because the depth to groundwater was already within the desired depth range. None of the willow swale locations are inundated by Rio Grande surface water flooding, although groundwater may emerge at or near the surface of the swale bottoms when flows at the Central Bridge Gage (USGS Gage 08330000) exceed approximately 160 cms (the approximate 2-year flow return interval; MEI 2006).

Table 1. Dimensions of constructed willow swales.

Willow Swale	*Width (m)*	*Length (m)*	*Distance to Channel Edge (m)*
I-40	50	90	95
RBSE-NS	30	114	95
RBSE-SS	16	127	64
RBSW-NT	18	115	8
RBSW-SS	18	145	9

Multiple, parallel linear trenches were excavated the full length of each swale. Trench spacing averaged 2.4 m apart and all trenches were excavated deep enough to expose groundwater. Dormant *S. exigua* cuttings were placed vertically in the trenches at approximately 1-m spacing between individual cuttings, with butt-ends in groundwater. Each trench was backfilled following willow installation.

Vegetation and Ground Cover

Field plots were established within the five willow swale locations between 7 August and 30 September 2009. For comparative purposes, monitoring plots were also established in five naturally occurring willow bars during the same time period. Locations for naturally occurring *S. exigua* were selected using ESRI ARC-GIS 9.2 software and high resolution digital ortho-photographs from 2004 and 2006 to identify naturally occurring *S. exigua* stands of similar age as those within the willow swales. Four *S. exigua* bars (Bars 2, 3, 4, and 5) were located approximately 24 km upstream of the I-40 swale plot. The fifth willow bar (Bar 1) was located approximately 3 km downstream of the Rio Bravo swale plots. General plot locations are displayed in Figure 1.

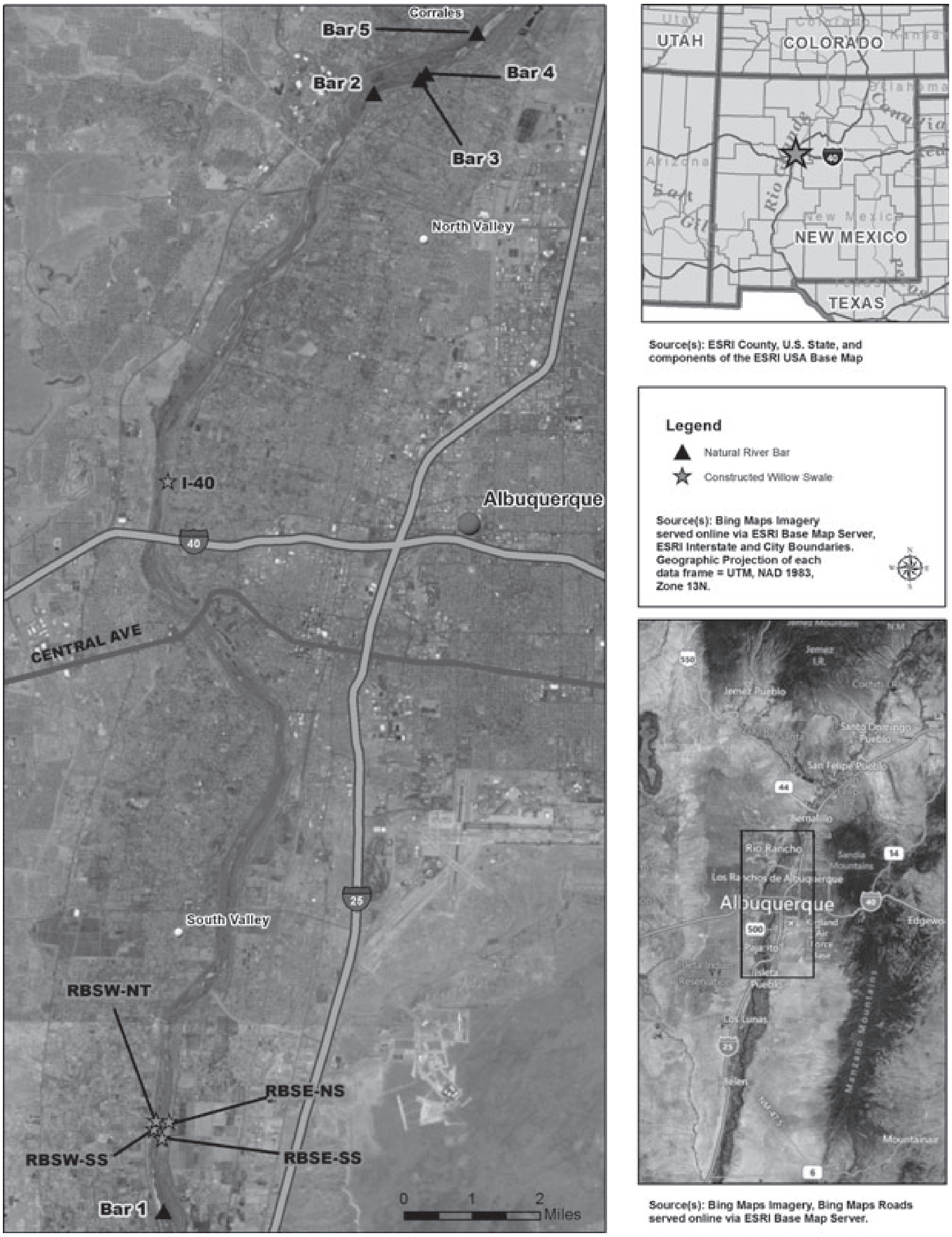

Figure 1. Project area map.

