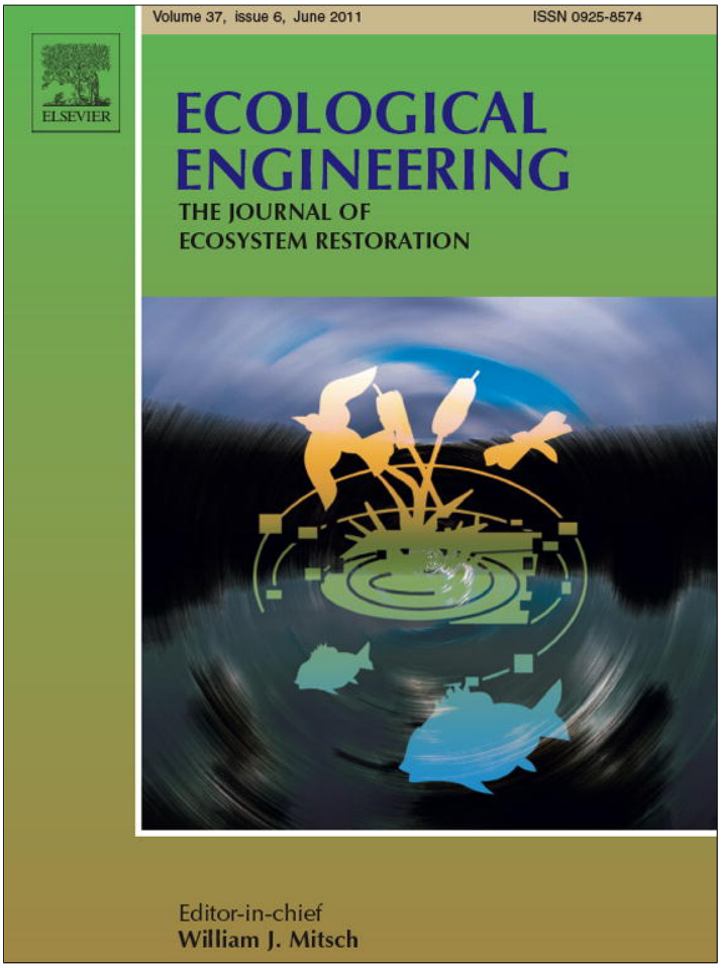
Volume 37, issue 6, June 2011
ISSN 0925-8574
ELSEVIER
ECOLOGICAL ENGINEERING
THE JOURNAL OF ECOSYSTEM RESTORATION
Editor-in-chief
William J. Mitsch

Ecological Engineering 37 (2011) 864–872

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Direct seeding for riparian tree re-vegetation: Small-scale field study of seeding methods and irrigation techniques

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ARTICLE INFO

Article history:
Received 1 December 2009
Received in revised form 19 January 2011
Accepted 23 January 2011
Available online 24 February 2011

Keywords:
Cottonwood
Populus
Re-vegetation
Riparian
Salix
Willow

ABSTRACT

Restoration of wetland and associated ecosystems is a major goal of land management agencies throughout the world. On the lower Colorado River, creation of riparian forests is planned to mitigate riparian habitat degradation by historic land-use conversions and river management. Current restoration practices use propagated plant stock. If direct seeding can be implemented, genetic and structural diversity could be enhanced at restoration sites even while reducing costs compared to vegetative propagation methods. A small-scale field study was implemented in Cibola, Arizona, to determine the effectiveness of direct seeding of Fremont cottonwood (*Populus fremontii*), Goodding's willow (*Salix gooddingii*), and coyote willow (*S. exigua*). For the first growing season, establishment of Fremont cottonwood averaged 7% of pure live seed rates for all treatments combined, whereas establishment of willows was less than 1%. Volunteer species were abundant, with grasses dominating cover and biomass after one growing season. Saltcedar (*Tamarix ramosissima*) established in abundance, but showed lower growth rates than Fremont cottonwood during the first growing season. Monitoring for three growing seasons indicated higher growth rates and survival of Fremont cottonwood compared to all volunteer species. Study results indicated that direct seeding of Fremont cottonwood is likely to be an efficient method for tree re-vegetation. Additional studies are required for willow species to determine if establishment from seed can be increased through enhanced weed control and elimination of Fremont cottonwood from the seed mix.

1. Introduction

1.1. Background

To mitigate historic destruction of wetlands, momentum is growing to restore or re-vegetate associated ecosystems to provide flood control and habitat for native fauna (Mitsch and Gosselink, 2000). Western U.S. land managers are tasked with restoring thousands of hectares of vegetation along streams, where flow regulation, clearing of native vegetation, grazing, and establishment of non-native species have resulted in soil salinization (Glenn et al., 1998), channel narrowing and incision (Shafroth et al., 2002), and increased frequency and intensity of wildfires (Busch, 1995). Along the lower Colorado River (LCR[1]), areas of riparian vegetation were historically cleared for agriculture. Additionally, dams and levees constructed between Lake Powell and the international border with Mexico reduced flooding and allowed for diversions of water for agricultural and urban use. However, land clearing and flow regulation have resulted in extensive degradation of riparian ecosystems within the historic floodplain.

To mitigate anthropogenic changes in river management and land use, the U.S. Bureau of Reclamation plans to re-vegetate 2400 ha of land on the LCR currently under agricultural use or dominated by saltcedar (*Tamarix ramosissima*), an introduced invasive species, with the native Salicaceae species Fremont cottonwood (*Populus fremontii*, FC), Goodding's willow (*Salix gooddingii*, GW), and coyote willow (*S. exigua*, CW) to provide habitat for native fauna

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[1] *Abbreviations*: FC, Fremont cottonwood; GW, Goodding's willow; CW, coyote willow; LCR, lower Colorado River; bgs, below ground surface; ANOVA, analysis of variance.

