The Importance of Soil Characteristics in Determining Survival of First-Year Cottonwood Seedlings in Altered Riparian Habitats

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Abstract

Most major rivers in the southwestern United States have been hydrologically altered to meet human needs. Altered hydrological regimes have been associated with declines in native riparian forests. Today, many riparian areas have little or no regeneration of native riparian species and are now dominated by exotic Saltcedar (*Tamarix chinensis* Lour.). Success of riparian restoration efforts at least partially depends on the number of seedlings surviving the first growing season. Seedling survival is influenced by many abiotic and biotic factors including competition from other plants and available soil moisture, which is partially dependent on soil texture. In this study, we evaluated the relative importance of four soil categories (sandy loam, loam, silt, and clay), rate of soil moisture decline, salinity, beginning- and end-season Saltcedar density, initial Cottonwood (*Populus deltoides* Marshall subsp. *wislizenii* (Wats.) Eckenw.) seedling density, percent vegetation cover by potential dominant competitors Pigweed (*Amaranthus* L.) and Barnyard grass (*Echinochloa crusgalli* L., Beauv.), and average total vegetation height to Cottonwood seedling survival. Factors influencing seedling survival differed among the four soil types. Rate of moisture decline was important in sandy soils, whereas vegetation height influenced seedling survival in loamy soils. Overall, models of seedling survival in all the four soil types indicated rate of moisture decline as the single most important variable influencing Cottonwood survival. High initial densities of Saltcedar were correlated to higher survival in Cottonwood seedlings. Therefore, it is important to identify soil texture and understand soil moisture decline rates when proposing riparian Cottonwood restoration.

Key words: Cottonwood seedling, Middle Rio Grande Valley, *Populus deltoides*, riparian restoration, soil moisture, soil texture.

Introduction

The maintenance of native species within riparian areas is often closely tied to natural disturbances. Periodic flood disturbances are critical in maintaining the population of four dominant tree species in a lowland floodplain podocarp forest in New Zealand (Duncan 1993). Periodic flooding as a natural disturbance has been used to regulate growth and survival of riparian vegetation in Lake Nakuru, Kenya, Africa (Mathookoand & Kariuki 2001). In a study of riparian vegetation along a regulated floodplain of the Murray River in Australia, Roberts and Ludwig (1991) reported the effect of disturbance (wave action and water current) in determining the structural diversity of a riparia.

Declines in Cottonwood (*Populus* spp.) forests have been observed throughout the Northern Hemisphere where land and water management activities have reduced surface flows or depleted alluvial groundwater (Groeneveld & Griepentrog 1985; Rood & Heinze-Milne 1989; Rood et al. 1995; Stromberg et al. 1996; Sprenger et al. 2002). In southwestern United States, successful establishment of native riparian vegetation occurred historically along channel banks that were subjected to overbank flooding. Native species such as Cottonwood and Willow (*Salix* spp.) primarily recruit along riverbanks that are moist, bare, and protected from subsequent disturbance (Sigafoos 1964; Everitt 1968; Nobel 1979; Bradley & Smith 1986; Stromberg et al. 1991; Johnson 1994). Therefore, growth and regeneration of Cottonwood forests are closely associated with peak flows and related channel processes such as meandering (Busch & Scott 1995). In areas where such hydrological processes have been disrupted, there has been considerable growth of exotic invasive Saltcedar (*Tamarix chinensis* Lour., synonymous to *T. ramosissima* Ledeb.; Allred 2002), making restoration efforts more difficult. Moreover, restoration of Cottonwood forests is mediated by complex interactions

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doi: 10.1111/j.1526-100X.2007.00328.x

among hydrology, geomorphology, light, and temperature. All these factors further influence the structure, dynamics, and composition of riparian zone communities (Brinson 1990; Malanson 1993).

Restoration of degraded areas with native plant species is contingent upon successful establishment and survival of seedlings (Taylor et al. 1999). Factors that influence Cottonwood seedling establishment and subsequent survival during the first growing season include soil moisture, salinity, texture, light, and relative elevation (Anderson 1989; Mahoney & Rood 1992; Shafroth et al. 1995; Cooper et al. 1999; Taylor et al. 1999; Sher et al. 2000; Sprenger et al. 2002). Stromberg (1997) also found that herbaceous vegetation influenced establishment of woody pioneering species in riparian areas. Moreover, height of herbaceous vegetation that co-recruits with native Cottonwood is critical in determining seedling survival because herbaceous plants grow faster and shade Cottonwood seedlings, resulting in their mortality (Johnson et al. 1976). The primary set of abiotic and biotic factors that determine survival of first-year Cottonwood seedlings is discussed as follows.

Several studies have reported on the role of soil moisture in determining Cottonwood seedling survival during the initial establishment years (Mahoney & Rood 1991; Segelquist et al. 1993; Shafroth et al. 1998, 2002; Scott et al. 1999; Somogyi et al. 1999; Taylor et al. 1999; Amlin & Rood 2002; Sprenger et al. 2002). Other studies (Mahoney & Rood 1991, 1992; Segelquist et al. 1993; Horton & Clark 2001) have emphasized the dependence of Cottonwood seedlings on the groundwater table. Adair and Binkley (2002) reported that growth of first-year Cottonwood seedlings is co-limited by nitrogen and water. However, during the first year of growth, Cottonwood seedlings may not be able to grow roots long enough to reach the groundwater table (Bhattacharjee et al. 2006); their survival almost depends entirely on the availability of moisture in the top 15–30 cm of the soil. The importance of soil moisture in this unsaturated zone to seedlings during the first season of growth has not been well documented. The amount of moisture in soil partially depends on its constitution (parts sand, silt, and clay). Different proportions of the above constituents in soil provide different water-retaining properties (e.g., Mahoney & Rood 1992). Soil texture influences the hydraulic conductivity of soils, which in turn influences germination, growth, and survival of Cottonwood (Mahoney & Rood 1991). Sprenger (1999) observed that soil texture affected germination of Cottonwood and was low especially in areas where soil consisted of more than 65% clay.