Each of the ten monitoring plots contained twenty randomly assigned 10-m line transects. All transects were oriented perpendicular to the river channel. Vegetation and ground cover data was collected at 2-m intervals along each transect (2, 4, 6, 8, and 10 m) using a 0.5×1.0-m quadrat frame. The starting position along each transect was reversed for adjacent transects (e.g. first transect starts on east end; second transect starts on west end, etc.). Vegetation attributes recorded in each quadrat included stem density, height (trees and shrubs only) and aerial cover (trees, shrubs, and herbaceous plant species). Tree and shrub stems within a quadrat were counted and recorded on data sheets as either live or dead. A stem was counted as a separate individual if there was no lateral branching within 1.25 cm above the ground surface.

A measuring rod was used to estimate heights of individual shrub and tree species with stems contained within the quadrat. For quadrats containing more than five individual trees or shrubs, the rod was placed in four corners, and the center of each quadrat and heights of the nearest individual shrub and tree were estimated to the nearest 0.3 m. If there were fewer than five individual trees and shrubs within or projected over a quadrat, heights of all individuals were recorded. If the heights of any individual trees or shrubs exceeded 3.5 m, the heights were estimated to the nearest 0.3 m.

Ocular estimates of aerial canopy cover were recorded for all plant species with aerial cover within, or projected over, the quadrat frame. Cover was estimated to the nearest 5%. For cover estimates less than 5%, the cover value was recorded as either 2.5% or "trace." Voucher specimens were collected and identified in the University of New Mexico herbarium. Ocular estimates of groundcover in each quadrat were also recorded to the nearest 5%, including cover of basal vegetation, plant litter, gravel, and bare ground.

Soil Moisture and Soil Texture

Soil samples were collected from eight random sampling locations within each willow swale. Samples were extracted at 0.15-m increments to a maximum depth of 1.8 m (i.e. 10–12 depth increments per sample location). Soil samples from each depth increment were placed in individual ziplock bags and labeled. Samples were shipped to Green Analytical Laboratory in Durango, Colorado, for analysis of soil texture (i.e. percent sand, silt, clay) and percent moisture (total and dry weight basis). The following tests were conducted on each sample:

(1) *Moisture Content*: Moisture content was determined gravimetrically following standard procedures described by Brady (1990).
(2) *Soil Particle Size Distribution (Texture)*: Soil texture was determined by the hydrometer method (6-hour hydrometer).
(3) *Available water capacity (WC)*: Available water capacity was estimated based upon standard guidelines (National Soil Survey Center 1998) that correlate soil particle size (texture) to available water (AW).
(4) *Bulk density*: Bulk density estimates were based upon the particle size distribution from laboratory test results. These estimates were necessary to convert the laboratory measured soil moisture by weight to the more meaningful plant-related expression of AW.
(5) *Soil moisture content expressed as percent of WC*: The percent of soil moisture expressed as percent of available moisture.

Data Analysis

Transect-level attributes were obtained (20 per plot) for all vegetation and ground cover variables by averaging across the five quadrat values measured for each transect. These attributes were used for all statistical methods, box plots, and summaries, with the exception of those involving soil moisture measurements.

Univariate ANOVA with multiple comparisons was used to characterize swale groupings and differences based on each of three vegetation variables: *Salix exigua* height, cover, and stem density. ANOVA was conducted on all swales and natural willow bars together to see if natural bars were statistically distinguishable from swales, and whether subgroups of similar swales could be distinguished when viewed by willow height, cover, or density. ANOVAs were followed by multiple comparisons involving all possible pairs of plots and adjusting the resulting p-values to meet an experiment-wide significance level of 0.90 using the Bonferroni method.

Soil moisture measurements taken on 0.15-m increment samples extracted from randomly placed bore-holes were used to calculate several depth-averaged soil variables for each bore-hole (e.g. surface to 0.76, 0.76 to 1.5 m, etc.), including AW, WC), and percent fines (PF). Since the randomized bore-hole locations did not uniformly represent individual vegetation transects, the bore-hole soil variables were used in two distinct ways.

First, the bore-hole variables were used as independent replicates of the plot-level soil moisture attribute (see box plots, plot-level averages, and plot-level soil categories). The appropriateness of characterizing swale plots by soil category was first tested using ANOVA and multiple contrasts, with the result that distinct groupings of swale plots existed and could be characterized with an ordered category (e.g. "low," "medium," or "high"). Swales were statistically indistinguishable for soil moisture within a soil moisture category; therefore, transect-level willow growth measurements could be grouped by soil attribute rather than by plot, allowing the relationship between soil moisture and willow growth to be tested using ANOVA.

A second use of the bore-hole variables was developed by creating "quadrat-level" soil moisture vegetation pairs which associated each bore-hole attribute with a particular quadrat-level vegetation value, a value established based on measurements at the vegetation quadrat(s) nearest to a particular bore-hole.

To investigate relative importance of different depth intervals, three averages for each soil moisture attribute were created: 0–0.76 m, 0.76–1.5 m, and 0–1.5 m. These depth-interval-specific soil moisture attributes were regressed against both *Salix exigua* height and cover and compared using the Pearson product moment correlation (r). Log and polynomial transformations were considered but abandoned because no enhanced linearity of the relationship or normality of error was noted.