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doi:10.1016/j.ecoleng.2011.01.003

(Bureau of Reclamation, 2006). Of particular concern are native avifauna, including the Southwestern willow flycatcher (*Empidonax traillii extimus*) and western yellow-billed cuckoo (*Coccyzus americanus occidentalis*). In addition to the benefits for native species habitats, re-vegetation with riparian species is often desired for erosion control and streambank stabilization (Mallik and Rasid, 1993; Pezeshki et al., 2007).

1.2. Standard re-vegetation practices

Salicaceae species can effectively be established via vegetative propagation, which typically consists of pole planting, or placement of rooted or bare cuttings. Pole planting involves cutting large branches while trees are dormant, and placing them within the capillary fringe to increase the availability of water (FISRWG, 1998). On the LCR, the U.S. Bureau of Reclamation has recently (since 2005) been propagating small Salicaceae cuttings, which are grown for a period of up to eight months within nurseries to establish roots, and then outplanted at very high densities (up to 1.7 m^{-2}, Bureau of Reclamation, 2007).

Despite high vegetation success, there are concerns with using vegetative propagation for large-scale re-vegetation. Stems are taken from a limited number of sources trees, affecting genetic diversity, growth rates, and sex ratios at restoration sites (Winfield and Hughes, 2002). Therefore, it has been suggested that sexual propagation should be used whenever possible (Landis et al., 2003). Vegetative propagation also results in high costs due to the need for collection, storage, transportation, and preliminary establishment in controlled environment agricultural systems (Bureau of Reclamation, 2007).

1.3. Direct seeding of Salicaceae species

High-density establishment of seedlings has been observed in riparian systems which still experience seasonal flooding. Dense establishment of FC and GW has been observed along the Bill Williams River, a tributary of the Colorado River which has experienced seasonal flooding during the past decade (Shafroth et al., 1998). Seedling densities of up to 35,000 m^{-2} have been observed following controlled flood releases during spring seed dispersal (Barbara Raulston, Biologist, Bureau of Reclamation, personal communication). Natural recruitment of native Salicaceae trees has also been observed following flooding in the Colorado River Delta (Nagler et al., 2005) and on the middle Rio Grande in New Mexico (Sher et al., 2002; Sprenger et al., 2002; Taylor and McDaniel, 1998; Taylor et al., 1999). Where native seed dispersal still occurs, pond drawdown during periods of Salicaceae seed dispersal has allowed micro-climates which support germination and seedling growth (Roelle and Gladwin, 1999; Roelle et al., 2001). Direct seeding and irrigation might promote establishment of riparian vegetation in areas where native tree seedfall has been reduced (as in Friedman and Scott, 1995).

Direct seeding typically reduces costs compared to hand planting due to reduction in handling time and equipment required per seed compared to per cutting or seedling, reduced transportation cost, and decreased costs of seeding compared to planting. Schuman et al. (2005) demonstrated a reduction of over 90% in the cost of native shrubs per plant by direct seeding compared to transplanting of nursery-grown seedlings. Other discussions of cost reductions due to direct seeding include (Balandier et al., 2009; Dissanayake et al., 2008; Willoughby et al., 2004). It is likely that if direct seeding can be implemented for the Salicaceae species, the costs of large-scale riparian habitat restoration could be dramatically reduced. Additionally, because Salicaceae species are dioeceous, the use of seed would ensures that genetic information from many trees is incorporated into restoration sites.

Several attempts have been made to direct seed riparian areas along the LCR. Previous efforts included manual spreading of pubescent seed, hydroseeding using a variety of mulch and tackifiers, and placement of seeding branches upwind of cleared land (Raulston, 2003; Bureau of Reclamation, 2005). However, lack of a scientific, replicated approach has precluded determination best practices for seed preparation, seeding, and irrigation methods. Additionally, seeding rate effects have not been analyzed.

To provide a more controlled, scientific analysis of the feasibility of direct seeding of FC, GW, and CW for large-scale riparian restoration, a small-scale field study was implemented on 48 m^2 (800 ft^2) study plots to analyze the effects of seeding and irrigation methods on the establishment and growth of these riparian trees.

2. Materials and methods

2.1. Study location

The study was conducted on a former agricultural field at the Cibola National Wildlife Refuge (NWR), Arizona approximately 2 km from the Colorado River. Near-surface soils are dominated by silt loam (Indio silt loam), underlain by sand at depths greater than 100 cm below ground surface. Prior to seeding the average near-surface soil salinity was 1.6 dS m^{-1}, considered moderately saline, but within the tolerance of FC, GW, and CW (Desert Research Institute, 1990; Glenn et al., 1998). Depth to groundwater has been observed to vary between 2 and 3 m, with maximum depth to groundwater occurring during July and minimum depth occurring during January (GeoSystems Analysis, Inc., 2008). Thus, the potential exists at this site for groundwater use by mature riparian trees.

2.2. Experimental design

A split-plot factorial design was used to determine the effects of germination-period (early-time sprinkler) irrigation method, seed treatment, seeding methods, and surface irrigation methods on FC, GW, and CW tree establishment and growth within 6 m (20 ft) by 12 m (40 ft) plots. Three blocks were arranged in a north–south orientation on the edge of an existing agricultural field. Each block was randomly divided into two sub-plots (sprinklers or no sprinklers), within which six seeding method-surface irrigation treatment combinations were randomized. Thus, combinations of seeding and irrigation methods were analyzed in triplicate. The resulting study treatment combinations are detailed in Table 1. The final field layout is provided in Fig. 1.

Early-time sprinkler irrigation was implemented to determine if germination rates could be increased and spatial variability of seedling density could be decreased by minimizing soil inundation and surface flow. Sprinklers were placed on a regular grid, with 12 m (north–south) lateral spacing by 9 m (east–west) sprinkler spacing. Sprinkler system management is described in Section 2.4.

Seeding methods initially considered included drill seeding, broadcast seeding, and hydroseeding of cleaned or uncleaned seed. It was determined that “fluffy seed” broadcasters and drill seeders would not be effective for uncleaned cottonwood and willow and that a rangeland drill seeder would be ineffective for small plots. Consequently, broadcasting of cleaned seed, and hydroseeding of cleaned seed and uncleaned seed were evaluated.