In most regulated river systems, lack of annual flooding events and infrequent surface water infiltration into the soil can result in high soil salinity values that are stressful to some native trees and shrubs in the southwestern United States (Busch & Scott 1995). Cottonwood seedling survival is negatively affected by increasing soil salinity (Jackson et al. 1990; Siegel & Brock 1990; Shafroth et al. 1995; Anderson et al. 2004).

Conditions favorable for germination and recruitment of native Cottonwood are also favorable for germination of several other species. Herbaceous species such as Pigweed (*Amaranthus* L.), Barnyard grass (*Echinochloa crusgalli* L., Beauv.), Salt heliotrope (*Heliotropium* L.), and Lambsquarter (*Chenopodium* L.) and woody species such as Saltcedar commonly occur with Cottonwood especially in restoration sites (Sprenger 1999; Bhattacharjee 2005). The competitive effect of these and other species on the recruitment and survival of Cottonwood has not been well documented. However, Stromberg (1997) reported the influence of Sweet clover (*Melilotus* sp.) on growth rates and abundance of some native riparian taxa. Friedman et al. (1995) and Katz et al. (2001) also demonstrated that herbaceous competitors could prevent establishment of Cottonwood seedlings even in the presence of abundant moisture.

Given these many interacting factors, Cottonwood seedling survival in the field cannot be completely understood by considering a single factor at a time. Our objective therefore was to identify the relative importance (RI) of several factors simultaneously in determining survival of Cottonwood seedlings in the Middle Rio Grande Valley (MRGV), New Mexico. We evaluated the effect of soil moisture decline, soil salinity, percent vegetation cover by the two most dominant herbaceous species (Pigweed and Barnyard grass), height of vegetation, Saltcedar densities at the beginning and end of the growing season, and initial Cottonwood density on the survival of Cottonwood seedlings during the first growing season. We evaluated seedling densities in impoundments that were cleared of Saltcedar and subjected to water drawdown treatments.

Methods

Study Site

The study was conducted at the Bosque del Apache National Wildlife Refuge (BDANWR) (33°48″N, 106°53″W), a part of the MRGV in central New Mexico, U.S.A. The MRGV extends from Cochiti Dam, New Mexico, downstream to San Marcial, New Mexico, about 260 km of river (Crawford et al. 1993). Historically, river flows were characterized by peak flows occurring in late May and June following snowmelt in upstream mountainous regions (Crawford et al. 1993). The Rio Grande Valley is 5.2 km wide at the study site. The active floodplain width is restricted to 1 km by a spoil levee built in the late 1950s on the west side of the river in conjunction with the construction of a low-flow conveyance channel.

Average annual precipitation at the refuge is 21.9 cm, with nearly 50% of the annual precipitation occurring during July, August, and September (Western Region Climate Center, from 1914 to 2003). Average daily maximum temperature from June through September is 23.6°C, and average daily low temperature during this period is 13.3°C (Western Region Climate Center, from 1971 to 2003).

The study was conducted in 12 impoundments along the Rio Grande, as described by Sprenger et al. (2002). Impoundments are within the historic Rio Grande floodplain west of the current channel. Each impoundment is approximately 4 ha and is rectangular in shape (except impound number 12, which is triangular). There are two water control structures (sluice gates) within each impoundment. Using these gates, water can be drawn either into or out of the impoundment at desired rate. The study area has been hydrologically isolated from the present river floodplain for more than 55 years due to the presence of the levee and low-flow conveyance channel between the study site and the river (Molles et al. 1998). Based on the historical hydrograph of the Rio Grande and results of previous research (Sprenger et al. 2002), we used two water drawdown treatments, 2 and 5 cm/day, in the study impoundments (Bhattacharjee et al. 2006). To negate the effects of drawdown treatments, all soil types were subjected to both treatments (2 and 5 cm/day). We used *Flora of the Great Plains* (McGregor & Barkley 1986) and the herbarium at the BDANWR as references for plant identification.

Vegetation Cover and Height

We conducted the first vegetation sampling during early July 2002, as soon as it was possible to distinguish Cottonwood seedlings from other species. Before any plants germinated in the study area, we established two hundred and forty 1 × 1–m vegetation plots (20 per impoundment, 12 impoundments). During each sampling, all Cottonwood seedlings within 1 × 1–m plots were counted. Because Saltcedar seedlings are small and reach high densities, we counted Saltcedars in a 0.25 × 0.25–m subplot nested in the southeast corner of each 1 × 1–m plot. To determine the percent herbaceous cover by Pigweed and Barnyard grass, we used a 1 × 1–m polyvinyl chloride (PVC) frame divided into four 0.5 × 0.5–m areas. Each of these four areas was subdivided into five 10 × 10–cm areas. The 1 × 1–m frame thus consisted of 100 such small squares. We placed the grid frame on each vegetation plot and visually estimated the percent cover of a given species by counting the number of such small grids covered by that species. We used a graduated survey rod to determine height of vegetation (including woody and herbaceous plants) in the center of each plot (Higgins et al. 1996). Using the same methods as described, we also conducted an end-season sampling during late September 2002 in all 240 plots.