Results

Vegetation

Salix exigua in constructed swales were tallest at RBSW-NT and RBSW-SS and lowest at I-40 and RBSE-NS (Fig. 2). A similar pattern was found for aerial cover (Fig. 3). Willows growing in RBSW-NT and RBSW-SS were similar in height and canopy cover to at least two of the natural willow bars (Figs. 2 & 3). *S. exigua* plants in the I-40 and RBSE-NS swales were significantly shorter and had lower canopy cover than willows recorded in all swale plots and natural willow bars.

S. exigua stem densities were similar between all swale plots except at the I-40 swale, where mean stem density ($8.52 \pm$ SE 0.97) was significantly ($p < 0.01$) lower than the other four swales. Mean stem density of *S. exigua* at all five swales combined ($17.76 \pm$ SE 2.66) were significantly ($p < 0.01$) higher than mean calculated for the five natural willow bars ($13.72 \pm$ SE 1.64). Summary statistics for willow stem density and other measured vegetation attributes are displayed in Table 2.

Soil Texture and Moisture Availability

Analysis of laboratory data found significant differences between swales for PF, WC, and AW. Soil samples from RBSW-NT and RBSW-SS had significantly ($p < 0.01$) higher PF (i.e. more silts and clays) and higher WC than the other three swales (Fig. 4a & 4b). However, PF and WC were highly correlated ($R^2 = 0.99$), so WC was dropped from further analysis without loss of information (i.e. data values for PF and WC were considered interchangeable). AW, which indicates soil moisture at the time of sampling, was greatest at RBSW-NT and lowest at I-40 and RBSE-NS (Fig. 4c). Analysis of variance on AW and PF discriminated swale plots into two PF categories ($a =$ low, $b =$ high) and three AW categories ($a =$ low, $b =$ medium, $c =$ high) (see Fig. 4b & 4c). ANOVA results (Table 3) found strongly significant relationships between PF and AW and *S. exigua* height, cover, and density ($p < 0.01$).

Further data exploration indicated a stronger consistency in pattern for *S. exigua* height and cover than for stem density, so regression analysis was performed for these two variables to evaluate correlations with soil attributes at various depth intervals. Regression analysis was performed by comparing quadrat-level values of *S. exigua* height and cover (independent variable) with depth-interval specific values for PF, AW, and soil field capacity (FC) (dependent variables). Soil attributes were averaged for 0.76-m increments (from ground surface to 0.76 and 0.76–1.5 m) and for the entire soil depth profile (from ground surface to 1.5 m). Results indicated variability in willow heights were best explained by AW in the upper (0–0.76 m) soil profile ($R = 0.77$) and by AW and PF through the entire (0 and 1.5 m) soil profile ($R = .74$ and $R = 0.76$, respectively). Variation in *S. exigua* aerial cover had a weaker, but still significant correlation and was best explained by AW averaged over the entire soil profile ($R = 0.65$) (Table 4).

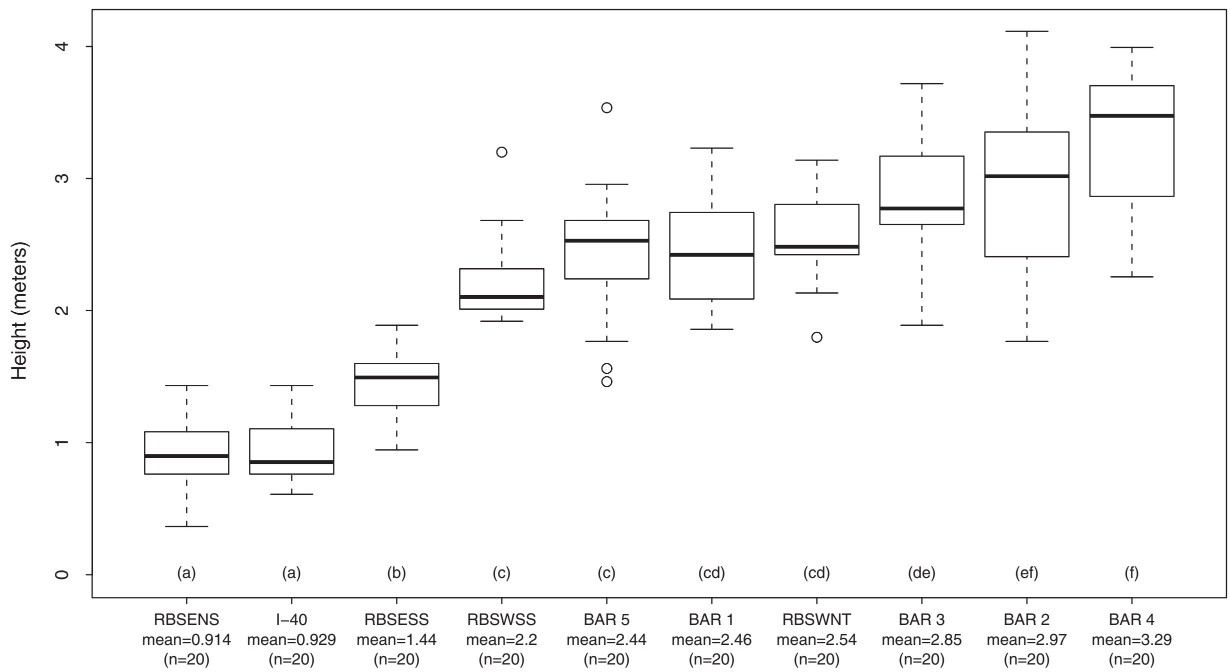

Figure 2. Boxplots showing height data distribution for *Salix exigua* at five willow swales and five natural willow bars. Lower case letters below boxes indicate statistical similarities or differences ($p < 0.01$) between sites. Open circles above and below box whiskers represent statistical outliers.

