WETLANDS, Vol. 26, No. 3, September 2006, pp. 691–702

CONTROLLED FLOODING AND STAGED DRAWDOWN FOR RESTORATION OF NATIVE COTTONWOODS IN THE MIDDLE RIO GRANDE VALLEY, NEW MEXICO, USA

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Abstract: Alteration of natural hydrologic regimes of most rivers in the southwestern United States has led to degradation of riparian habitats. Most areas historically covered by Rio Grande cottonwood [*Populus deltoides* Marshall subsp. *wislizenii* (Wats.) Eckenw.] have been replaced by exotic saltcedar (*Tamarix chinensis* Lour.). Following an earlier study in the Middle Rio Grande Valley, New Mexico that evaluated faster staged water drawdowns to restore riparian habitat, we evaluated slower rates, 2 cm/day and 5 cm/day (starting depth = 30 cm) to determine if cottonwood seedling density could be increased. During the period of spring flood recession of the Rio Grande, we placed seed-bearing branches of cottonwood in experimental basins and applied the drawdown treatments. Following the end of drawdowns, we conducted the first vegetation sampling to determine cottonwood and saltcedar seedling densities in the area. We also conducted a mid-season, an end-season, and an over-winter vegetation sampling to observe changes in seedling densities over time. Saltcedar and cottonwood seedling densities did not differ statistically between the drawdown treatments. However, survival of cottonwood seedlings during the first growing season in the 2 cm/day drawdown was greater than in the 5 cm/day drawdown. Greater seedling survival in the slower drawdown was likely due to increased soil moisture levels in that treatment, corresponding to a more gradual descending limb of the historical hydrograph. Use of a slow water drawdown (2 cm/day; about 20 days duration) synchronized with natural seed rain of cottonwoods will result in high first season densities of this important riparian species.

Key Words: cottonwood, Middle Rio Grande Valley, *Populus deltoides*, restoration, riparian, *Tamarix chinensis*

INTRODUCTION

The physical setting and dynamic fluvial processes of most major rivers of the southwestern U.S. have been changed (Stromberg 2001). Construction of dams and levee structures has often disconnected rivers from their adjacent riparian areas and altered timing of peak flows and overbank flooding (National Research Council 2002:9). Impounding water has negatively influenced downstream riparian vegetation due to lowering of ground-water tables and reducing frequency of overbank flooding downstream (Gordon et al. 1992). These hydrologic changes within river systems and replacement of native species by exotic species such as saltcedar (*Tamarix chinensis* Lour. synonymous to *T. ramosissima* Ledeb. based on recent studies on chloroplast and nuclear DNA; Allred 2002) and Russian olive (*Elaeagnus angustifolia* L.) have led to a decline in the cottonwood-willow (*Populus* spp.- *Salix* spp.) riparian associations, making them one of the most endangered habitats in the U.S. (Knopf and Olson 1984, Stromberg 1993). Historically, water regulations have been framed to favor perceived human needs at the cost of environmental degradation. Recently, the values of natural systems have been realized, and steamflows have been managed to aid restoration of riparian plant communities (Stanford et al. 1996, Scott et al. 1997, Rood et al. 1998, Shafroth et al. 2002, Sprenger et al. 2002). Because functioning of riparian systems requires a full range of variation in the hydrologic regime, the reintroduction or simulation of such flow regimes is essential for restoring and sustaining riparian systems.

Controlled water manipulations timed with dispersal of native plant seeds have been used to regenerate riparian habitats (Freidman et al. 1995, Taylor and McDaniel 1998, Taylor et al. 1999, Sprenger et al. 2002). Flooding of areas that have been cleared of vegetation creates germination sites similar to those created within floodplains following scouring by floodwaters (Freidman et al. 1995). Even though studies (Anderson and Ohmart 1982, Taylor and McDaniel 1998) have demonstrated that pole planting is successful, use of natural seed rain along with staged water drawdowns may be more desirable than other methods in restoration processes because (1) it can be performed at a lower cost than pole plantings (pole plantings cost =$2,223/ha, Taylor and McDaniel 1998), (2) native trees are not always available as a source of poles, and (3) plants that are established from seed rain within the natural habitat should be better adapted to local conditions (Heslop-Harrison 1965, Friedman et al. 1995). Moreover, recent studies have shown that cottonwoods seedlings inherit certain traits, such as tolerance to higher water stress and increased soil salinity from parent trees that have been growing in altered environmental conditions (Rowland et al. 2004), and poles obtained from nurseries may not have the desirable traits.

Overall, effective management of riparian ecosystems requires an integrated understanding of surface and alluvial ground-water dynamics (Scott et al. 1999). Increased soil moisture (Segelquist et al. 1993, Mahoney and Rood 1998) and shallow water tables (Stromberg et al. 1996) are critical in determining success of restoration; however, only a few studies have determined the optimum conditions leading to greater initial recruitment of seedlings and subsequent survival during the first year.