Soil Texture

We assigned numerical values to soil class as follows: 1 = loamy sand and sandy loam, 2 = loam and silt loam, 3 = silt and clay loam, and 4 = clay (as per Taylor et al. 1999). Sandy loam or loamy sand was composed of 50–65% sand, 20–30% silt, and 13–22% clay. Loam or silt loam soil contained 40–45% sand, 35–40% silt, and 19–21% clay. Silt or clay loam soil was composed of 38–41% sand, 28–31% silt, and 30–31% clay. Soil was categorized as clay if it contained 19–25% sand, 20–34% silt, and 41–61% clay. We used soil texture and percent composition (% silt, sand, and clay) data collected by Sprenger (1999) to describe soil particle size and their percent composition in the study area. Our vegetation plots were located in the same study area as used by Sprenger et al. (2002).

Salinity Monitoring

We used an electromagnetic induction meter (Geonics EM38; Geonico Ltd., Mississauga, Ontario, Canada) to measure soil conductivity at each plot during early July. Conductivity measurements were used as an index to soil salinity (Sheets et al. 1994). This instrument measured bulk soil electrical conductivity in a non-invasive manner. We measured vertical and horizontal conductivity (Rhoades et al. 1990), where the vertical measurement provided an index to conductivity in the vertical plane at 1.5 m soil depth and the horizontal measurement an index of conductivity in the horizontal plane at a depth of 0.75 m (Sheets et al. 1994). We then converted EC_a (apparent electrical conductivity) measurements to EC_e (electrical conductivity of a soil saturation extract) following methods suggested by Rhoades et al. (1990). Salinity indices in the two planes were averaged for each plot and used as soil salinity measure for the plot. We qualitatively compared present soil salinity in the area with salinity values obtained by Sprenger (1999).

Soil Moisture

We used a digital meter (Aquaterr 200; Aquaterr Instruments, Fremont, CA, U.S.A.) to measure soil moisture. The instrument displayed percentage of pore space occupied by water at approximately 15 cm below the soil surface (volumetric soil moisture). The digital readout is color coded (for three different soil types: sand, loam, and clay) and read from 0 to 100%. High readings reflected higher soil water content and vice versa. The instrument was recalibrated after every reading. The readings obtained using this instrument are qualitative (frequency domain reflectometry) in nature and may not be comparable to readings obtained using a neutron probe or other time domain reflectometry methods. This instrument allowed an efficient way to record and evaluate relative moisture throughout the study area in a short time period. The ease of use and portability of this instrument have led to its use in several field studies in measuring soil moisture (Taylor et al. 1999; Gallardo 2003; Meneke & Holway 2006). We recorded moisture biweekly in each of the 240 plots throughout the growing season. This was done to determine the soil moisture variation in each plot during the growing period and after precipitation events. For analysis, we used the rate of moisture decline by calculating the difference between the first and the last round of moisture readings and divided the difference by 58 days (interval between first and last rounds of measurements).

Analyses and Modeling

We used the following variables in the analysis to predict Cottonwood seedling survival (difference between initial Cottonwood seedling density, CI, and end-season density, CF): percent cover by Pigweed (PW), percent cover by Barnyard grass (BG), initial (early July) and end-season (late September) Saltcedar densities (SI and SF, respectively), initial Cottonwood density (CI), rate of soil moisture decline (RMD), vegetation height (HT), and soil salinity (SAL) (Table 1). Based on Taylor et al. (1999), plot soil characteristics were categorized into four types: sandy loam or loamy sand ($n = 100$), loam or silt loam ($n = 40$), silt or clay loam ($n = 60$), and clay ($n = 40$). We analyzed Cottonwood survival within each of the four soil types.

We used Akaike's Information Criterion (AIC) to develop models for Cottonwood survival based on biological significance, and plausible interactions between variables were included in the process. For any given model, AIC is defined as twice the difference between the number of free parameters and the maximum of the likelihood for that model. AIC was calculated as follows:

$$\mathrm{AIC} = -2\{\log[L(\hat{\theta}|y)] - K\}.$$

AIC values indicated the maximum point on the log-likelihood function that corresponded to the values of the maximum likelihood estimates. The number of estimable parameters in the model was denoted by K. The use of AIC provided a simple, effective, and objective means for selecting a "best approximating model" for data analysis and inference (Burnham & Anderson 2002). The difference between AIC for each model and the lowest AIC among all models within each soil type was calculated and denoted by $\triangle$AIC. This selection process was based on a log-likelihood function and adjusted for the number of parameters estimated in each model. We used a generalized linear model (GENMOD procedure in SAS 9.1, logistic regression with a logit link function) based on a maximum likelihood estimation procedure (Agresti 1990) to develop models that described survival of Cottonwood seedlings. We considered models with $\triangle$AIC less than or equal to 2 as having substantial support to the data in our analyses. Greater $\triangle$AIC values correlate with less support, and models with $\triangle$AIC greater than 10 had essentially no support (Burnham & Anderson 2004). We used multimodel inference for assessment of RI of variables (Burnham & Anderson 2002). RI of a variable was calculated by adding the Akaike's weights (w) of all the models that contained the predictor variable as follows:

$$x_j, \quad j = 1 \dots n \quad (n \text{ set of models}).$$

Finally, the predictor variable with the largest predictor weight, $w + (j)$, was considered the most important predictor variable and the variable with the smallest predictor weight was the variable of least importance among the n set of models. This procedure is superior to making inferences based on the RI of one model because it reduces the bias of using variables that appeared in models with lower AIC values only (Burnham & Anderson 2004). We assessed 22 models for predicting Cottonwood seedling survival within each soil category. We also present models that had the highest empirical support in explaining Cottonwood seedling survival within each soil category.

Results

Sandy Loam/Loamy Sand

The best single-variable model that explained Cottonwood seedling survival in sandy loam/loamy sand soil was rate of moisture decline, RMD [logit (probability of survival) = $-2.01 + 0.05 \times$ RMD]. Other important models ($\triangle\mathrm{AIC} \leq 2$) in this soil category included BG and an interaction between BG and RMD (Table 2). RMD had the highest RI (79%) compared to all other variables in

Table 1. $\bar{X}$ and SD (in parentheses) of variables used in the analysis for modeling Cottonwood seedling survival in sandy loam/loamy sand, loam/silt loam, silt/clay loam, and clay soils during the first growing season at the BDANWR, New Mexico, 2002.