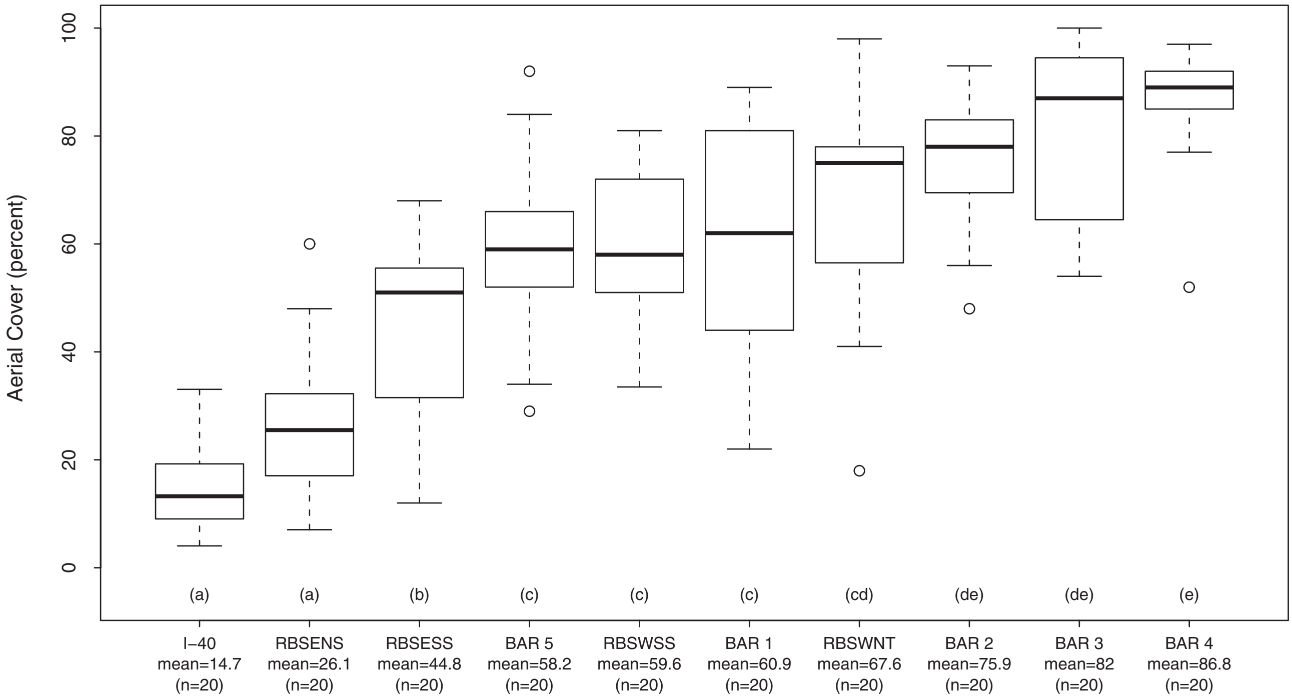

Figure 3. Boxplots showing aerial cover data distribution for *Salix exigua* at five willow swales and five natural willow bars. Lower case letters below boxes indicate statistical similarities or differences ($p < 0.01$) between sites. Open circles above and below box whiskers represent statistical outliers.

Discussion

Results from this study support the hypothesis that growth of *Salix exigua* plants established from cuttings was significantly related to both soil texture and available moisture. Plots with relatively higher percentages of silts and clays supported significantly taller willows with greater aerial cover and higher stem densities than those with predominately sandy textured soils. Similar findings have been reported for Black willow (*Salix nigra*) cuttings along the Mississippi River (Pezeshki et al. 2007).

At face value, the results seems fairly intuitive—alluvial soils exclusively comprised of sands or gravels drain more quickly, have weaker capillary forces, and provide plant roots an overall drier growing medium than alluvial sediments with higher silt and clay content. However, high concentrations of silts and clays can also be detrimental to willow growth. For example, Schaff et al. (2003) found that *S. nigra* posts planted along Twenty-Mile Creek (upper Mississippi River) in sandy sediments had significantly greater shoot biomass, leaf biomass, and total aboveground biomass than posts planted in soils with higher percentage of silts and clays. Black willow posts grown in fine textured alluvium also had lower survival rates by the end of the first growing season. Schaff et al. (2003) suggested that *S. nigra* root elongation was probably restricted in the finer textured sediments, facilitating significant reductions in aboveground biomass and lower survival. However, in their study mean silt and clay content from plots with “fine” textured alluvium ranged between 35 and 48 vs. 21% in “sandy” plots. In the present study, plots with the highest percentage of fines (RBSW-NT: 25.9% and RBSW-SS: 19.2%; see Fig. 4b) were comparable to the sandy sites reported by Schaff et al. (2003). It seems, therefore, that the relative percentage of fines in the alluvial stratigraphy is important. Too many fines can result in limited aeration and restricted root growth and too few fines can translate to low water holding capacity and a propensity for periodic drought stress. Results from the present study and those reported by Pezeshki et al. (2007) and Schaff et al. (2003) indicate that intermediate levels of fines (e.g. mean of 15–25%) within the alluvial profile may benefit growth of *Salix* spp. by balancing the benefits of adequate soil aeration and water holding capacity.