Sprenger et al. (2002) evaluated Rio Grande cottonwood recruitment using two water drawdown rates (5 cm and 10 cm/day) and found that seedling root growth was unable to keep up with the declining water tables. To increase cottonwood survival, they proposed use of slower drawdown rates, which would be closer to the historical hydrograph of the Rio Grande (Taylor et al. 1999). In this study, we therefore evaluated seedling densities and survival of cottonwood and saltcedar in response to simulated river flooding and controlled water drawdown treatments (2 cm/day and 5 cm/day; starting depth = 30 cm) timed with natural seed rain in areas within the historic Middle Rio Grande floodplain. We expected these treatments to produce greater recruitment than found by Sprenger et al. (2002), and we expected greater recruitment in the slowest drawdown, as it should provide high soil moisture for a longer period during the critical period of early seedling growth. We compared water-table decline rates as well as soil moisture in both treatments.

STUDY AREA

The study was conducted at the Bosque del Apache National Wildlife Refuge (BDANWR) (33°48″, 106°53″), a part of the Middle Rio Grande Valley (MRGV) in central New Mexico, USA. The MRGV extends for about 260 km from Cochiti Dam, New Mexico, downstream to San Marcial, New Mexico (Crawford et al. 1993). Historically, the annual hydrograph of the Rio Grande was typical of many other rivers in western North America, including the Colorado and Pecos (Scott et al. 1993), with peak flows in late May and June following snowmelt in upstream mountainous regions (Crawford et al. 1993).

The Rio Grande valley was 5.2 km wide at the study site. The active floodplain width was 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. The Middle Rio Grande basin in the study area was bounded by mountain ranges that rise 2000 m to the west and 1600 m to the east (Bullard and Wells 1992).

Average annual precipitation at the refuge was 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 was 23.6°C, and average daily low temperature during this period was 13.3°C (Western Region Climate Center, from 1971 to 2003).

The study was conducted in 12 impoundments along the Rio Grande at BDANWR as described by Sprenger et al. (2002:50). These impoundments were constructed within the historic Rio Grande floodplain west of the current channel. Each covered an approximate area of 4 ha. The presence of replicate impoundments, along with precisely controlled water drawdown structures, allowed us to repeat experimental overbank flooding treatments in a single year. The study area has been hydrologically isolated from the present river floodplain for more than 55 years due to the presence of a levee and a low-flow conveyance channel between the study site and the river (Molles et al. 1998). Hydrology, soils, and biological processes within the impoundments are similar to those of active river floodplains of most rivers in southwestern U.S. (Ellis et al. 1999, 2001, Smith et al. 2002, Sprenger et al. 2002). Mean soil salinity in the study area was 10.1 dS/m (Sprenger et al. 2002).

METHODS

Each of the 12 impoundments received one of two drawdown treatments, 2 cm/day or 5 cm/day. Treatments (six replicates each) were randomly assigned to impoundments. Water tables in the 12 impoundments were controlled by means of sluice gates. The water table within each impoundment was monitored using three wells installed along the elevational gradient (one in the center and other two at eastern and western edges of an impoundment). A piezometer (4 m in length) was placed in each well. Each piezometer consisted of a 5-cm-diameter polyvinyl chloride pipe with several hundred 2 mm holes in the lowest 1 m, to allow water to seep in the well. Nylon gauze covered holes at the lower end to reduce siltation into the well.

Experimental Flooding and Drawdown

Impoundments were flooded to 30 cm on 12 May 2002. Water for the study was diverted from the riverside canal on the west side of the study area and supplemented with water from the low-flow channel and irrigation return flows. To ensure accurate drawdowns, each impoundment was filled to a fixed level determined using staff gauges. Water was maintained at a constant level for three weeks, allowing soil saturation. Stage drawdowns of 2 and 5 cm/day were initiated on 4 June and completed by 24 June. The fast drawdown lasted for nine days, the slow 20 days. Drawdown timing coincided with natural seed rain of cottonwood in the study area. Drawdown rates were monitored at staff gauges located at each water-control structure within an impoundment three times a day, seven days a week to ensure consistent stage-level declines.

Supplemental Seeding

A wildfire in the study area in 1996 destroyed most of the existing riparian forest. This resulted in a reduced number of cottonwood and other native trees. As in Sprenger et al. (2002), the study area was supplemented with seed-bearing cottonwood branches obtained from adjoining area as an additional seed source. Equal numbers of seed-bearing branches were placed in all impoundments. The branches were placed at intervals of 5–7 m along the water's margin on the south edge to take advantage of the prevailing winds to disperse seeds. As waters receded, new branches bearing fresh seeds were moved along the drawdown gradient.

Vegetation Sampling

Five transects were established across the width of each impoundment. The first transect was placed approximately 3 to 5 m from the borrow ditch on the west side of each impoundment, and the remaining four were stratified to ensure complete coverage of the impoundment (Cabrera and Dieringer 1992). After drawdowns were complete, four 1 $\times$ 1m equally-spaced quadrats were established along each transect, for a total of 20 quadrats per impoundment. Seedlings of cottonwood and other woody species were counted in the 1 $\times$ 1m quadrats. Saltcedar seedlings were counted within a 0.5 $\times$ 0.5m quadrat nested in the southwest corner of each 1 $\times$ 1m quadrat (due to their small size and high densities, Sprenger et al. 2002). Vegetation was sampled four times from July 2002 to May 2003: first week of July (pre-monsoon), second week of August (monsoon), third week of September (post-monsoon), and second week of May 2003. This last sampling was conducted to determine over-winter seedling survival. Only cottonwood seedlings that were a few days old and week-old saltcedar seedlings could be correctly identified visually during the first sampling; seedlings of most other woody species could not be identified with certainty during that period.