*Variables**	*Sandy Loam/Loamy Sand*	*Loam/Silt Loam*	*Silt/Clay Loam*	*Clay*
HT (cm)	76.38 (30.10)	70.75 (24.20)	79.95 (28.70)	81.25 (28.90)
SAL (dS/m)	3.51 (1.40)	4.78 (1.59)	4.52 (1.79)	4.81 (1.17)
CI (stems/m^2)	47.12 (68.39)	3.68 (4.54)	11.17 (17.40)	1.53 (4.68)
CF (stems/m^2)	5.97 (29.52)	0.20 (0.61)	1.40 (4.17)	0.83 (3.40)
SI (stems/m^2)	24.80 (34.08)	14.20 (21.21)	22.28 (26.17)	20.75 (80.59)
SF (stems/m^2)	5.56 (14.48)	0.83 (2.02)	2.37 (4.64)	1.60 (4.71)
PW (%)	11.57 (18.25)	13.65 (22.50)	24.85 (28.03)	36.75 (33.29)
BG (%)	16.25 (24.09)	17.30 (18.24)	5.35 (13.87)	14.88 (22.97)
RMD (%/day)	1.31 (0.34)	1.63 (0.04)	1.65 (0.06)	1.66 (0.04)

*HT, vegetation height, SAL, average soil salinity in horizontal and vertical planes; CI, Cottonwood density at the first vegetation sampling; CF, Cottonwood density at the end-season vegetation sampling; SI, Saltcedar density at first vegetation sampling; SF, Saltcedar density at the end-of-season vegetation sampling; PW, cover by Pigweed (*Amaranthus* sp.); BG, cover by Barnyard grass (*Echinochloa* sp.); RMD, rate of soil moisture decline.

explaining seedling survival in sandy loam soil (Table 3). As the RMD increased, there was a decrease in Cottonwood survival.

Loam/Silt Loam

In loam/silt loam soil, vegetation height, HT [logit (probability of survival) = $-3.19 + 0.1221 \times$ HT], was the only variable present in the model with the highest empirical support for Cottonwood seedling survival (Table 2). However, single-variable models with HT, SF, CI, SI, SAL, and RMD also had considerable support based on $\triangle$AIC values. Compared to all variables in determining Cottonwood seedling survival in this soil type, HT had the highest RI (empirically accounted for 25% Cottonwood survival; Table 3). Cottonwood seedling survival decreased as HT of vegetation increased.

Silt/Clay Loam

The model that explained Cottonwood seedling survival best in this soil type contained only initial Saltcedar density, SI [logit (probability of survival) = $-1.93 - 0.00121 \times$ SI]. Other models that included SF, RMD, PW, HT, and CI also had high empirical support in determining Cottonwood seedling survival in clay loam soil (Table 2). In this soil type, SI also had the highest RI (empirically accounted for 37% Cottonwood survival) among all variables, followed by RMD and SF (Table 3).

Clay

In clay, the best model determining Cottonwood seedling survival had only Pigweed cover, PW [logit (probability of survival) = $-0.07 + 0.003 \times$ PW] included. However, models with BG, RMD, and SI also had high empirical support (Table 2). In addition, PW was the variable of highest RI, accounting for 53% of Cottonwood survival, followed by BG and RMD (Table 3). Increased cover by PW in vegetation plots led to a decrease in survival of Cottonwood seedlings.

Soil salinity, SAL, did not appear as an important variable in this study. Soil salinity levels in the study area in 2003 were lower (3–5 dS/m) than that observed by Sprenger in 1999 (10.1 dS/m). A statistical test could not be carried out because plot-level data were not available for the earlier study to be compared with the present study.

Discussion

Factors that most influenced Cottonwood seedling survival varied among soil types. In all soil types, models with

Table 2. Models used for predicting Cottonwood seedling survival in sandy loam/loamy sand, loam/silt loam, silt/clay loam, and clay soils during the first growing season at the BDANWR, New Mexico, 2002.

Model No.	Variables[a]	Number of Parameters[b]	Sandy Loam/Loamy Sand $\triangle AIC$	Sandy Loam/Loamy Sand w^c	Loam/Silt Loam $\triangle AIC$	Loam/Silt Loam w	Silt/Clay Loam $\triangle AIC$	Silt/Clay Loam w	Clay $\triangle AIC$	Clay w
1	RMD	2	0.00	0.509	1.29	0.068	0.48	0.161	3.92	0.008
2	CI	2	19.50	0.000	0.47	0.154	1.85	0.041	22.99	0.000
3	SAL	2	2.47	0.043	0.81	0.109	3.26	0.010	5.64	0.001
4	HT	2	50.76	0.000	0.00	0.246	0.73	0.116	33.46	0.000
5	PW	2	6.93	0.000	6.21	0.000	1.05	0.092	0.00	0.405
6	BG	2	1.13	0.165	17.57	0.000	3.21	0.011	0.30	0.300
7	SI	2	7.92	0.000	0.74	0.118	0.00	0.262	1.35	0.105
8	SF	2	5.93	0.001	0.03	0.238	0.39	0.178	2.76	0.026
9	RMD CI	3	3.57	0.014	3.29	0.009	2.91	0.014	21.79	0.000
10	BG RMD	3	1.33	0.134	17.04	0.000	3.58	0.007	2.54	0.032
11	BG SI	3	8.54	0.000	17.70	0.000	3.94	0.005	5.32	0.002
12	SAL SI	3	9.72	0.000	2.36	0.023	3.65	0.007	16.82	0.000
13	CI RMD SAL	4	24.43	0.000	5.43	0.001	16.21	0.000	17.72	0.000
14	RMD SAL RMD × SAL	4	3.70	0.013	4.26	0.003	4.34	0.003	8.45	0.000
15	RMD SI RMD × SI	4	39.38	0.000	3.17	0.010	1.28	0.073	46.18	0.000
16	BG SI BG × SI	4	9.88	0.000	17.21	0.000	4.35	0.003	44.02	0.000
17	CI SI CI × SI	4	64.78	0.000	2.59	0.019	2.52	0.021	20.90	0.000
18	PW RMD PW × RMD	4	8.11	0.000	6.69	0.000	2.33	0.025	1.21	0.121
19	BG RMD BG × RMD	4	1.45	0.119	16.49	0.000	8.55	0.000	16.61	0.000
20	BG HT PW RMD SAL	6	54.60	0.000	39.25	0.000	11.22	0.000	61.54	0.000
21	BG CI HT RMD SAL SI PW	8	60.99	0.000	48.15	0.000	29.06	0.000	17.40	0.000
22	BG CI HT RMD SAL SI SF PW	9	75.94	0.000	67.11	0.000	29.13	0.000	47.90	0.000

