Native Plant Regeneration on Abandoned Desert Farmland: Effects of Irrigation, Soil Preparation, and Amendments on Seedling Establishment

Monisha J. Banerjee,[1,2] Vanda J. Gerhart,[1] and Edward P. Glenn[1]

Abstract

Direct seeding methods to revegetate abandoned farmland were tested at a desert site west of Phoenix, Arizona. Native seeds were broadcast onto plots prepared by mulching, imprinting, chiseling, and fertilizing with phosphorous in a split-plot design. Each main plot was split into subplots that were not irrigated, irrigated with saline (3.25 dS/m) well water, or irrigated and hand weeded of *Salsola iberica*. Native seeds germinated poorly on all treatments, and three annual exotic weeds (*Brassica nigra*, *S. iberica*, and *Schismus* spp.) dominated the plots. None of the main plot treatments (mulching, imprinting, chiseling, or fertilizing) had a significant effect on seed germination or canopy cover. Irrigation increased plant cover on plots, but weeds dominated the cover (<4% native species, up to 50% weeds). Near the end of the second growing season a seed bank study was conducted in the greenhouse. Undisturbed desert soil had relatively few weed seeds and more native plant seeds than the disturbed agricultural soil samples, which had few viable native seeds and were dominated by *Schismus* spp., *B. nigra*, and *S. iberica*. The results illustrate the difficulty of establishing native plants on abandoned desert farmland due to the dominance of weedy species, the presence of salts in the soil, and the lack of adequate soil moisture in the treatments without supplemental irrigation.

Key words: ***Brassica nigra*, desert agriculture, restoration, revegetation, *Salsola iberica*, Schismus spp., weeds.**

Introduction

Disturbed land in the southwestern United States is the source of numerous environmental and ecological problems due to their saline soils and susceptibility to flooding and erosion (Allen 1988, 1995; Roundy et al. 2001). For example, wind erosion can produce large-scale dust storms that degrade air quality and cause traffic accidents, whereas floods can cut deep gullies in the landscape. Sealed and compacted soil surfaces limit water infiltration and percolation and cause sheet flooding. In Arizona, over 400,000 ha of once-irrigated farmland have been abandoned since the 1950s (Charney & Woodward 1990). Revegetation of this land with native plants is desirable but difficult (Roundy et al. 2001).

Most revegetation efforts use dry seeding methods with various treatments added to enhance germination and establishment (Munshower 1994; Le Floc'h et al. 1999; Anderson & Ostler 2002). Treatments include mulching, which decreases evaporation from the soil surface and may increase infiltration by slowing surface water movement, and chiseling, which increases infiltration and percolation and aerates the soil (Winkel & Roundy 1991; Winkel et al. 1991; Montalvo et al. 2002). Seed germination may also be enhanced by imprinting, a method in which small depressions are pressed into the soil to provide microcatchment sites for moisture and organic matter accumulation (Winkel & Roundy 1991; Roundy et al. 1992; Dixon 1995). Addition of fertilizer may also be helpful to restore natural nutrient cycles (Anderson & Ostler 2002). For example, phosphorous may become limiting due to the reduction of mycorrhizal fungi in cultivated soil (Atkinson et al. 2005; Plenchette et al. 2005).

Despite these soil preparation methods, dry seeding may be unreliable in locations with less than 200 mm/yr of rainfall (McKell 1986; Grantz et al. 1998; Le Houérou 2000). On the other hand, even low amounts of supplemental irrigation, applied at the right time, can reportedly improve the germination and establishment of native seeds (Roundy et al. 2001). For example, addition of 112 mm of irrigation water to a Mojave Desert site with natural annual precipitation of 130 mm markedly enhanced the germination of native shrubs over control plots without irrigation (Anderson & Ostler 2002).

The objective of this study was to determine the effectiveness of direct seeding for revegetating a 400-ha parcel of abandoned farmland in an arid environment near Phoenix, Arizona (Gerhart 2005). We examined the effects of supplemental irrigation and different land preparation methods on the establishment of native species and their interaction with weedy species. Experiments were conducted in replicated plot trials on abandoned farmland

[1] Department of Soil, Water, and Environmental Science, Environmental Research Laboratory, University of Arizona, 2601 East Airport Drive Tucson, AZ 85706, U.S.A.
[2] Address correspondence to Monisha Banerjee, email monisha@email.arizona.edu

and in a seed bank study in a greenhouse. Our hypothesis was that supplemental irrigation and land preparation would allow the establishment of native species in this arid environment.