Seedlings were identified as dead by visual examination of tissue material. To determine the condition of the plant, the stem was bent, and if it broke off, the plant was considered dead. In suspect cases, a tissue sample from the base was removed for analysis. Plants were considered alive if they had any green foliage or if the cambium layer of the stem was green and pliable (Gladwin and Roelle 1998, Sprenger et al. 2001).

Survival of cottonwood seedlings was estimated from density measurements within each quadrat. Survival for cottonwood was calculated as the percentage difference in the number of seedlings present from one sampling period to the next. This method of survival estimation was accurate, as cottonwood seed dispersal and germination are restricted to about two weeks during early July. Survival of saltcedar seedlings could not be determined accurately because seeds were liberated for about six months (May through October) in the study area and newly germinated seedlings were observed in quadrats during all sampling periods. Thus, seedling density changes from one period to the next were used to evaluate population dynamics of saltcedar within a year.

Statistical Analysis of Seedling Densities and Survivorship

We only analyzed data for cottonwood and saltcedar, as seedlings of other woody species recruited in insufficient densities (*Salix* sp., 5 plants/ha) to enable conclusive statistical analyses. To test for differences in seedling density of cottonwood and saltcedar between treatments, we used a repeated measure analysis of variance with a logit link (GENMOD procedure in SAS® 9.1) for each species. To test for differences in survival of cottonwood seedlings across the four sampling periods, we used an analysis of variance with a log link and with repeated measure (GENMOD procedure in SAS® 9.1). Percent survival of cottonwood seedlings between two consecutive sampling periods was the dependent variable and treatment was the independent variable with sampling periods as repeated measures. Because survivorship could not be determined for saltcedar, we examined its seedling density dynamics by comparing densities between sampling periods. We used an analysis of variance with repeated measure (GENMOD procedure in SAS® 9.1) to evaluate differences in densities among sampling periods. Saltcedar seedling density was the dependent variable, and sampling periods (repeated measure) and treatment were independent variables.

In biological data (counts, densities, frequencies, etc.), the variance is typically greater than the mean; thus, the data tend to be over dispersed. Overdispersion leads to underestimation of standard errors and overestimation of the test statistic, resulting in high type I error rates. Cameron and Trivedi (1998) suggested a test for overdispersion based on an auxiliary regression of the Poisson residual. The null hypothesis of equidispersion is tested against the alternative of overdispersion of the dependent variable. We used a log-likelihood ratio (LR) test to examine the appropriateness of using a negative binomial distribution and of using a Poisson distribution. We tested the null hypothesis (equality of mean and variance), H_0: $\alpha = 0$, against the hypothesis $\alpha \neq 0$, using the critical value of Chi-square distribution corresponding to significance level 2α (Cameron and Trivedi 1998), and rejected H_0 if the LR statistic was greater than $\chi^2_{(1-2\alpha,\ 1\text{df})}$.

For cottonwood:

$$\begin{aligned}\text{Chi-Sq} &= -2(\text{Log likelihood}_{\text{Poisson}} \\ &\quad - \text{Log likelihood}_{\text{Negative binomial}}) \\ &= -2(28899.995 - 34377.794) \\ &= 10955.598,\end{aligned}$$

which corresponds to $P < 0.001$. Therefore, we concluded the mean and variance are not equal, and a negative binomial distribution was more appropriate than a Poisson distribution.

For saltcedar:

$$\begin{aligned}\text{Chi-Sq} &= -2(\text{Log likelihood}_{\text{Poisson}} \\ &\quad - \text{Log likelihood}_{\text{Negative binominal}}) \\ &= -2(101384.069 - 102649.706) \\ &= 2531.274,\end{aligned}$$

which corresponds to $P < 0.001$. Therefore, we concluded that the mean and variance are not equal, and a negative binomial distribution was more appropriate than a Poisson distribution. We calculated density and survival of cottonwood and density and seedling dynamics of saltcedar using a repeated measure analysis of variance with a negative binomial distribution.

We conducted an effect size analysis (Cohen 1988) by using Cohen's "*d*" to determine the magnitude of treatment effect (2 cm/day and 5 cm/day) on density and survival of the seedlings of the two species. To determine effect size differences between treatments, we used the following formula:

$$d = (M_{fast\ drawdown} - M_{slow\ drawdown})/\sigma_{pooled},$$

where M is the total density of a species in each treatment and where $\sigma_{pooled} = \sqrt{\left[\sigma^2_{slow} + \sigma^2_{fast}\right]/2}$. Assessing the magnitude of difference in recruitment densities of cottonwood and saltcedar seedlings in the two drawdown treatments is important as it aids management decisions.

To examine the relationship between cottonwood seedling survival and moisture, we used a generalized linear model (GENMOD procedure in SAS® 9.1). The data were modeled as a negative binomial distribution with a log link. We used percent seedling survival as the dependent variable and moisture as the explanatory variable.