[a]Where $\triangle$AIC is the difference between each model AIC and the lowest AIC for the entire set of models, BG, cover by Barnyard grass (*Echinochloa* sp.); CI, Cottonwood density during the first vegetation sampling; PW, cover by Pigweed (*Amaranthus* sp.); SI, Saltcedar density during the first vegetation sampling; SF, Saltcedar density during the end-of-season vegetation sampling; RMD, rate of soil moisture decline; SAL, average soil salinity in horizontal and vertical planes; HT, vegetation height.
[b]Including intercept.
[c]Akaike's weight is denoted by *w*.

Table 3. RI of variables and percent support (sum of Akaike's weights of a given variable across all models in which the variable appeared) used to predict survival of Cottonwood seedlings in sandy loam/loamy sand, loam/silt loam, silt/clay loam, and clay soils during the first growing season at the BDANWR, New Mexico, 2002.

RI[b]	*Sandy Loam/ Loamy Sand*	*Percent Support*	*Loam/Silt Loam*	*Percent Support*	*Silt/Clay Loam*	*Percent Support*	*Clay*	*Percent Support*
1	RMD[b]	0.79	HT	0.25	SI	0.37	PW	0.53
2	BG	0.42	SF	0.24	RMD	0.28	BG	0.33
3	SAL	0.06	CI	0.18	SF	0.18	RMD	0.16
4	CI	0.01	SI	0.17	PW	0.12	SI	0.11
5	SF	0.00	SAL	0.14	HT	0.09	SF	0.03
6	PW	0.00	RMD	0.09	CI	0.08	SAL	0.00
7	HT	0.00	PW	0.00	BG	0.03	CI	0.00
8	SI	0.00	BG	0.00	SAL	0.02	HT	0.00

[a]RI of variables, where 1 indicates variable of highest importance and 8 indicates least important variable.
[b]RMD, rate of soil moisture decline; BG, percent cover by Barnyard grass (*Echinochloa* sp.); SAL, average soil salinity in horizontal and vertical planes; CI, Cottonwood density during the first vegetation sampling; SF, Saltcedar density during the end-of-season vegetation sampling; PW, percent cover by Pigweed (*Amaranthus* sp.); HT, vegetation height; SI, Saltcedar density during the first vegetation sampling.

multiple variables and interactions had lower AIC weights and were not as important as single-variable models in predicting Cottonwood seedling survival. Rate of moisture decline (RMD) was in the top six of all the 22 models tested in each soil type ($\triangle AIC \leq 2$), making it a variable of importance for all soil types. Soil texture is often used as a surrogate variable for water availability in plants (Hillel 1980). Sher and Marshall (2003) also reported that growth of newly recruited Cottonwood was influenced by soil texture. Soil texture affects both water drainage rates and extent of capillary rise, which plays an important role in the ecology of Cottonwood (Mahoney & Rood 1992). Cottonwood seedlings grow rapidly following germination (Horton et al. 1960; Fenner et al. 1985), but this initial surge of growth can be inhibited by low soil moisture (Segelquist et al. 1993). Although it is natural for any floodplain to lose moisture as floodwaters recede, a gradual rate of moisture decline will promote Cottonwood seedling survival through increased soil moisture (Bhattacharjee et al. 2006) as compared to a rapid rate of moisture decline.

In sandy loam/loamy sand soil, rate of moisture decline (RMD) was the single most important factor influencing Cottonwood seedling survival. RMD was the lowest in this soil, which was reflected by the highest end-season Cottonwood density. Soil texture was coarse in this soil type as compared to others, and its coarse texture may have allowed Cottonwood roots to grow faster than in a fine-textured soil. These findings support Friedman et al. (1995) and Sher and Marshall (2003), who reported highest Cottonwood seedling densities in coarser soil types and where densities of competing vegetation were low.

In our study, there was no other significant source of mortality such as scouring by subsequent flooding and animal damage; thus, seedling mortality can primarily be attributed due to shading and moisture stress. From this study, we speculate that as vegetation height (HT) increased, it reduced the amount of sunlight received by Cottonwood seedlings, which in turn resulted in seedling mortality. Johnson et al. (1976) also reported mortality in Cottonwood seedlings due to shading by co-recruiting herbaceous species. Although we did not directly measure moisture stress in seedlings, it is conceivable that Cottonwood seedlings in loam or silt loam soil experienced greater moisture stress (due to higher RMD) than in sandy loam soils, which further contributed to seedling mortality.