The seed cleaning treatment was implemented to investigate potential increases in cottonwood and willow establishment due to removal of seed hairs, as observed during previous studies of

Table 1
Field study specifications and treatment codes for 2007 Salicaceae seeding trials conducted at Cibola National Wildlife Refuge, Cibola, Arizona.

Variable	Treatment	Specifications
Sprinkler treatment (sub-plot factor)	No sprinklers (N)	No sprinklers used, surface irrigation implemented immediately after seeding.
	Sprinklers (Y)	Sprinklers irrigation used during germination period (3 weeks after seeding), surface irrigation thereafter.
Seeding method	Uncleaned, hydroseed (UH)	Pubescence not removed from seed coats, seed applied with a hydroseeder.
	Cleaned, hydroseed (CH)	Pubescence removed from seed coats, seed applied with a hydroseeder.
	Cleaned, broadcast (CB)	Pubescence removed from seed coats, seed applied with a broadcast seed spreader.
Surface irrigation method	Border (B)	Small-scale basin irrigation.
	Furrow (F)	Furrows on 1.0 m spacing.
Plot position (blocking factor)	Block 1 (1)	Northernmost replication.
	Block 2 (2)	Middle replication.
	Block 3 (3)	Southernmost replication.

riparian tree species establishment in greenhouses (GeoSystems Analysis, Inc., 2007). Likewise, it was speculated that hydroseeding would result in reduced movement due to wind and irrigation for both cleaned and uncleaned seed.

Furrow and border surface irrigation methods were investigated. Border irrigation consisted of small-scale basins enclosed by soil berms on all sides. Furrows on 1.0-m (40-in.) centers with a depth of approximately 15 cm (6 in.) were installed via ripping and bed shaping. Following seeding, berms were constructed at the ends of the plots to eliminate surface runoff. All surface irrigation was applied via 15 cm (6 in.) outer-diameter aluminum gated pipe to maximize distribution uniformity.

Because of variations observed in soil salinity and subsurface texture within the study (GeoSystems Analysis, Inc., 2008), it was expected that plot position might significantly affect plant establishment and growth. Therefore, potential "Plot Position" nuisance effects were reduced through the split-plot design. Plot position was denoted by Block 1, Block 2, or Block 3 (refer to Fig. 1).

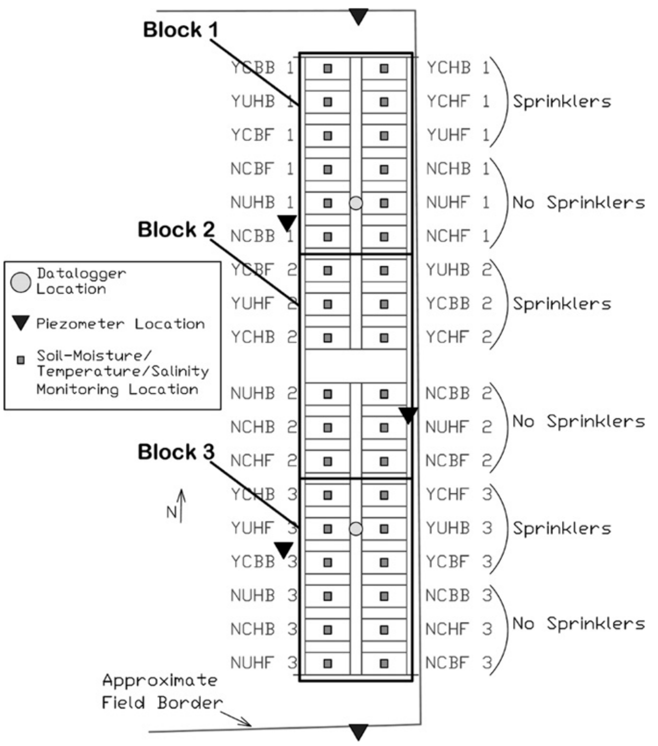

Fig. 1. Treatment layout for small-scale field study of Salicaceae direct seeding at Cibola National Wildlife Refuge, Cibola, Arizona. Treatment codes are as detailed in Table 1.

The design seeding rate for the small-scale plots was 1345 pure live seeds (PLS) m^{-2}, which consisted of 270 PLS m^{-2} of FC, and 538 PLS m^{-2} each of Gooding's and CW, seeding rates which showed dominance by seeded species in previous greenhouse studies (GeoSystems Analysis, Inc., 2007). It was understood that eventual mortality of trees would result in long-term thinning. However, excessive seeding rates were considered an acceptable trade-off for potential outcompetition of undesired volunteer vegetation while mimicking natural regeneration of trees on the LCR. Additionally, according to preliminary analysis during this study, these seeding rates were anticipated to be economically superior to current vegetative propagation methods.

2.3. Seed collection, preparation and application

Seed was collected on the LCR between March 12 and April 16, 2007 at Beal Lake Habitat Restoration Site (8 km southeast of Needles, CA), Bill Williams River NWR, Ahakhav Tribal Preserve (Parker, Arizona), and Cibola NWR. Catkins were collected from trees which had begun actively dispersing seed, as recommended by the U.S. Bureau of Reclamation, 2005. After drying on laboratory benches, all seed was transferred to freezers. Freezer temperature was maintained at −10 °C (GW and CW) or −19 °C (FC) per recommendations from the US Department of Agriculture National Seed Storage Laboratory (Didericksen, Biological Science Laboratory Technician, January 9, 2005, personal communication). To remove seed pubescence for the "cleaned seed" treatment, sufficient seed of each species was cleaned using a Wiley mill (Model #2 and Model #4, Arthur H. Thomas Company, Philadelphia, PA) with subsequent separation of seed from debris with a #25 sieve (Newark Wire Cloth Company, Newark, NJ). After cleaning, seed was returned to freezers. Two weeks prior to seeding, incubator germination studies were conducted for each seed source to determine the PLS rate for the small-scale studies.