Water-Table Monitoring and Analysis

In 2002, water-table levels were recorded with a beep measuring tape (Solonist®). Water levels were monitored daily in the beginning and at interval of

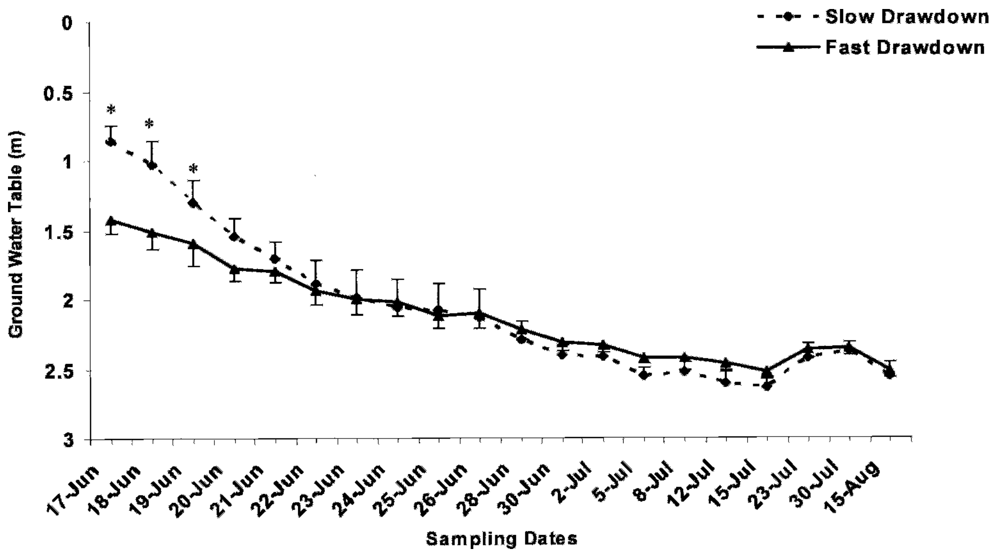

Figure 1. Mean water-table measurements, recorded by beep-meter in 12 impoundments, six with slow (2 cm/day) and six with fast (5 cm/day) drawdown treatment in 2002, at Bosque del Apache National Wildlife Refuge, New Mexico. Ground level is indicated by 0.0 m. Means within a period followed by an asterisk, are different ($P < 0.1$). Differences in means that are significant ($P < 0.1$) have only been labeled in the figure.

two, three, and seven days thereafter until 15 August (Figure 1). We used an analysis of mixed models using method=type 3 in MIXED procedure (SAS® 9.1) to evaluate differences in water tables between the two treatments through successive water sampling periods. In this analysis, impoundments within a treatment type were used as random effects and water sampling periods as repeated measure.

Soil Moisture Monitoring and Analysis

Moisture levels were determined using a digital Aquaterr® 200 Moisture Meter (Aquaterr Instruments, Fremont, CA). The instrument displayed percent measure of pore space occupied by water at approximately 15 cm below the ground surface. We recorded soil moisture at each of the 240, 1 × 1m vegetation quadrats on two consecutive days beginning 7 July, thereafter at intervals of seven days until 15 August (Figure 2) and after any precipitation event. Moisture readings obtained in the quadrats were percent measures, and we used GENMOD procedure (SAS® 9.1) assuming a binomial distribution with a logit link to model the response variable (soil moisture) between the two treatments during the growing season (11 rounds of soil-moisture measurement).

Soil Salinity Monitoring and Analysis

We used an electromagnetic induction meter (Geonics EM38, Ontario, CA) to measure soil conductivity and used it as an index of soil salinity (Sheets et al. 1994). Vertical and horizontal conductivity (Rhoades et al. 1990) of soil was measured in each of the 240, 1 × 1m quadrats. 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 converted EC_a (apparent electrical conductivity) measurements to EC_e (electrical conductivity of a soil saturation extract) following Rhoades et al. (1990). Soil salinity indices were taken after drawdowns in the 12 impoundments were complete and the surface was dry, as required for proper functioning of the instrument. Salinity indices in the two planes were averaged for each plot. Linear regression (REG procedure in SAS® 9.1) was used to evaluate the effect of soil salinity on seedling density of cottonwood and saltcedar across the 12 study impoundments. Mean number of seedlings of each species per quadrat was the dependent variable, and soil salinity in the quadrat was the predictor variable.

RESULTS

Seedling Recruitment

Cottonwood. The mean number of cottonwood seedlings did not differ significantly between 2 cm/day and 5 cm/day drawdowns during vegetation samplings. Although not significant, cottonwood seedling density was slightly higher in the slow

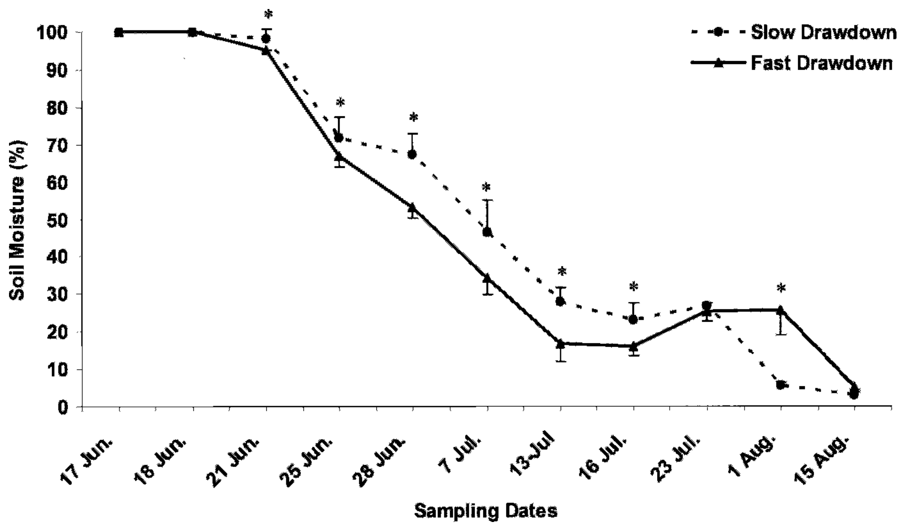

Figure 2. Mean soil-moisture measurements in the 12 impoundments that received slow or fast drawdown treatments (six slow and six fast) during the first growing season in 2002 at Bosque del Apache National Wildlife Refuge, New Mexico. Means within a period followed by an asterisk are different ($P < 0.1$). Differences in mean that are significant ($P < 0.1$) have only been labeled in the figure.