In silt/clay loam soil, initial Saltcedar densities (SI) had important influence on Cottonwood seedling survival. An increase in SI values correlated to an increase in CW survival. Albeit counterintuitive, the observed correlation is likely because of two reasons: similarity in germinations conditions results in high densities of both Cottonwood and Saltcedar and at higher densities, Cottonwood is able to outcompete Saltcedar, leading to higher survival. Sher et al. (2000) and Sher and Marshall (2003) found in greenhouse studies that Cottonwood is a superior competitor between Cottonwood and Saltcedar.

In our study area, Pigweed (PW) was one of the two dominant species that potentially competed with Cottonwood seedlings. We found Pigweed to grow best in clay soils, as was reported by Bond and Turner (2005). The importance of PW on Cottonwood seedling survival in clay soils may be because PW not only drew moisture from the soil but also shaded Cottonwood seedlings. Although we did not make measurements on the amount of light/shade on the seedlings, the above conclusion is based on the shade-intolerant nature of Cottonwood that has been well documented in several studies (Read 1958; Strahan 1984; Scott et al. 1996). Competition from particular herbaceous species will vary among regions; thus, future studies of the effect of species that recruit concurrently with target species (species that needs to be restored, Cottonwood in this case) would aid understanding of restoration results. Furthermore, herbaceous vegetation cover found historically in undisturbed river floodplains might differ from vegetation seen in the area today; thus, evaluating competitive outcome between associated and native species will further enhance restoration in riparian areas.

Although germination and survival of Cottonwood seedlings have been reported to decrease beyond a threshold value of 3.0 dS/m (Sheets et al. 1994), soil salinity levels in our study averaged between 3 and 5 dS/m^2 depending on the soil type with no effect on seedling germination and survival. Thus, in our study, given the narrow range, soil salinity was not an important factor in influencing Cottonwood seedling survival. Soil salinity levels in our study area were lower as compared to values obtained by Sprenger in 1999, mainly due to successive flooding of the impoundments. Lower salinity levels in our study (as compared to Sprenger et al. 2002) also might have resulted in higher Cottonwood seedling density, 28 plants/m^2 against 8 plants/m^2 in their study.

Conclusions

Seedling germination and recruitment of native riparian species, including Cottonwood, are closely tied to the hydrograph and annual overbank flooding of rivers. Riparian restoration plans should emphasize on taking into account the soil texture in restoration sites. The texture of soil primarily determines its water-retaining capabilities, which is an important factor influencing survival of Cottonwood seedlings. Thus, in altered river floodplains, soil moisture in the nonsaturated zones is of critical importance to successful restoration. Restoration sites with predominantly coarser soil may be more suitable for restoration of Cottonwoods than finer soils because coarser soils not only provide better rooting medium for the seedlings but also are associated with lower herbaceous vegetation, hence reducing moisture depletion and shading effects. In areas where the soil has been compacted naturally, mechanical loosening of the soil, using rakes attached to a tractor or bulldozer, prior to flooding and seeding may potentially increase seedling recruitment by removing competing vegetation and allowing easier rooting for the seedlings.

The number of competing species (primarily for light and moisture) in restoration sites can be reduced by mechanical clearing of sites prior to flooding. This has been suggested as an effective tool for restoration (Bhattacharjee et al. 2006). Flooding and staged water drawdown (to augment soil moisture) can be used to create recruitment sites for the establishment of riparian vegetation and can provide favorable soil moisture during recruitment and growth of Cottonwoods. Subsequent periodic flooding of restoration sites creates favorable growing conditions for the native species by providing moisture to growing seedlings. A slow drawdown rate (2 cm/day; Bhattacharjee et al. 2006) that holds moisture longer is effective in increasing seedling survival in Cottonwoods. Flooding of restoration sites to ameliorate conditions for germination of Cottonwoods also results in the co-recruitment of unwanted herbaceous species. However, most herbaceous vegetation including Pigweeds die with the first frost of the season and can be easily controlled with herbicides (McLachlan et al. 1995). Therefore, carefully timed overbank flooding and drawdown (synchronized with seed rain of native species) can be used as an effective restoration tool in most riparian areas where natural hydrological regimes have been disturbed.

Implications for Practice

- Restoration plans for riparian areas should be formulated based on site-specific biotic and abiotic factors.
- Although it is important to monitor soil moisture in restoration sites, it is critical to consider soil texture because it determines moisture available for plants.
- In regulated rivers, staged water release that mimics natural disturbance in the floodplain may lead to conditions favorable for recruitment of native riparian species.
- Annual herbaceous plants that recruit simultaneously with desired riparian species may compete for resources and increase mortality of desired species. This is species specific and should not be generalized to all riparian zones.

Acknowledgments

We thank J. Savery and the staff at the BDANWR for logistic support. Research was supported by the U.S. Fish and Wildlife Service through the Bosque Improvement Group (through the efforts of C. Abeyta), Caesar Kleberg Foundation for Wildlife Conservation, Turner Enterprises (through the efforts of C. Kruse and T. Wadell), and Texas Tech University. We appreciate help provided by the YCC crew (2002) and the fire crew at the BDANWR for their help in fieldwork. We thank G. DelloRusso for suggestions in the field and C. Lee for field assistance. We also thank D. Haukos, N. McIntyre, S. McMurry, D. Wester, and J. Friedman for comments on manuscript drafts. Comments from M. Briggs and an anonymous referee helped improve the manuscript, and we are thankful to them.

LITERATURE CITED

Adair, E. C., and D. Binkley. 2002. Co-limitation of first year Fremont cottonwood seedlings by nitrogen and water. Wetlands **22:**425–429.

Agresti, A. 1990. Categorical data analysis. John Wiley and Sons, New York.

Allred, K. 2002. Identification and taxonomy of *Tamarix* (Tamaricaceae) in New Mexico. Desert Plants **18:**26–31.