Cleaned, broadcast treatment seed was allocated per plot at the rate of 270 PLS m^{-2} of FC and 538 PLS m^{-2} each of GW and CW. Sufficient hydroseed treatment seed was combined for thirteen plots at the design seeding rate, to seed the twelve treatment plots and an additional test area. The seed was then returned to freezer bags, and stored in the freezers until transport to the Cibola NWR small-scale plots for seeding. All PLS rates were estimated based on weight calibrations of cleaned and uncleaned riparian seed.

Hydroseed was applied with a 2000 l-capacity Finn Hydroseeder (Finn Corporation, Fairfield, OH). The application rate was approximately 3.53 m^3 ha^{-1} of hydroseed consisting of water, mulch, and seed. No chemical tackifiers were applied. Mulch consisting of Conwed Fibers 2000 wood fiber (Profile Products, LLC, Buffalo Grove, IL) was applied at approximately 18.4 kg ha^{-1}.

It was desired to apply identical seeding rates to all plots; however, because the hydroseeder pump flow rate was greater than

Table 2
Estimated total seeding rates, as 20% Fremont cottonwood, 40% Goodding's willow, and 40% coyote willow, for 2007 Salicaceae seeding trials conducted at Cibola National Wildlife Refuge, Cibola, Arizona.

Plot	Seeding rate (PLS m^{-2})	Plot	Seeding rate (PLS m^{-2})	Plot name	Seeding rate (PLS m^{-2})
NCBB 1	1345	NUHB 1	1293	YCHB 1	1242
NCBB 2	1345	NUHB 2	1293	YCHB 2	1242
NCBB 3	1345	NUHB 3	1293	YCHB 3	1242
NCBF 1	1345	NUHF 1	1072	YCHF 1	1242
NCBF 2	1345	NUHF 2	1170	YCHF 2	1242
NCBF 3	1345	NUHF 3	1848	YCHF 3	1242
NCHB 1	1242	YCBB 1	1345	YUHB 1	1232
NCHB 2	1242	YCBB 2	1345	YUHB 2	1170
NCHB 3	1242	YCBB 3	1345	YUHB 3	1170
NCHF 1	1242	YCBF 1	1345	YUHF 1	1330
NCHF 2	1242	YCBF 2	1345	YUHF 2	1293
NCHF 3	1242	YCBF 3	1345	YUHF 3	1293

anticipated, excess seed was applied to those plots seeded first. At the initial application rate, insufficient seed mix would be available to seed all plots. Therefore, the duration of seeding was reduced for plots seeded later. The actual time of hydroseed application in each plot was used to calculate PLS rates via the following equation:

$$\mathrm{PLS}\,(\mathrm{m}^{-2}) = \frac{(T_p/T_t)(S_t)}{A}$$

where T_p is the time of application within a given plot, T_t is the total time of hydroseed application, S_t is the total seeds placed in the hydroseeder, and A is the plot area. These calculations apply to both cleaned and uncleaned hydroseed treatments, as one tank of hydroseed was applied for each seed type. The estimated seeding rate for hydroseeded plots varied from 1071 to 1848 PLS m^{-2}, as shown in Table 2.

Broadcast seeding was accomplished with a push-style broadcast spreader (The Scotts Company, Marysville, OH). The seeding rate for broadcast-seeded plots was the nominal rate (i.e. 1345 PLS m^{-2}). The total amount of seed for each plot was placed in the spreader, and spread throughout each plot.

2.4. Irrigation management

Sprinkler irrigation was applied daily for the first 22 days after seeding for 6–14 h. Sprinklers were managed to keep the soil surface moist throughout the day while minimizing ponding – individual sprinkler laterals were shut off as needed. Daily applied water for sprinkler irrigation averaged 2 cm day^{-1}. Sprinklers were removed 22 days after seeding, and all plots were subsequently irrigated with the gated pipe.

For the first 10 days after seeding, surface irrigation plots were irrigated daily. Between day 10 and day 25, surface irrigation was applied every other day. To promote wetting of the entire width of the furrow beds, furrowed plots were filled to approximately 75% of capacity. Likewise, border plots were irrigated until they were 60–75% inundated. On the first day of irrigation, approximately 15 and 9 cm of water were required for border and furrow plots, respectively. Thereafter, approximately 3–5 cm of applied water was applied to surface-irrigated plots during each irrigation event for the first 25 days. Although this irrigation rates is excessive compared to estimated evapotranspiration (reference evapotranspiration was estimated at 1 cm day^{-1}), this depth was needed to wet the entire plot area for seedlings and to ensure that near-surface soil remained moist between irrigation events.

It was planned to reduce the irrigation frequency slowly over the course of the growing season to correspond to increasing rooting depth. During June and July (the first two months after seeding), the maximum gap between irrigation events was eight days. During August and September, gaps of greater than 10 days occurred on four occasions. Additionally, the irrigation contractor used a large-scale irrigation culvert on four occasions during the growing season, which likely resulted in uneven distribution of water between plots during these irrigation events. For subsequent growing seasons, irrigation rates were reduced to 80% or less of reference evapotranspiration, with water applied at experimental frequencies.

2.5. Vegetation monitoring

Vegetation monitoring consisted of cover measurements and quadrat analysis. One sample type was located randomly within each third of the plot. Point transects on one foot – (30.5 cm) intervals were surveyed to determine crown and canopy cover, and 0.5 m^2 (1 m by 0.5 m) quadrats were harvested to determine tree density, height, and above-ground dry biomass. The first vegetation survey was implemented in September 2007, after approximately four months of growth. Thereafter, plots were surveyed twice per year, at the approximate beginning and end of the growing season. Species-specific data were analyzed for seeded riparian species (FC, GW, and CW) and saltcedar.

2.6. Statistical analysis

Linear analysis of variance (ANOVA) modeling was accomplished through use of JMP V 9 (SAS Institute, Cary, NC) to determine the impacts of treatments on cover, stem density, height, and biomass. To simplify data analysis and results presentation, seeding and surface irrigation method combinations were paired, resulting in 6 "seeding/surface irrigation method" combinations. Significant treatment effects and interactions on a given result were determined by *F*-tests. Least-squared means were compared via Student's *t*-tests to determine significant differences at $\alpha = 0.05$ between treatments. To compare overall vegetation density and biomass between species, paired Student's *t*-tests were conducted to determine significant differences at $\alpha = 0.05$. To compare overall vegetation cover between species, *z*-tests were conducted on proportion test statistics to determine significant differences at $\alpha = 0.05$.