Materials and Methods

Site Description

The experimental site was located at lat 33°19′21″N, long 112°50′1″W, elevation 250 m, in Arlington, Arizona, on the site of the Redhawk Power Plant owned by Pinnacle West Energy Corporation (PWE). PWE agreed to restore a portion of the site as part of an environmental offset to obtain permission to construct an electric generating facility (Gerhart 2005). The land consisted of former irrigated cotton fields that were farmed for 30 years and then abandoned in 1987.

The 1.2-ha test site used for this experiment was mainly bare soil, with a sparse annual growth of Russian thistle (*Salsola iberica*) in summer and Black mustard (*Brassica nigra*) and Mediterranean grass (*Schismus* spp.) in winter. The deep, well-drained soil is predominantly a saline-alkali Gilman loam (Hendricks 1986). Dominant shrubs in the surrounding, undisturbed landscape are Four-wing saltbush (*Atriplex canescens*), Desert saltbush (*A. polycarpa*), Creosote bush (*Larrea tridentata*), and White bursage (*Ambrosia dumosa*). Small trees found in the area included Blue palo verde (*Cercidium floridum*), Ironwood (*Olneya tesota*), Velvet mesquite (*Prosopis velutina*), and Catclaw acacia (*Acacia greggii*). The climate at this site is typically hot summers (average low of 23°C and high of 42°C), mild winters (average low 1°C and high of 19°C), and a seasonally variable, bimodal rainfall pattern. Average annual rainfall is 188 mm/yr divided between a summer monsoon season and a winter/early spring season (Arizona Meteorological Network [AZMET] 2004).

Methods for Direct Seeding Replicated Plot Experiment

In February 2002, the experimental site was disked to remove existing vegetation and divided into three equal-sized blocks. Treatments consisted of four soil preparation methods (mulching, imprinting, phosphorous fertilization, and chiseling) and three postseeding management methods (supplemental irrigation, supplemental irrigation with hand removal of *S. iberica*, and no irrigation or *S. iberica* removal). The experiment was laid out in a split-plot design (Fig. 1). Each block consisted of sixteen 9 × 9–m main plots treated with four soil preparation treatments combined in a four-way factorial arrangement (16 combinations of treatments including a control plot with no treatment). The design was repeated in each of the three blocks (total main plots = 48, each approximately 81 m^2). Each main plot was divided into three subplots that were not irrigated, irrigated, or irrigated and hand weeded of *S. iberica* (total subplots = 144). Treatments in main plots

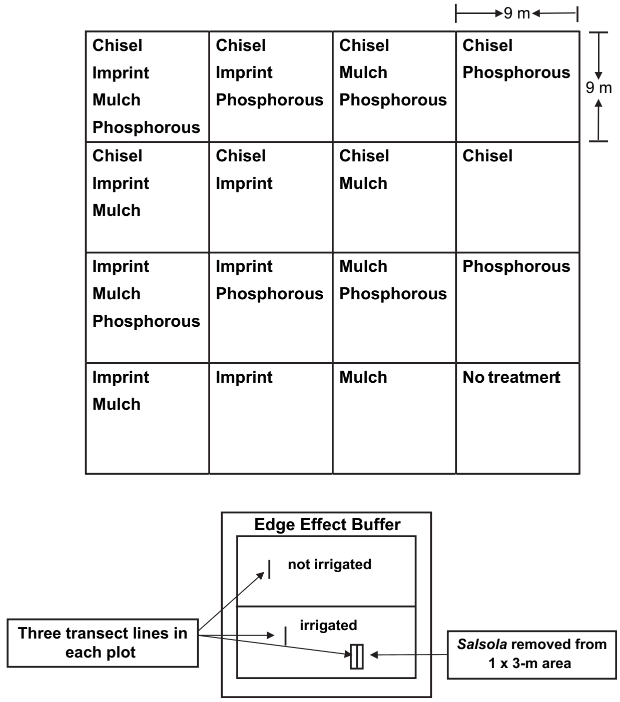

Figure 1. Top box—one of three blocks on a 1.2-ha test site on abandoned farmland in Arlington, Arizona. Sixteen 9 × 9–m plots were laid out in each block. Treatments were applied in vertical (mulch and imprint) or horizontal (chisel, phosphorous) strips across each replicate. Bottom box—split plot, showing the layout of irrigation and *S. iberica* removal treatments within each 9 × 9–m main plot.

were laid out in a systematic rather than a random way (Snedecor & Cochran 1989) to facilitate the use of a tractor in applying the soil treatments.