Regression analysis only partially explained the variability in willow growth associated with depth specific soil attributes. Slightly higher correlations were found between willow height and PF in the upper soil horizons compared with the lower profile (Table 4). Although other unidentified factors were also contributing to these growth differences, the regression results were not expected. In fact, this study originally hypothesized that *S. exigua* growth would be most strongly affected by the PF in the zone immediately above the seasonal water table, as this would extend the height of the capillary fringe above the water table. However, the differences between correlations in the upper and lower profiles was too slight to put much emphasis on either, but this does not negate the strong statistical relationship between willow growth and PF and AW across the entire profile. We conclude that the *S. exigua* plants in RBSW-NT and RBSW-SS plots probably had the advantage over the sandier swales because the distribution of moderate

Table 2. Means and standard errors for vegetation attributes and ground cover at swale and bar plots.

Type	*Plot*	*Height (m)*			*Aerial Cover (%)*			*Stem Density (m²)*		
		Mean	*SE*	*n*	*Mean*	*SE*	*n*	*Mean*	*SE*	*n*
Salix exigua										
BAR	BAR 1	2.46	0.09	20	60.9	4.63	20	10.60	0.96	20
BAR	BAR 2	2.97	0.14	20	75.9	2.68	20	16.20	1.02	20
BAR	BAR 3	2.85	0.11	20	82	3.71	20	12.90	1.12	20
BAR	BAR 4	3.29	0.12	20	86.8	2.20	20	18.70	1.97	20
BAR	BAR 5	2.44	0.11	20	58.1	3.51	20	10.20	0.94	20
All bars		**2.80**	**0.16**	**5**	**72.74**	**5.69**	**5**	**13.72**	**1.64**	**5**
SWALE	I-40	0.93	0.05	20	14.7	1.72	20	8.52	0.97	20
SWALE	RBSENS	0.91	0.07	20	26.1	3.06	20	24.30	2.57	20
SWALE	RBSESS	1.44	0.05	20	44.8	3.42	20	19.10	1.76	20
SWALE	RBSWNT	2.54	0.07	20	67.5	4.29	20	16.20	1.22	20
SWALE	RBSWSS	2.20	0.07	20	59.6	3.20	20	20.70	1.61	20
All swales		**1.60**	**0.33**	**5**	**42.54**	**9.91**	**5**	**17.76**	**2.66**	**5**

Type	*Plot*	*Cover (%)*			*Spp. Richness (Number of Species)*		
		Mean	*SE*	*n*	*Mean*	*SE*	*n*
Herbaceous plants							
BAR	BAR 1	86.40	5.46	20	11.10	0.42	20
BAR	BAR 2	23.30	4.99	20	4.35	0.54	20
BAR	BAR 3	16.50	3.33	20	6.35	0.69	20
BAR	BAR 4	63.60	5.75	20	8.60	0.60	20
BAR	BAR 5	32.50	3.18	20	4.95	0.42	20
All bars		**44.46**	**13.22**	**5**	**7.07**	**1.24**	**5**
SWALE	I-40	9.95	1.83	20	3.00	0.42	20
SWALE	RBSENS	6.35	1.45	20	3.25	0.30	20
SWALE	RBSESS	9.30	2.46	20	3.65	0.30	20
SWALE	RBSWNT	1.79	0.49	20	1.40	0.20	20
SWALE	RBSWSS	10.30	1.33	20	6.60	0.37	20
All swales		**7.54**	**1.60**	**5**	**3.58**	**0.85**	**5**

Type	*Plot*	*Litter (%)*			*Basal Vegetation (%)*			*Bare Ground (%)*		
		Mean	*SE*	*n*	*Mean*	*SE*	*n*	*Mean*	*SE*	*n*
Ground cover										
BAR	BAR 1	66.80	3.35	20	16.10	1.38	20	17.10	3.24	20
BAR	BAR 2	69.00	3.49	20	4.93	0.50	20	26.10	3.38	20
BAR	BAR 3	72.20	4.11	20	6.33	0.71	20	21.50	4.29	20
BAR	BAR 4	71.80	3.31	20	8.30	0.79	20	19.90	3.35	20
BAR	BAR 5	74.30	3.42	20	4.97	0.40	20	20.80	3.35	20
All bars		**70.82**	**1.31**	**5**	**8.13**	**2.09**	**5**	**21.08**	**1.46**	**5**
SWALE	I-40	39.30	3.31	20	1.79	0.41	20	58.60	3.47	20
SWALE	RBSENS	43.40	4.41	20	2.65	0.21	20	53.40	4.34	20
SWALE	RBSESS	77.00	3.06	20	2.88	0.37	20	20.20	3.26	20
SWALE	RBSWNT	88.50	1.55	20	4.65	0.30	20	6.88	1.65	20
SWALE	RBSWSS	79.30	1.21	20	3.68	0.37	20	17.00	1.22	20
All swales		**65.50**	**10.07**	**5**	**3.13**	**0.48**	**5**	**31.22**	**10.39**	**5**

concentrations of fine textured alluvium through the upper and middle soil profile allowed plant roots to obtain adequate moisture from a greater volume of soil for longer periods through the growing season (i.e. from both rainfall and rising groundwater levels associated with changes in river stage).