drawdown than the fast, during the second, third, and fourth sampling periods (Table 1). During the first and second sampling periods, the effect of two drawdown treatments on recruitment of cottonwood seedlings was small (d = 0.22, d = 0.35). During the third sampling, the effect of treatment increased (d = 0.51 medium effect) (Figure 3). Cottonwood seedling survival from July 2002 to May 2003 was 3.6%. Survival of cottonwood seedlings decreased over time ($\chi^2_2 = 7.39$, $P = 0.02$), and was lowest over winter (Table 2). Survival of cottonwood seedlings differed between treatments ($\chi^2_1 = 2.71$, $P = 0.09$) and was greater in the slow drawdown than in the fast (Table 2) throughout the season. There was no interaction between treatment and period ($\chi^2_2 = 0.96$, $P = 0.62$).

Saltcedar. There was no difference in the mean number of saltcedar seedlings recruited in the slow and the fast drawdowns ($\chi^2_1 = 0.08$, $P = 0.77$, Table 2). Drawdown treatment had a small effect (d = 0.02) on initial recruitment of saltcedar seedlings. The effect of drawdown treatment on densities of saltcedar seedlings was small during the second sampling (d = 0.22) and medium (d = 0.65) during the third (Figure 3). Mean saltcedar density in the study area decreased ($\chi^2_3 = 30.00$, $P < 0.01$) through the first growing season (Table 3). There was no

Table 1. Mean cottonwood seedling density (plants/m^2) in slow (2 cm/day) and fast (5 cm/day) drawdown treatments during four consecutive sampling periods in 2002 and 2003, and mean cottonwood density averaged across treatments during each sampling period at the Bosque del Apache National Wildlife Refuge, New Mexico.

		Treatment seedling density[1] (plants/m^2)		Period seedling density[2] (plants/m^2)	
Period	Treatment	$\bar{x}$	SE	$\bar{x}$	SE
Early-July – 2002	Slow	19.27^A	10.96	24.12^a	12.49
	Fast	28.98^A	23.62		
Mid-August – 2002	Slow	12.60^A	8.50	9.71^a	4.67
	Fast	6.83^A	4.52		
Late-September – 2002	Slow	4.52^A	3.37	3.01^b	1.71
	Fast	1.49^A	0.73		
Mid-May – 2003	Slow	2.40^A	2.08	1.44^b	1.04
	Fast	0.50^A	0.37		

[1] Treatment means within a sampling period followed by the same upper case letter are not different ($P>0.1$).
[2] Mean density among sampling periods followed the different lower case letter are different ($P<0.1$).