3. Results

3.1. Vegetation establishment and growth for the first growing season

FC tree density (per plot) ranged from 0 to over 59 m^{-2} at the end of the first growing season. The average FC stem density was approximately 18 m^{-2} (7% of PLS). GW was observed in quadrats of twelve plots, with an overall establishment of approximately 0.08% of PLS. CW was observed in quadrats of six plots, with an overall establishment rate of approximately 0.05% of seeded PLS rates. Because the quadrat sampling size was designed for high plant establishment, the survey methods may have limited effective characterization of GW and CW. The maximum FC dry biomass was 220.3 g m^{-2}, with an average of 45.2 g m^{-2}. The maximum GW dry biomass was 5.6 g m^{-2}, with an average of 0.46 g m^{-2}, and the maximum CW dry biomass was 1.9 g m^{-2}, with an average of 0.14 g m^{-2}.

Bermudagrass (*Cynodon dactylon*) established immediately after irrigation, and exhibited superior initial growth rates to tree seedlings. Arrow 2EC (Arysta LifeScience North America, LLC, Cary, North Carolina) grass-specific herbicide was applied approximately 5 weeks after seeding. Thereafter, jungle rice (*Echinochloa colona*), other grasses, and fragrant flatsedge (*Cyperus odoratus*) increased in abundance, and, despite additional application of grass-specific herbicide, composed the majority of crown cover (average of 82.3%) and biomass (average of 437.6 g m^{-2}) after four months of growth.

Saltcedar establishment ranged from 2 to 70 m^{-2}, with an average of 25 m^{-2}. Saltcedar dry biomass was as high as 93.5 g m^{-2}, with an average of 20.1 g m^{-2}. Overall saltcedar density was greater than that of FC after four months ($P < 0.05$, Fig. 2). However, FC crown cover was greater than that of saltcedar ($P < 0.05$, Table 3). Likewise, overall biomass of FC was greater than that of saltcedar ($P < 0.05$, paired Student's *t*-test). These results indicate that although saltcedar density was greater than that of FC, saltcedar was primarily in the understory and FC growth rates were higher during the first growing season.

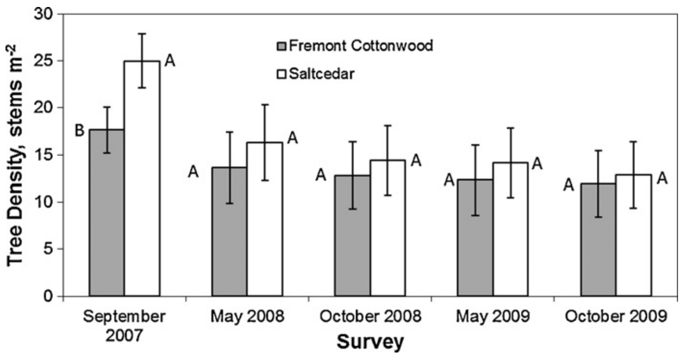

Fig. 2. Fremont cottonwood and saltcedar density through three growing seasons in small-scale field study plots of Salicaceae direct seeding. Error bars encompass one standard error, letters indicate significant differences for a given survey at $\alpha = 0.05$ according to matched-pairs *t*-tests.

Sprinkler irrigation reduced FC and saltcedar crown and canopy cover, and the canopy cover of GW and CW (Tables 3 and 4). Grass and sedge biomass did not increase with sprinkler irrigation (Table 5), indicating that grass growth was similar between sprinkler treatments ($P > 0.05$). Establishment of FC, GW, and CW was unaffected by sprinkler irrigation ($P > 0.05$, Table 6). However, saltcedar establishment decreased by approximately 50% with sprinkler irrigation ($P < 0.05$, Table 6). The biomass of both FC and saltcedar significantly decreased with sprinkler irrigation by approximately 70% and 80%, respectively, compared to surface irrigation ($P < 0.05$, Table 5), and the average height of FC and saltcedar was reduced ($P < 0.05$, Table 7).

Table 3
Linear ANOVA modeling results for field study of Salicaceae direct seeding after one growing season, seeded species cover.

Results		Crown cover		Canopy cover					
		Fremont cottonwood		Fremont cottonwood		Gooding's willow		Coyote willow	
Effect tests	d.f.	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Sprinkler treatment	1	28.10	<0.0001	17.43	0.0005	5.71	0.0268	5.00	0.0369
Seed/irrigation method	5	1.73	0.1734	2.99	0.0356	16.00	<.0001	2.33	0.0801
Sprinklers × seed/irrigation method	5	1.74	0.1723	1.65	0.1921	10.00	<0.0001	2.33	0.0801
Sprinkler treatment	Least-squared means and significant differences[a]								
No sprinklers	1	0.12A		0.22A		0.01A		0.003A	
Sprinklers	1	0.04B		0.10B		0.00B		0.000B	
Seeding/surface irrigation method									
Uncleaned hydroseed border	5	0.09AB		0.20A		0.00B		0.000B	
Uncleaned hydroseed furrow	5	0.09AB		0.21A		0.02A		0.005A	
Cleaned hydroseed border	5	0.11A		0.19AB		0.00B		0.000B	
Cleaned hydroseed furrow	5	0.06AB		0.11BC		0.00B		0.003AB	
Cleaned broadcast border	5	0.04B		0.07C		0.00B		0.000B	
Cleaned broadcast furrow	5	0.08AB		0.17AB		0.01B		0.000B	

[a] Numbers denote least-squared means, letters denote significant differences at $\alpha = 0.05$ within each column according to least-squared means differences Student's *t*-test.

Table 4
Linear ANOVA modeling results for volunteer species during the field study of Salicaceae direct seeding after one growing season.