For the three swale plots with relatively low PF values, the principal driver of willow height and cover differences appears to be related to the depth of AW associated with the seasonal groundwater table. For example, mean willow height and cover values from RBSE-SS were intermediate between the more

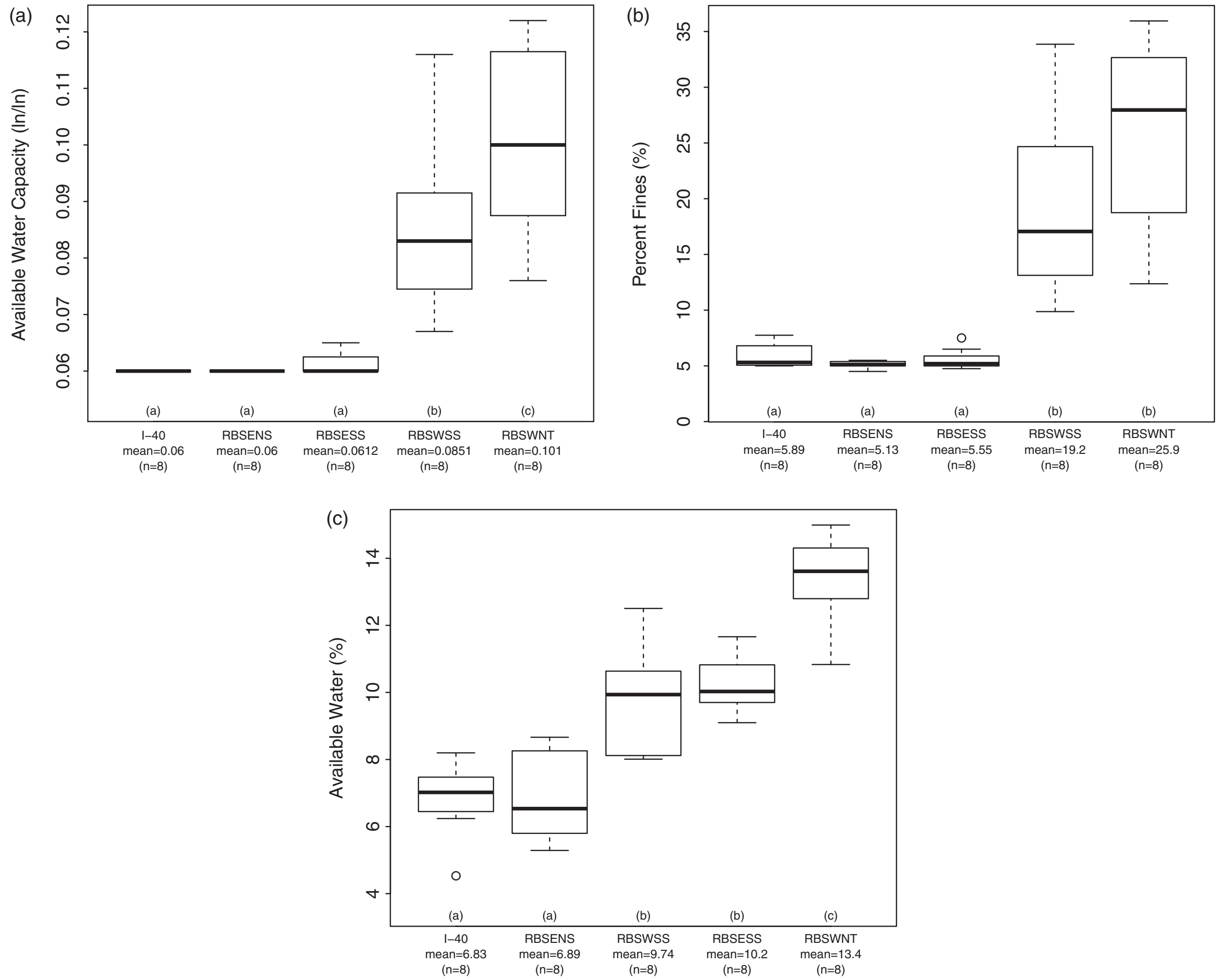

Figure 4. Boxplots showing data distribution between swales for (a) soil water capacity (WC), (b) percent fine (PF) textured soil, and (c) available water (AW). Lower case letters below boxes indicate similar statistical groupings ($p < 0.001$). Open circles above and below box whiskers represent statistical outliers.

Table 3. Analysis of variance table for the effects of percent fines (or available water capacity) and available water on *Salix exigua* growth attributes.

	Percent Fines				*Available Water*			
	df	*MS*	*F*	*p*	*df*	*MS*	*F*	*p*
Salix cover height	2	148.058	1179.2	<0.01	3	98.366	716.17	<0.01
Salix cover percent	2	105,227	345.27	<0.01	3	72,274	298.32	<0.01
Salix stem density	2	15806.6	184.61	<0.01	3	629	127.02	<0.01

Table 4. Correlation (*R*) of S*alix exigua* height and cover with depth average soil variables.