Soil preparation methods and rates of mulch and phosphate addition were based on recommendations in Munshower (1994). The soil was chiseled to a depth of 10 cm. Phosphate pellets (00-45-00) were applied at a rate of 105 kg/ha. Prior to seeding, the seeds were hand mixed with wheat bran at a rate of 28 kg/ha to prevent clumping. Then the whole site was broadcast seeded at a rate of 18 kg/ha (see Table 1 for the seed mix composition). Germination rates of all seeds were tested by the supplier, and seed rates were based on the percentage of pure live seeds of each species. Prior to sowing, we tested a sample of the seed mix (circa 10 g) for germination in a tray filled with a mixture of sand and mulch (3:1) set under a sprinkler in a greenhouse. Seeds of all species except *Haplopappus laricifolius* germinated. After seeding, a tractor pulled the 1.83-m-wide imprinter. Imprinting was followed by mulching with wheat straw at a rate of 25 kg/ha.

Half of each 9 × 9–m test plot was sprinkler irrigated and half was not irrigated. Sprinklers delivered 3.5–3.8 L/hr of water over an area of approximately 3 m^2. Plots were irrigated 0.5 hr/day from February 2002 to October 2003, at frequencies varying from five times per week from May to October to 1–2 times per week from November to

Table 1. Custom native seed mix used in direct seeding experiments to revegetate abandoned farmland in Arlington, Arizona.

Scientific Name	*Common Name*	*% of Seed mix*	*Viable Seeds/m²*
Shrubs			
Acacia greggii	Catclaw acacia	4.32	0.40
Ambrosia dumosa	White bursage	13.17	27.45
Atriplex canescens	Fourwing saltbush	7.54	8.39
A. lentiformis	Quailbush	1.42	20.17
A. polycarpa	Desert saltbush	2.88	32.28
Cassia covesii	Desert senna	2.59	8.87
Encelia farinosa	Brittlebush	1.85	7.06
Haplopappus laricifolius	Turpentine bush	1.82	*
Larrea tridentata	Creosote bush	22.22	38.74
Forb			
Baileya multiradiata	Desert marigold	1.42	42.76
Grasses			
Aristida purpurea	Purple three awn	2.36	20.21
Bouteloua aristidoides	Needle grama	4.46	66.83
Plantago insularis	Wooly Indian wheat	22.3	*
Inert matter		11.65	N/A

* indicates data not supplied by seed company. N/A = not applicable.

April; total application of water was about 100 mm over 15 months. The water source was a former agricultural well with an average salinity of 3.2 dS/m (range: 2.2–4.2 dS/m).

The *S. iberica* removal treatment was conducted in a 3 × 1–m area within each irrigated subplot. *Salsola iberica* plants were removed through September 2002 and then weeding was discontinued for the second growing season.

For all treatments, plants located in three 3 × 1–m quadrats were counted in each treatment subplot every 3 months beginning October 2002 to October 2003. Soil samples were also collected every 3 months and analyzed for electrical conductivity (EC, dS/m) and pH in 1:5 extracts and gravimetric moisture content. At the end of the experiment, plant cover was determined by the line intercept method in each quadrat by totaling the cover of each species along a 3-m measuring tape running the length of the quadrat through the middle of the plot.

Methods for Seed Bank Experiment

A seed bank study was conducted on surface soil collected from several treatments in the direct seeding experiment and from control sites. The soil samples were collected in August 2003 to determine how many viable native seeds remained in the seed bank 18 months after the initial sowing. Four soils were evaluated: (1) surrounding natural desert soil as a reference; (2) untreated abandoned farmland soil taken from an area adjacent to the direct seeded replicated plot experimental site; (3) unirrigated soil taken from seeded experimental plots; and (4) irrigated soil taken from seeded experimental plots.

Ten random soil samples were taken from each of the above conditions by collecting the top 3 cm of soil within a 50-cm^2 area with a trowel (four soil types × 10 replicates = 40 samples). 1.5 kg of each of the 40 soil samples were placed in 47 × 30 × 7–cm trays lined with plastic mesh to prevent soil loss. The trays were placed in a completely randomized design in a greenhouse and automatically watered by overhead sprinkler three times per day for 15 minutes for 2 months, and then daily for 15 minutes for the remainder of the experiment. As seedlings emerged they were identified and removed. The last seedlings were observed in January 2004 but the trays were kept in the greenhouse under irrigation until May 2004, but no additional germination occurred.