Results		Crown cover						Canopy cover					
		Saltcedar		Grass and sedge		Shrubs and forbs		Saltcedar		Grass and sedge		Shrubs and forbs	
Effect tests	d.f.	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Sprinklers	1	18.99	0.0003	28.01	<0.0001	1.36	0.2584	56.47	<0.0001	4.43	0.0481	5.14	0.0347
Seed/irrigation method	5	0.53	0.5280	0.54	0.7452	1.05	0.4192	0.92	0.4881	1.20	0.3443	1.45	0.2486
Sprinklers × seed/irrigation method	5	0.16	0.1610	2.33	0.0809	0.99	0.4524	1.66	0.1906	1.70	0.1802	2.10	0.1071
Sprinklers	Least-squared means and significant differences[a]												
No sprinklers	1	0.07A		0.73B		0.07A		0.30A		0.90B		0.51A	
Sprinklers	1	0.01B		0.89A		0.05A		0.07B		0.94A		0.43B	

[a] Numbers denote least-squared means, letters denote significant differences within each column at $\alpha = 0.05$ according to least-squared means differences Student's *t*-test.

Table 5
Linear ANOVA modeling results for study of Salicaceae direct seeding after one growing season, above-ground dry biomass.

Results		Above-ground dry biomass ($g\,m^{-2}$)											
		Fremont cottonwood		Gooding's willow		Coyote willow		Saltcedar		Grass and sedge		Shrubs and forbs	
Effect tests	d.f.	F	P	F	P	F	P	F	P	F	P	F	P
Sprinklers	1	14.26	0.0012	2.94	0.1019	1.10	0.3062	13.01	0.0018	0.09	0.7733	3.34	0.0828
Seed/irrigation method	5	1.73	0.1746	3.57	0.0180	0.85	0.5322	0.89	0.5033	1.56	0.2157	0.41	0.8346
Sprinklers × seed/irrigation method	5	1.56	0.2176	3.62	0.0172	0.64	0.6711	0.80	0.5601	0.65	0.6623	1.51	0.2307
Sprinklers	Least-squared means and significant differences[a]												
No sprinklers	1	71.45A		0.73A		0.21A		32.43A		429.70A		105.99A	
Sprinklers	1	18.94B		0.19A		0.06A		7.77B		445.54A		58.58A	
Seeding/surface irrigation method													
Uncleaned hydroseed border	5	63.44A		0.04B		0.16A		24.82A		288.71B		110.70A	
Uncleaned hydroseed furrow	5	66.28A		1.89A		0.33A		18.03A		485.44A		63.26A	
Cleaned hydroseed border	5	31.76AB		0.07B		0.01A		13.08A		511.86A		55.64A	
Cleaned hydroseed furrow	5	41.49AB		0.43B		0.32A		33.88A		393.23AB		85.68A	
Cleaned broadcast border	5	8.76B		0.01B		0.00A		13.99A		472.23AB		96.16A	
Cleaned broadcast furrow	5	59.46A		0.31B		0.00A		16.80A		474.24A		82.27A	

[a] Numbers denote least-squared means, letters denote significant differences within each column at $\alpha = 0.05$ according to least-squared means differences Student's *t*-test.

Table 6
Linear ANOVA modeling results for field study of Salicaceae direct seeding after one growing season, seeded and saltcedar vegetation density.

Results		Density, stems m^{-2}							
		Fremont cottonwood		Gooding's willow		Coyote willow		Saltcedar	
Effect tests	d.f.	F	P	F	P	F	P	F	P
Sprinkler treatment	1	0.08	0.7832	0.66	0.4264	2.50	0.1295	19.78	0.0006
Seed/irrigation method	5	2.43	0.0704	3.34	0.0235	0.76	0.5890	2.16	0.0997
Sprinklers × seed/irrigation method	5	3.03	0.0338	1.19	0.3506	0.88	0.5123	1.84	0.1501
Sprinkler treatment	Least-squared means and significant differences[a]								
No sprinklers	1	18.2A		0.56A		0.44A		33.8A	
Sprinklers	1	17.1A		0.33A		0.07A		16.1B	
Seeding/surface irrigation method									
Uncleaned hydroseed border	5	24.9A		0.22B		0.44A		39.0A	
Uncleaned hydroseed furrow	5	22.9AB		1.67A		0.44A		21.0B	
Cleaned hydroseed border	5	12.1AB		0.11B		0.11A		25.6AB	
Cleaned hydroseed furrow	5	9.6B		0.44B		0.56A		26.6AB	
Cleaned broadcast border	5	12.0AB		0.11B		0.00A		21.0B	
Cleaned broadcast furrow	5	24.3A		0.11B		0.00A		16.7B	

[a] Numbers denote least-squared means, letters denote significant differences within each column at $\alpha = 0.05$ according to least-squared means differences Student's *t*-test.

Effects of seeding and surface (non-sprinkler) irrigation methods are described below. As no significant effects were observed for volunteer species cover ($P > 0.05$, Table 4) or above-ground dry biomass ($P > 0.05$, Table 5), these results are not discussed in detail.

Under border irrigation treatments, FC canopy cover was higher for uncleaned hydroseed and cleaned hydroseed than for cleaned broadcast ($P < 0.05$, Table 3). Canopy cover of GW and CW did not vary significantly between seeding methods for border irrigation ($P > 0.05$, Table 3). FC above-ground dry biomass was significantly higher for uncleaned hydroseed than cleaned broadcast ($P < 0.05$, Table 5), whereas cleaned hydroseed biomass was not significantly different from other seeding methods ($P > 0.05$, Table 5). GW and CW biomass did not differ between seeding methods ($P > 0.05$, Table 5). For border irrigation, no significant differences were observed in seeded species establishment between seeding methods ($P > 0.05$, Table 6).