	Response Variable – Correlation (R)	
	Salix exigua Height	*Salix exigua Cover*
Surface to 1.5 m		
PF	0.76	0.56
AW	0.74	0.65
Surface to 0.76 m		
PF	0.72	0.54
AW	0.77	0.62
0.76–1.5 m		
PF	0.69	0.48
AW	0.50	0.52

robust plots at RBSW-NT and RBSW-SS and the relatively weak growth in the RBSE-NS and I-40 plots. Note in Figure 5 that plot RBSE-SS has a similarly low percentage of fines throughout the soil profile compared to RBSE-NS and I-40 plots; yet, the soil moisture content at this site is considerably higher in the depths range between 0.9 m (91 cm) and 1.5 m (Fig. 6). This indicates that the seasonal groundwater levels are relatively higher in the RBSE-SS plot, and even though the percentage of fines were very low, this elevated water table enabled the intermediate *S. exigua* growth response recorded in this swale.

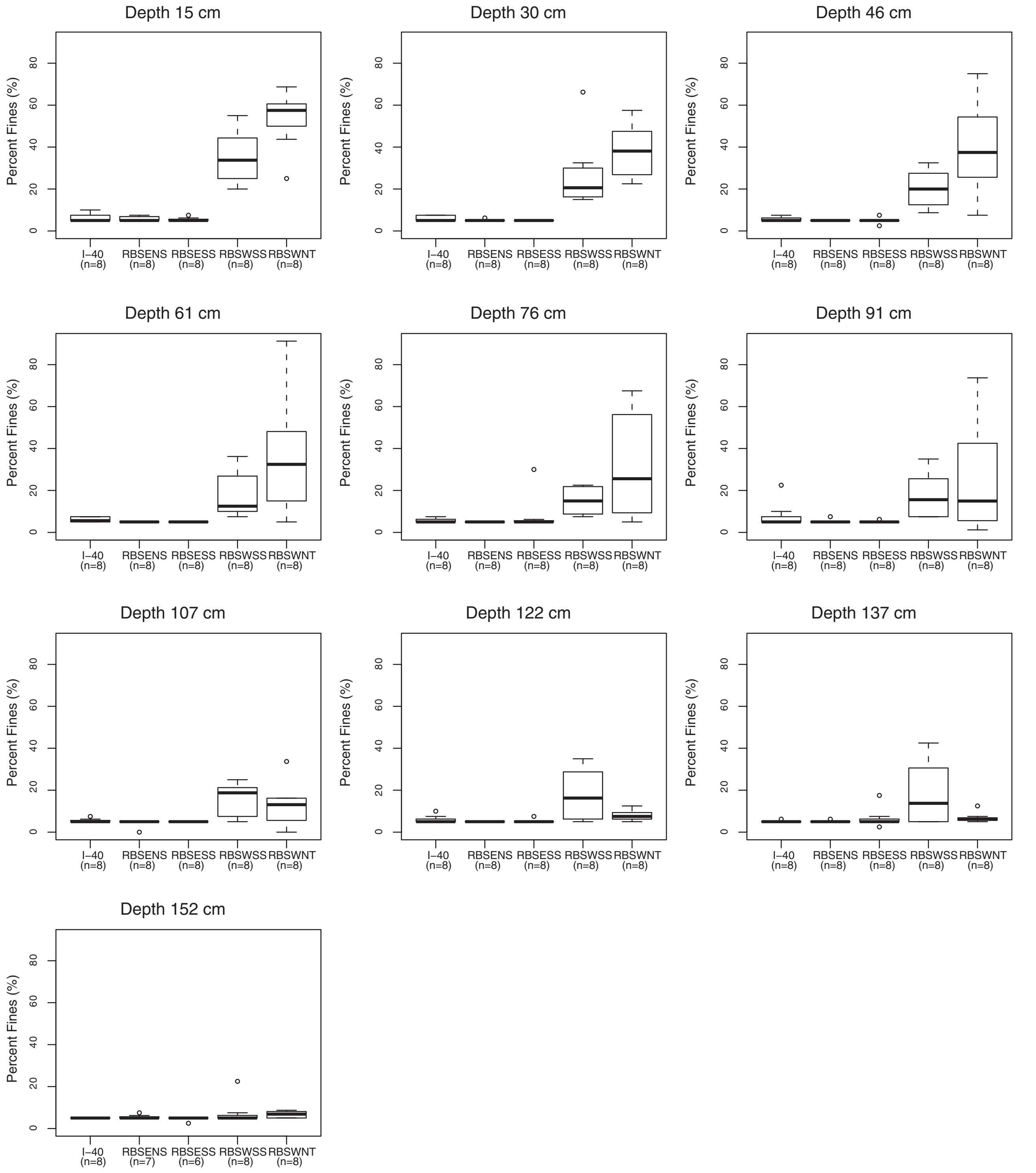

Figure 5. Box plots showing percent fine textured soils within five willow swales at various depth increments.

Perhaps the greatest limitations to relating soil water availability to willow growth in this current study are the lack of precise seasonal groundwater data and repeated soil moisture measurements. While piezometers were installed immediately adjacent to each swale, none of them were placed directly in the swales. As each swale was excavated to slightly different depths, the existing piezometer data do not provide a clear picture of the precise depth to groundwater within each swale. Furthermore, the moisture content measured in this study was done at a single time of the year, at one sampling event per