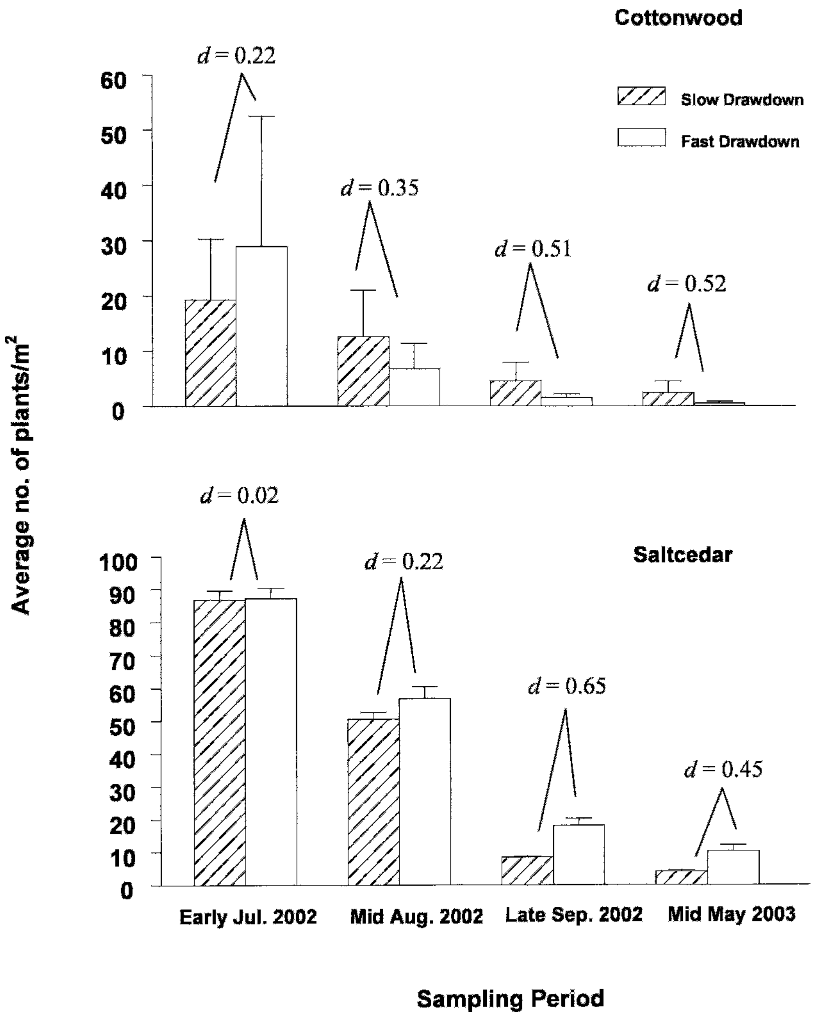

Figure 3. Mean density of cottonwood and saltcedar seedlings during four sampling periods at the Bosque del Apache National Wildlife Refuge, New Mexico (2002–2003). Effect size analysis values are denoted by *"d"*.

effect of treatment ($\chi^2_1 = 1.18$, $P = 0.18$) on the seedling dynamics through the different sampling periods, and there was no interaction between treatment and period ($\chi^2_3 = 2.06$, $P = 0.56$). Although not statistically significant ($\chi^2_1 = 1.96$, $P = 0.16$), there was about 50% decline in saltcedar density between late-September 2002 and mid-May 2003.

Water-Table

Water-table measurements varied between the two treatments depending on the sampling period. There was a significant interaction between treatment and period on water-table levels ($F_{19,152} = 6.09$, $P < 0.001$) as indicated by the repeated measure analysis of variance (Period $F_{19,152} = 117.76$ $P < 0.001$, Treatment $F_{1,8} = 0.09$ $P = 0.766$). Results of simple main effect (treatment within period) suggested that the water table between the two treatments differed only during the first three samplings ($F_{1,152} = 12.44$ $P = 0.006$, $F_{19,152} = 9.15$ $P = 0.029$, $F_{19,152} = 3.31$ $P = 0.07$ for Periods 1, 2, and 3, respectively) following the drawdowns (Figure 1). During later sampling periods, there was no difference in ground-water tables between drawdown treatments.

Soil Moisture

Soil moisture difference between treatments ($\chi^2_1 = 0.002$, $P = 0.97$) was dependent on the period ($\chi^2_{10} = 1573.4$, $P < 0.001$), as suggested by a significant interaction ($\chi^2_{10} = 42.33$, $P < 0.001$). Soil moisture did not differ between treatments early in the sampling period, based on examination of simple main effects within periods (Figure 2). However, the third round (mid-June) readings differed between the two treatments, and the higher moisture in impoundments with the slow drawdown continued

Table 2. Mean percent seedling survival in cottonwoods during the first growing season (2002) and over-winter survival (2003) in impoundments with slow and fast drawdown treatments at Bosque del Apache National Wildlife Refuge, New Mexico.

		Percent seedling survival[1] (Treatment)		Percent seedling survival[2] (Period)	
Period	Treatment	$\bar{x}$	SE	$\bar{x}$	SE
Early-July to Mid-August-2002	Slow	58.25^{A}	7.94	48.16^{a}	6.62
	Fast	38.08^{B}	9.44		
Mid-August to Late-September-2002	Slow	37.60^{A}	8.90	35.20^{b}	5.91
	Fast	32.79^{B}	8.50		
Late-September 2002- to Mid-May-2003	Slow	26.00^{A}	10.57	21.57^{c}	6.28
	Fast	17.13^{B}	7.34		

[1] Mean percent survival within a period followed by different upper case letters are different ($P<0.1$).
[2] Mean seedling survival among periods followed by different lower case letters are different ($P<0.1$).

until mid-July. Thereafter, there were no differences in soil moisture between drawdowns.

Effect of Moisture on Recruitment

Soil moisture positively influenced cottonwood seedling survival ($\chi^2_1 = 2.67$, $P = 0.10$). However, saltcedar seedling dynamics over the growing season were not affected by soil moisture ($\chi^2_1 = 2.09$, $P = 0.15$) in the study area.

Effect of Soil Salinity on Recruitment

There was no relationship ($r^2 = 0.02$, $F_{2,237} = 3.02$, $P = 0.05$) between soil salinity (ranged from 2.7 to 5.4 dS/m) and seedling density of cottonwoods across the 12 impoundments. The density of saltcedar seedlings across the 12 impoundments also was independent ($r^2 = 0.006$, $F_{2,237} = 0.75$, $P = 0.47$) of soil salinity.

DISCUSSION

A slow drawdown of 2 cm/day (20 days) and a fast drawdown of 5 cm/day (9 days) permitted similar recruitment of cottonwood seedlings, but survival was greatest at 2 cm/day. Although the mean density in the slow drawdown was five-fold higher than in the fast drawdown, large variability in the data (mainly due to the nature of seedling establishment patterns in cottonwood) may have masked statistically significant differences in density between treatments. However, a difference of this magnitude between treatments calls more for biological interpretation of results than statistical significance.

There was a small difference in density of cottonwood seedlings between the two treatments

Table 3. Mean saltcedar seedling density (plants/m^2) in slow (2 cm/day) and fast (5 cm/day) drawdown treatments during four consecutive sampling periods in 2002 and 2003, and mean saltcedar densities averaged across treatments during each sampling period at the Bosque del Apache National Wildlife Refuge, New Mexico.