Under furrow irrigation treatments, FC canopy cover was higher for uncleaned hydroseed than cleaned hydroseed ($P > 0.05$, Table 3), whereas FC canopy cover for cleaned broadcast was not significantly different from other seeding methods ($P > 0.05$, Table 3). Canopy cover of GW was higher for uncleaned hydroseed than other seeding methods ($P < 0.05$, Table 3). CW canopy cover was

Table 7
Linear ANOVA modeling results for field study of Salicaceae direct seeding after one growing season, Fremont cottonwood and saltcedar height.

Results		Average height, cm			
		Fremont cottonwood		Saltcedar	
Effect tests	d.f.	F	P	F	P
Sprinkler treatment	1	27.85	<0.0001	3.78	0.0662
Seed/irrigation method	5	1.67	0.1923	0.23	0.9442
Sprinklers × seed/irrigation method	5	0.43	0.8239	1.44	0.2521
Sprinkler treatment	Least-squared means and significant differences[a]				
No sprinklers	1	63A		31.0A	
Sprinklers	1	31B		25.2A	

[a] Numbers denote least-squared means, letters denote significant differences within each column at $\alpha = 0.05$ according to least-squared means differences Student's *t*-test.

Table 8
Crown and canopy cover trends for 2007 Salicaceae seeding trials conducted at Cibola National Wildlife Refuge, Cibola, Arizona. Cover codes indicate Fremont cottonwood (FC), saltcedar (SC), grasses and sedges (G/S) and shrubs and forbs (S/F). Letters indicate significant differences within columns at $\alpha = 0.05$ based on z-test proportion statistics.

Survey cover	September 2007		May 2008		October 2008		May 2009		October 2009	
	Crown	Canopy	Crown	Canopy	Crown	Canopy	Crown	Canopy	Crown	Canopy
FC	0.08B	0.16D	0.41A	0.42B	0.57A	0.60B	0.63A	0.64A	0.70A	0.72A
SC	0.04D	0.18C	0.10D	0.26C	0.12C	0.36C	0.12C	0.31C	0.12C	0.37C
G/S	0.81A	0.92A	0.32B	0.61A	0.21B	0.71A	0.21B	0.59B	0.15B	0.59B
S/F	0.06C	0.47B	0.14C	0.63A	0.09D	0.24D	0.00D	0.01D	0.00D	0.02D

greater for uncleaned hydroseed than cleaned broadcast ($P < 0.05$, Table 3), and CW canopy cover for cleaned hydroseed was not significantly different from other seeding methods ($P > 0.05$, Table 3). GW above-ground dry biomass was significantly higher for uncleaned hydroseed than cleaned hydroseed or cleaned broadcast ($P < 0.05$, Table 5). FC and CW biomass did not differ between seeding methods ($P > 0.05$, Table 5).

For furrow irrigation, FC establishment was greater for cleaned broadcast furrow than cleaned hydroseed ($P < 0.05$, Table 6), whereas uncleaned hydroseed tree density was not significantly different from other seeding methods ($P > 0.05$, Table 6). GW tree density was greater for uncleaned hydroseed than cleaned hydroseed or cleaned broadcast treatments ($P < 0.05$, Table 6). CW density did not vary between seeding treatments ($P > 0.05$, Table 6). However, it is of note that no GW or CW was observed within any quadrats of sprinkler-irrigated, cleaned seed, broadcast treatments.

Furrow irrigation resulted in higher FC canopy cover ($P < 0.05$, Table 3) and above ground dry biomass ($P < 0.05$, Table 5) compared to border irrigation for broadcast cleaned seed, and higher GW and CW canopy cover for uncleaned hydroseed ($P < 0.05$, Table 3). GW biomass (Table 5) and tree density (Table 6) were also significantly greater ($P < 0.05$) for furrow irrigation than border irrigation for uncleaned hydroseed. Surface irrigation method did not have consistent effects on volunteer species.

3.2. Vegetation dynamics for the first three growing seasons

Crown and canopy cover trends over the first three growing seasons are shown in Table 8. Fremont cottonwood crown cover after four months was less than 10%. However, FC crown cover increased to approximately 70% after three growing seasons by growing over saltcedar and other volunteer species. FC canopy cover was less than all other cover types after four months ($P < 0.05$, Table 8), but was greater than all other canopy types by the third growing season ($P < 0.05$, Table 8). Saltcedar crown cover increased

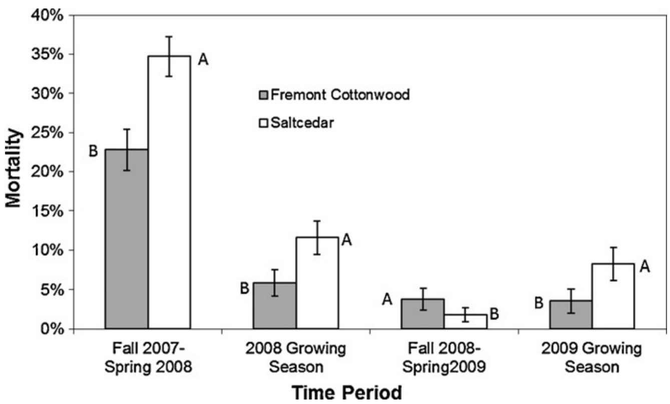

Fig. 3. Fremont cottonwood and saltcedar mortality between vegetation surveys in small-scale field study plots of Salicaceae direct seeding. Error bars encompass one standard error, letters indicate significant differences for a given time period at $\alpha = 0.05$ according to z-test proportion statistics.

from less than 5% to approximately 10% over the first dormant season (winter 2007–2008), but has remained at approximately 10% since. Total canopy cover of saltcedar increased from approximately 8% after four months to 37% after three growing seasons. Canopy cover of grasses and sedges decreased from greater than 80% after four months to approximately 60% after three growing seasons. Despite a canopy cover of nearly 50% after four months, canopy cover of shrubs and forbs decreased to less than 5% by the third growing season.