Amlin, N. M., and S. B. Rood. 2002. Comparative tolerances of riparian willows and cottonwoods to water-table decline. Wetlands **22:**338–346.

Anderson, B. W. 1989. Research as an integral part of revegetation projects. Pages 413–419in D. L. Abell, technical coordinator. California riparian systems conference. Pacific Southwest Forest and Range Experimental Station. U.S. Department of Agriculture Forest Service General Technical Report PSW-110.

Anderson, B. W., P. E. Russell, and R. D. Ohmart. 2004. Riparian revegetation: an account of 2 decades of experience in the Arid Southwest. Avvar Books, Blythe, California.

Bhattacharjee, J. 2005. Restoration of native riparian vegetation and competition between cottonwoods and saltcedar in the Middle Rio Grande Valley, New Mexico. Ph.D. dissertation. Texas Tech University, Lubbock.

Bhattacharjee, J., J. P. Taylor Jr, and L. M. Smith. 2006. Controlled flooding and staged drawdown for restoration of native cottonwoods in the middle Rio Grande Valley, New Mexico. Wetlands **26:** 691–702.

Bond, W., and R. Turner. 2005. The biology and non-chemical control of common amaranth (*Amaranthus retroflexus* L.). HDRA, Ryton Organic Garden. Coventry, United Kingdom.

Bradley, C. E., and D. G. Smith. 1986. Plains cottonwood recruitment and survival on a prairie meandering river floodplain, Milk River, southern Alberta and northern Montana. Canadian Journal of Botany **64:**1433–1442.

Brinson, M. M. 1990. Riverine forests. Pages 87–141 in A. E. Lugo, M. Brinson, and S. Brown, editors. Ecosystems of the world. Forested ecosystems, vol. 14. Elsevier, Amsterdam, The Netherlands.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference—a practical information—theoretical approach. 2nd edition. Springer-Verlag, New York.

Burnham, K. P., and D. R. Anderson. 2004. Multimodel inference: understanding AIC and BIC in model selection. Sociological Methods and Research **33:**261–304.

Busch, D. E., and M. L. Scott. 1995. Our living resources: a report to the nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems. U.S. Department of the Interior, National Biological Service, Washington, D.C.

Cooper, D. J., D. M. Merritt, D. C. Andersen, and R. A. Chimner. 1999. Factors controlling the establishment of Fremont cottonwood seedlings on the Upper Green River, USA. Regulated Rivers: Research and Management **15:**419–440.

Crawford, C. S., A. C. Cully, R. Leutheuser, M. S. Sifuentes, L. H. White, and J. P. Wilber. 1993. Middle Rio Grande ecosystem: Bosque biological management plan. U.S. Department of the Interior, Fish, and Wildlife Service, Albuquerque, New Mexico.

Duncan, R. P. 1993. Flood disturbance and coexistence of species in a lowland podocarp forest, south Westland, New Zealand. Journal of Ecology **81:**403–416.

Everitt, B. L. 1968. Use of the cottonwood in an investigation of the recent history of a floodplain. American Journal of Science **266:**417–439.

Fenner, P., W. W. Brady, and D. R. Patton. 1985. Effects of regulated water flows on regeneration of Fremont cottonwood. Journal of Range Management **38:**135–138.

Friedman, J. M., M. L. Scott, and W. M. Lewis Jr. 1995. Restoration of riparian forest using irrigation, artificial disturbance, and natural seedfall. Environmental Management **19:**547–557.

Gallardo. A. 2003. Spatial variability of soil properties in a floodplain forest in Northwest Spain. Ecosystems **6:**564–576.

Groeneveld, D. P., and T. E. Griepentrog. 1985. Interdependence of groundwater, riparian vegetation, and stream bank stability: a case study. USDA Forest Service General Technical Report RM 120.

Higgins, K. F., J. L. Oldermeyer, K. J. Jenkins, G. K. Clambey, and R. F. Harlow. 1996. Vegetation sampling and measurement. Pages 567–591 in T. A. Bookhout, editor. Research and management techniques for wildlife and habitats. 5th edition. The Wildlife Society, Bethesda, Maryland.

Hillel, D. 1980. Fundamentals of soil physics. Academic Press, New York.

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.

Horton, J. S., F. C. Mounts, and J. M. Kraft. 1960. Seed germination and seedling establishment of phreatophyte species. U.S. Department of Agriculture, Rocky Mountain Forest and Range Experiment Station Paper No. 48.

Jackson, J. J., T. Ball, and M. R. Rose. 1990. Assessment of salinity tolerance of eight Sonoran Desert riparian trees and shrubs. Desert Research Institute, University of Nevada System, Biological Science Center, Reno.

Johnson, W. C. 1994. Woodland expansion in the Platte River, Nebraska: patterns and causes. Ecological Monographs **64:**45–84.

Johnson, W. C., R. L. Burgess, and W. R. Keammerer. 1976. Forest overstory vegetation and environment on the Missouri River floodplain in North Dakota. Ecological Monographs **46:**59–84.

Katz G. L., J. M. Friedman, and S. W. Beatty. 2001. Effects of physical disturbance and granivory on establishment native and alien riparian trees in Colorado, U.S.A. Diversity and Distributions **7:**1–14.

Mahoney, J. M., and S. B. Rood. 1991. A device for studying the influence of declining water table on poplar growth and survival. Tree Physiology **8:**305–314.

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.

Malanson, G. P. 1993. Riparian landscapes. Cambridge University Press, Cambridge, United Kingdom.

Mathookoand, J. M., and S. T. Kariuki. 2001. Disturbance and species distribution of the riparian vegetation of a Rift Valley stream. African Journal of Ecology **38:**123–129.

McGregor, R. L., and T. M. Barkley, editors. 1986. Flora of the Great Plains. University Press of Kansas, Lawrence.