		Treatment seedling density[1] (plants/m^2)		Period seedling density[2] (plants/m^2)	
Period	Treatment	$\bar{x}$	SE	$\bar{x}$	SE
Early-July-2002	Slow	86.67^{A}	11.59	86.91^{a}	8.26
	Fast	87.16^{A}	12.87		
Mid-August – 2002	Slow	50.60^{A}	8.25	53.73^{a}	7.98
	Fast	56.87^{A}	14.42		
Late-September - 2002	Slow	8.37^{A}	1.49	13.25^{b}	4.42
	Fast	18.13^{A}	8.61		
Mid-May – 2003	Slow	4.06^{A}	1.84	7.15^{b}	3.88
	Fast	10.23^{A}	7.68		

[1] Treatment means within a sampling period followed by the same upper case letter are not different ($P>0.1$).
[2] Mean density among sampling periods followed by different lower case letter are different ($P<0.1$).

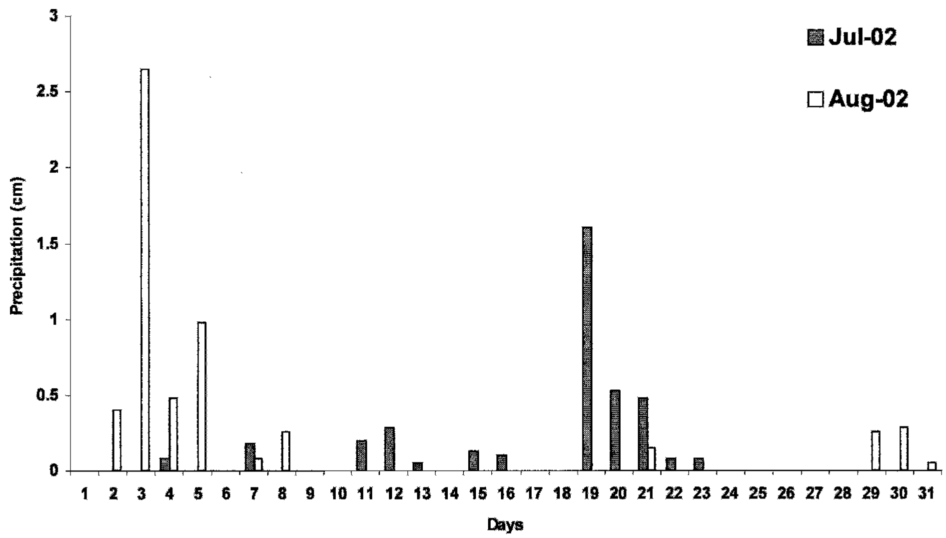

Figure 4. Precipitation during July and August 2002 in the study area at Bosque del Apache National Wildlife Refuge, New Mexico.

during the first two samplings, but a larger difference by the third and fourth samplings. The primary reason for the small treatment effect during initial sampling is that both treatments provide similar substrate conditions for germination. The reason for the greater treatment effect during later sampling is the greater soil moisture provided at the later dates by the slow drawdown.

Results of our study suggest that soil moisture is important in cottonwood seedling recruitment. This finding supports that of Segelquist et al. (1993), who observed no recruitment of cottonwood seedlings when simulated flooding was immediately followed by drawdown. They also reported seedling survival rates to be highest at 0.4 and 0.7 cm/day drawdown (experiment was conducted in planters); however, such rates would be very difficult to achieve under large-scale restoration projects. Mahoney and Rood (1991) also observed increased seedling mortality and decreased shoot growth rates at 4 and 8 cm/day water drawdowns.

Cottonwood seedling survival was dependent more on soil moisture than on water-table levels. Seedlings during the first year of growth do not have deep enough roots to maintain contact with the ground-water table at the depth recorded during our study, wherein the water-table dropped >1 m within two months following seedling recruitment to a final depth of 250 cm. Cottonwood seedlings are capable of growing roots at a rate of 6–13 mm/day (Fenner et al. 1984, McBride et al. 1988). If seedlings grew roots at the maximum growth rate (13 mm/day), roots would have been 78 cm long after two months, and the water table would have been more than three times as deep as the roots. Our results support studies by Pope et al. (1990) and Shafroth et al. (1998), who emphasized that seedling survival was more dependent on soil moisture after recruitment than on water-table level. Mahoney and Rood (1998) described capillary fringe as the zone of moisture extending above the saturated riparian water table. The extent of capillary fringe is soil texture dependent and can range from 5 cm in coarse gravel to 70 cm in fine texture sand. However, the idea that seedlings are capable of using the capillary fringe is not supported by our study. Water tables in the study area dropped to 250 cm by mid-July. With the capillary fringe somewhere at about 150–200 cm below the ground level, it is unlikely that 45-day-old seedlings could use the capillary fringe moisture. Thus, seedlings may use other sources of moisture such as precipitation for survival. Similar conclusion has been reported in studies by Stromberg (1993, 1996), Snyder and Williams (2000), and Sprenger et al. (2002).

This finding of dependency on soil moisture does not support the concept of the "Recruitment Box" model proposed by Mahoney and Rood (1991), according to which, cottonwood seedlings are dependent primarily on the water table as a source of water. If the model was universally valid, we should have observed a much greater mortality of cottonwood seedlings in our study area, given the rate of water-table decline. However, there was 35% survival in seedlings from early August to late September primarily due to availability of soil moisture at the depth of at least 15 cm (sensor length of the moisture measurement probe). Monsoonal rain showers during late July and early

August (Figure 4) likely contributed in elevating soil moisture.