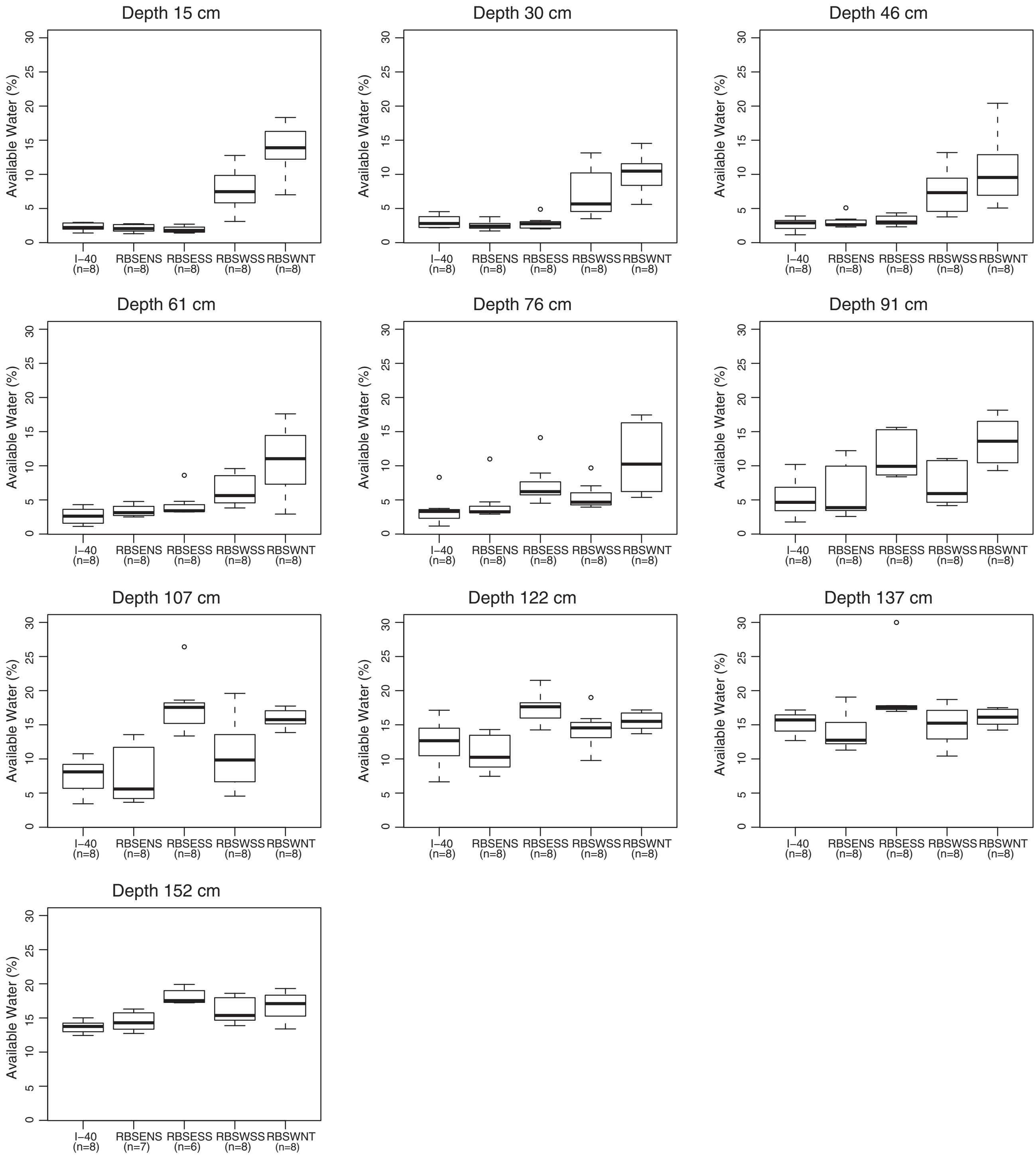

Figure 6. Box plots showing percent available water (field capacity basis) within five willow swales at various depth increments.

plot from September 25–30. Moisture conditions in these temporal samples reflect those that existed at the time of sampling, and not necessarily those that are present during the bulk of the growing season.

Nonetheless, comparing the piezometer data to local precipitation and river gage records indicates relatively stable surface water and groundwater levels through the summer base-flow period (15 July–30 September, 2009). Flow records from the nearest river gaging station (Rio Grande at Albuquerque, USGS Gage 0833000) shows that river flows during this period track closely with the median discharge levels over the preceding 30 years. Thus even though the available soil water data in this study were collected from one point in time, we suggest those data (Fig. 6) may reasonably depict typical mid to late summer soil moisture conditions. We also suggest those data may reasonably approximate relative differences in soil moisture availability between swales that could be extrapolated to other times of the mid to late summer growing season.

This study provides a starting point for understanding the relationship between soil texture, water availability, and growth of *S. exigua* plants established from rootless cuttings. Since *S. exigua* is widely distributed along rivers in the western United States and along the Colorado River and delta areas of northern Mexico, these results may be applicable to a much broader geographical area than the Rio Grande in central New Mexico.

Implications for Practice

- Land managers planning riparian revegetation projects using rootless willow cuttings should closely evaluate soil attributes and seasonal groundwater depths before initiating site construction or planting.
- Growth of *Salix exigua* cuttings in sites with coarse alluvium may be improved by ensuring groundwater depths at restoration sites do not exceed approximately one meter.
- Any opportunities to facilitate deposition of fine texture alluvium onto constructed willow swales (e.g. via a backwater or flow-through channel) may improve *S. exigua* growth responses by increasing soil water availability.
- Further research on this topic would benefit from piezometers placed directly in willow swales and from monitoring seasonal soil moisture availability in depth increments between the ground surface and late summer water table.

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