Mortality between survey efforts is shown in Fig. 3. Saltcedar mortality was greater than that of FC for all periods except the winter of 2008–2009, when FC mortality was greater ($P < 0.05$, Fig. 3). Summarized tree density data for FC and saltcedar are provided in Fig. 2. After four months of growth (September 2007), the density of saltcedar was significantly greater than that of FC ($P < 0.05$, Fig. 3). However, after the first winter and through at least three growing seasons (September 2009), density of FC and saltcedar was no longer significantly different ($P > 0.05$, paired Student's t-test) due to higher saltcedar mortality.

4. Discussion and conclusions

FC establishment was approximately 7% of PLS rates during the first growing season, whereas GW and CW establishment was less than 1% of PLS rates. Volunteer species (primarily grasses and sedges) dominated biomass, and saltcedar density was greater than that of FC, GW, or CW. Similar dominance by volunteer vegetation has been observed for other re-vegetation efforts on former agricultural land (Banerjee et al., 2006). For the Cibola NWR study plot area, irrigation water travels approximately 2.75 km in an open ditch through areas dominated by saltcedar, which actively disperses seed throughout the summer. Consequently, it is likely that irrigation water carried the majority of the saltcedar seed that invaded the plots. This observation is supported by the reduction of saltcedar in sprinkler-irrigated plots, as an in-line filter was used for the sprinkler system. Saltcedar seed sources near restoration sites should be reduced to limit their establishment, particularly for revegetation by direct seeding.

Although early-time sprinkler irrigation minimized overland irrigation flow, growth rates were reduced for both seeded species and saltcedar with sprinkler irrigation compared to surface irrigation only. The cause cannot be determined, but it is possible that physical injury of seedlings due to the water droplets impacts, soil water logging, and/or increased near-surface soil salinity due to near-surface evapoconcentration caused stress in seedlings. Plant establishment was not significantly affected by sprinkler irrigation. Thus, results indicate that sprinkler irrigation is not necessary for direct seeding of these species.

Hydroseeding did not consistently increase establishment of the desired riparian tree species compared to broadcast seeding. Hydroseeding of uncleaned seed might remain the preferred seeding method because less seed preparation effort is required. However, broadcast seeding might be an effective method where hydroseeding is logistically or economically prohibited.

Furrow irrigation did not increase FC or CW establishment in study plots. Establishment on furrowed plots was primarily on the side-slope of furrows near the high water mark during irrigation, and sometimes linear along furrows. Salt accumulation likely limited establishment on furrow crests, whereas establishment in the bottom of furrows was likely reduced due to regular inundation during irrigation events. Visually, the distribution of FC within furrow-irrigated plots was more even than in border-irrigated plots; regular distribution was observed along the high-water mark on the sides of furrows, whereas open space of several square meters was common in border-irrigated plots. This observation is supported by higher FC canopy cover in furrowed plots than border plots for cleaned broadcast seeding, and GW and CW canopy cover for uncleaned hydroseed. Therefore, furrowing is likely a more favorable method of surface irrigation for direct seeding, especially if broadcasting is the selected seeding method. Larger-scale research plots are necessary to confirm this speculation.

Higher survival and growth rates of FC compared to saltcedar through three growing seasons indicates that, despite higher initial establishment of saltcedar than FC, FC is outcompeting saltcedar. During the first three growing seasons, FC grew above other vegetation types, and has essentially replaced grasses, sedges, shrubs, and forbs in the crown. Similar values of crown and canopy cover for FC after three growing seasons indicate that this species dominates the overstory. Additionally, FC survival has been greater than that of saltcedar.

Superior growth of FC and plains cottonwood (*Populus deltoides*) compared to saltcedar has been observed in several other seedling studies (e.g. Marler et al., 2001; Sher et al., 2000, 2002; Sher and Marshall, 2003). Other studies in Arizona have shown that given shallow, fresh ground water, FC has been observed to maintain dominance over saltcedar in mature stands (Lite and Stromberg, 2005; Stromberg et al., 2006). Typically, only under adverse (e.g. saline) conditions does saltcedar have a competitive advantage over GW and FC (Glenn et al., 1998; Glenn and Nagler, 2005; Vandersande et al., 2001).

Results to date from this study indicate that FC tree communities can likely be successfully re-vegetated by direct seeding. Direct seeding could enhance genetic and structural diversity while significantly reducing re-vegetation costs compared to outplanting of nursery stock. Study results for GW and CW were inconclusive, and further seeding studies will be needed to determine direct seeding feasibility for these species. Specifically, consistent irrigation, removal of FC from the seed mix, and enhanced volunteer species control might improve establishment of GW and CW. GW has been observed to be more sensitive to soil moisture decline than CW (e.g. Hartwell et al., 2010). Contradicting observations exist regarding the comparative growth rates of FC, GW, and saltcedar. Shoot and root growth of rooted FC and GW cuttings for a period of approximately 70 days was observed to be similar, and greater than that of saltcedar (Vandersande et al., 2001); however, shoot and root growth in seedlings of FC has been observed to be superior to GW, with GW growth superior to saltcedar (Marler et al., 2001). Site-specific growing conditions (e.g. light, soil water, and nutrient abundance) and propagation methods likely affect comparative above and below-ground growth rates, and therefore resource availability.

To enhance the potential for success with seeding of any of these riparian tree species, grass growth should be controlled during the first growing season. Minimizing saltcedar seed sources adjacent to restoration plots will also limit initial establishment and long-term saltcedar density. However, saltcedar was outcompeted after three growing seasons, indicating that saltcedar exclusion may not be necessary to ensure dominance by native species.

Role of the funding source

This project was funded by the Bureau of Reclamation, Lower Colorado Regional Office in Boulder City, Nevada through the LCR Multi-Species Conservation Program (MSCP). LCR MSCP project managers and directors within the Restoration Group provided input on the study design and selection of treatment variables, and assisted with the interpretation of results.

Acknowledgements

We thank the Bureau of Reclamation for ongoing support for this project. Thanks to Cibola National Wildlife Refuge, Bill Williams River National Wildlife Refuge, and the Colorado River Indian Tribes for allowing access for seed collection. We thank the University of Arizona Southwest Center for Natural Products Research and Commercialization, and specifically Dr. Leslie Gunatilaka for use of facilities and equipment.

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