Saltcedar seedling densities in the slow drawdown were slightly lower than in the fast drawdown by the end of the study. During the growing season, density of saltcedar seedlings in the slow drawdown decreased at a higher rate than in the fast drawdown. This may be because greater survival of cottonwood seedlings in the slow drawdown led to more competition for moisture between cottonwood and saltcedar seedlings. Cottonwood may have a competitive advantage over saltcedar seedlings because of its higher growth rate (Sher et al. 2000, Sher and Marshall 2003).

In our study, it was not possible to estimate saltcedar seedling mortality rates because we did not tag individual saltcedar seedlings and seeds continued to germinate throughout summer whenever moisture was available (i.e., after any precipitation event). Similar difficulties in estimating saltcedar survival/mortality were reported by Sprenger et al. (2002). Saltcedar densities reported during each vegetation sampling included seedlings that were newly recruited and older seedlings. However, observations indicated that newly recruited seedlings died due to mid-summer heat (average 36°C), lowering the overall density of saltcedar in vegetation quadrats during subsequent samplings.

Recruitment of cottonwood and saltcedar seedlings in the study area was not affected by soil salinity. Shafroth et al (1995) reported that salinity levels of up to 3.45 dS/m had no negative effect on germination, mortality, or aboveground or belowground growth of cottonwoods. Siegel and Brock (1990) observed high percent germination of cottonwood seeds at salinity level of 4.6 dS/m using a solution of NaCl in the laboratory. Jackson et al. (1990) reported cottonwood germination at salinity levels of 9.98 dS/m. Mean salinity level in our study was 4.19 dS/m; therefore, it might not have affected germination of cottonwood seeds.

Management Recommendations

Restoration of riparian areas requires a holistic understanding of the intricate mechanisms that regulate the process of recruitment of native species. Horton and Clark (2001) suggested a careful determination of the species-specific requirements for establishment of species of the semi-arid riparia of the western U.S. Overbank flooding, timed with seedfall, has been used to aid restoration of riparian areas (Scott et al. 1997, Rood et al. 1998). Creating bare seed beds prior to increased waterflow, (such as by mechanically clearing vegetation), is essential for restoration of cottonwood forests (Taylor et al. 1999). In managed areas, controlled water drawdown timed with natural seed release from native trees augments seedling recruitment (Shafroth et al. 1998, Sprenger et al. 2002). In areas with low seed-source trees, supplemental seeding (using seed-bearing branches) is an effective way to increase seed availability (Sprenger et al. 2002).

Results of our study support the suggestions made by Sher and Marshall (2003) that water drawdown may be used to promote cottonwood establishment and may aid in the reduction of saltcedar establishment in riparian areas. In addition, results from our study and several others indicated that newly recruited seedlings depend more on soil moisture than on water-table (Pope et al. 1990, Stromberg 1996, Shafroth et al. 1998). Water drawdown rates should not exceed 2 cm/day (or extend for 20 days), as this slow drawdown provides the adequate moisture required for the initial growth in cottonwood seedlings. This initial growth is important, as it gives the cottonwood seedlings the height to overtop saltcedars and possibly shade and reduce their growth, as saltcedars are shade intolerant (Sher et al. 2000, Lesica and Miles 2001). Faster drawdown rates result in reduced soil moisture, which induces seedling mortality due to moisture stress. It is important to time the drawdown such that peak seed dispersal of cottonwoods in the area coincides with the near-completion of the drawdown. Drawdown rates in our study might have been timed better to coincide with the natural seed rain for cottonwoods (4 June instead of 11 June in the study by Sprenger et al. (2002)). We recorded higher cottonwood density, 28 plants/m^2 compared to 8 plants/m^2 in Sprenger et al. (2002) at 5 cm/day drawdown rate. Timing is crucial, as seeds of cottonwood lose viability in a couple of weeks (Braatne et al. 1996), and microsites that are created by drawdowns may lose moisture and become unsuitable for later seed germination. In addition, successive flooding and drawdowns of the same study site resulted in reduced soil salinity levels [from 10.1 dS/m in the study by Sprenger et al. (2002) to 4.19 dS/m in our study]. Therefore, repeated flooding of dammed floodplains and restoration sites during good water years can potentially reduce soil salinity.

ACKNOWLEDGMENTS

We thank the staff at Bosque del Apache National Wildlife Refuge for their logistic and infrastructural support. We also thank Liter E. Spence for his help in the field throughout the study. Research was supported by the U.S. Fish and Wildlife Service through the Bosque Improvement Group (through the efforts of Cyndie Abeyta), Caesar Kleberg Foundation for Wildlife Conservation, Turner Enterprises (through the efforts of Carter Kruse and Tom Wadell), and Texas Tech University. We thank David Haukos, Nancy McIntyre, Scott McMurry, and David Wester for their comments. We also thank Juliet Stromberg and two anonymous referees for their valuable suggestions on the manuscript. This is manuscript T- 9-1095 of the College of Agricultural and Natural Resources at Texas Tech University.

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Manuscript received 29 August 2005; revisions received 17 January 2006 and 21 February 2006; accepted 30 May 2006.