McLachlan, S. M., S. D. Murphy, M. Tollenaar, S. F. Weise, and C. J. Swanton. 1995. Light limitation and reproduction and variation in allometric relationship between reproductive and vegetative biomass in *Amaranthus retroflexus* (Red-root pigweed). Journal of Applied Ecology **32:**157–165.

Meneke, S. B., and D. A. Holway. 2006. Abiotic factors control invasion by Argentine ants at the community scale. Journal of Animal Ecology **75:**368–376.

Molles M. C Jr, C. S. Crawford, L. M. Ellis, H. M. Valett, and C. N. Dahm. 1998. Managed flooding for riparian ecosystem restoration. BioScience **48:**749–756.

Nobel, M. G. 1979. The origin of *Populus deltoides* and *Salix* interior zones on point bars along the Minnesota River. American Midland Naturalist **102:**59–67.

Read, R. A. 1958. Silvical characteristics of plains cottonwood. USDA, Forest Service, Rocky Mountain Range Experimental Station Paper No. 33, Washington, D.C.

Rhoades, J. D., P. J. Shouse, W. J. Alves, N. A. Manteghi, and S. M. Lesch. 1990. Determining soil salinity from soil electrical conductivity using different models and estimates. Soil Science Society of America Journal **54:**46–54.

Roberts, J., and J. A. Ludwig. 1991. Riparian vegetation along current—exposure in floodplain wetlands of the river Murray, Australia. Journal of Ecology **79:**117–127.

Rood S. B., and S. Heinze-Milne. 1989. Abrupt downstream forest decline following river damming in Southern Alberta. Canadian Journal of Botany **67:**1744–1749.

Rood S. B., J. M. Mahoney, D. E. Reid, and L. Zilm. 1995. Instream flows and the decline of riparian cottonwoods along the St. Mary River. Canadian Journal of Botany **73:**1250–1260.

SAS/STAT user's guide, version 9.1. 4th edition. SAS Institute, Inc., Cary, North Carolina.

Scott, M. L., J. M. Freidman, and G. T. Auble. 1996. Fluvial processes and the establishment of bottomland trees. Geomorphology **14:** 327–339.

Scott, M. L., P. B. Shafroth, and G. T. Auble. 1999. Responses of riparian cottonwoods to alluvial water table declines. Environmental Management **23:**347–358.

Segelquist, C. A., M. L. Scott, and G. T. Auble. 1993. Establishment of *Populus deltoides* under simulated alluvial ground water declines. American Midland Naturalist **130:**274–285.

Shafroth, P. B., G. T. Auble, J. C. Stromberg, and D. Patten. 1998. Establishment of woody riparian vegetation in relation to annual patterns of stream flow. Bill Williams River, Arizona. Wetlands **18:**577–590.

Shafroth, P. B., J. M. Friedman, and L. S. Ischinger. 1995. Effects of salinity on establishment of *Populus fremontii* (cottonwood) and *Tamarix ramosissima* (salt cedar) in southwestern United States. Great Basin Naturalist **55:**58–65.

Shafroth, P. B., J. C. Stromberg, and D. Patten. 2002. Riparian vegetation response to altered disturbance and stress regimes. Ecological Applications **12:**107–123.

Sheets, K. R., J. P. Taylor, and J. M. H. Hendricks. 1994. Rapid salinity mapping by electromagnetic induction for determining riparian restoration potential. Restoration Ecology **2:** 242–246.

Sher, A. A., and D. L. Marshall. 2003. Competition between native and exotic floodplain tree species across water regimes and soil textures. American Journal of Botany **90:**413–422.

Sher, A. A., D. L. Marshall, and S. A. Gilbert. 2000. Competition between native *Populus deltoides* and invasive *Tamarix ramosissima* and the implications for reestablishing flooding disturbance. Conservation Biology **14:**1744–1754.

Siegel, R. S., and J. H. Brock. 1990. Germination requirements of key southwestern woody riparian species. Desert Plants **10:**3–8.

Sigafoos, R. S. 1964. Botanical evidence of floods and floodplain deposition. United States Geological Survey Professional Paper No. 485-A.

Somogyi, Z., I. Szabados, and G. Veperdi. 1999. Growth and health of floodplain forests in the Szigetkoz (N-W Hungary) before and after diversion of the Danube: results of a ten-year monitoring. Ekologia **18:**50–68.

Sprenger, M. D. 1999. Restoration of riparian wildlife habitat in the Middle Rio Grande Valley following historical river hydrographs. M.S. thesis. Texas Tech University, Lubbock.

Sprenger, M. D., L. M. Smith, and J. P. Taylor. 2002. Restoration of riparian habitat using experimental flooding. Wetlands **22:**49–57.

Strahan, J. 1984. Regeneration of riparian forests of the Central Valley. Pages 58–67 in R. E. Warner and K. M. Hendrix, editors. California riparian systems: ecology, conservation and productive management. University of California Press, Berkeley.

Stromberg, J. C. 1997. Growth and survivorship of Fremont cottonwood, Gooding willow, and saltcedar seedlings after large floods in central Arizona. Great Basin Naturalist **57:**198–208.

Stromberg, J. C., D. T. Patten, and B. D. Richter. 1991. Flood flows and dynamics of Sonoran riparian forests. Rivers **2:**221–235.

Stromberg, J. C., R. Tiller, and B. D. Richter. 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: The San Pedro, Arizona. Ecological Applications **6:**113–131.

Taylor, J. P., D. B. Wester, and L. M. Smith. 1999. Soil disturbance, flood management, and riparian woody plant establishment in the Rio Grande floodplain. Wetlands **19:**372–382.

Western Region Climate Center. Western Region Climate Center—climatological data for Bosque del Apache National Wildlife Refuge, New Mexico (available from http://www.wrcc.dri.edu/) accessed December 2003.