Statistical Analyses

The effects of soil treatments, irrigation, and removal of *S. iberica* on seedling establishment were tested by split-plot analysis of variance (ANOVA) where density of seedlings (plants/m^2) at each quarterly measurement period was the dependent variables (five sample events), soil preparation method was the main plot independent variable ($n = 16$ treatment combinations), and irrigation treatment was the split-plot independent variable ($n = 3$). For soil treatments (main plots), degrees of freedom (*df*) were 15 for soil treatment, and 30 for error (soil treatment *df* × block *df*); for irrigation treatments (subplots), *df* were 2 for treatment and 60 for error (soil treatment *df* × block *df* × irrigation treatment *df*). Each species encountered in the plots was analyzed separately and the total seedlings per plot were also analyzed. The same type of analysis was conducted on plant cover determined at the end of the experiment.

Emergence of seedlings in the seed bank experiment was compared by soil type ($n = 4$) with a one-way ANOVA. The *df* were 3 for treatment (soil type) and 36 for error. When ANOVAs were significant, individual treatment means were compared using the Tukey Honestly Significant Difference (HSD). Treatment effects and differences between individual means were tested for significance at the 95% confidence probability. Hence, throughout the text comparisons are declared significant if p was less than 0.05.

Weather Data and Other Sources of Information

Temperature and precipitation data for the Redhawk site were obtained from the AZMET. Plant identification was based on Epple (1995) and Whitson and Burrill (2000). Species that could not be identified were taken to the University of Arizona Herbarium for identification. Identification only to the genus level or no identification (in Seed Bank Experiment) occurred occasionally because flowers and/or fruits were not present. *Schismus* spp. could not be identified to the species level, but two species (*S. arabicus* and *S. barbatus*) are present in southwestern deserts (Brooks 2000).

Results

Meteorological Conditions during the Study Period

Figure 2 presents temperature and precipitation data for the study period. Seeds were sown during a period of relative drought; however, temperatures and precipitation during the data collection period (after October 2002) were close to the long-term mean based on data from the AZMET. In 2002, 94 mm of rain fell, of which 66 mm arrived in July through September in the summer monsoons and the rest arrived in fall or winter. In 2003, 225 mm of rain fell, of which 111 mm arrived in winter and 114 mm arrived in summer monsoons. Irrigation added approximately 40 mm of extra water during the summer season and 20 mm in winter to those plots equipped with sprinklers.

Seedling Density in Plot Experiment

Twenty-eight species germinated in the plots (1 native tree, 7 native shrubs, 1 native forb, 3 native grasses, 13 non-native forbs, and 3 non-native grasses), although only 12 were present at the end of the study (6 non-native forbs, 4 native shrubs, 1 native grass, and 1 non-native grass) (Table 2). ANOVA results for total seedlings at all sample dates are in Table 3. Blocks and interaction terms were not significant. None of the main plot treatments or combinations (chisel, imprint, mulch, phosphorous addition) had a significant effect on germination or survival of plants compared to untreated plots, but irrigation was significant (Fig. 3).

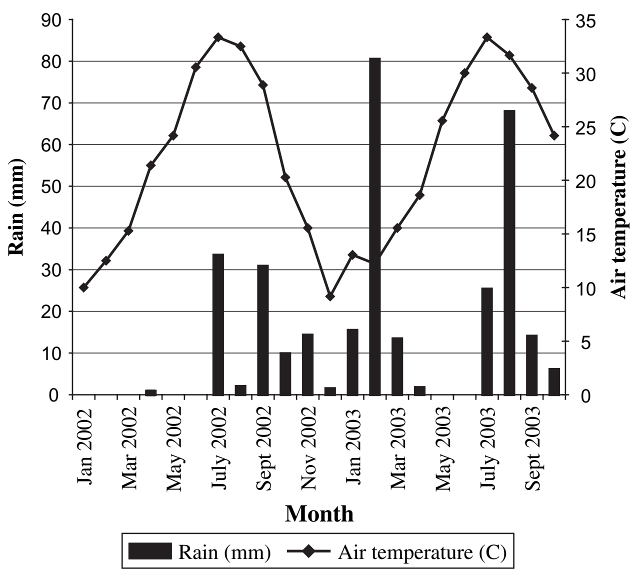

Figure 2. Weather data from January 2002 to October 2003 for an abandoned farm site in Arlington, Arizona. Data were averages from nearby monitoring stations in Buckeye and Harquahala, Arizona, obtained from the Arizona Meteorological Network during the revegetation experiment.

Table 2. Species list of plants that germinated in direct seeding experiment.

Scientific Name	*Common Name*
Native seeded shrubs	
Acacia greggii+	Catclaw acacia
Ambrosia dumosa	White bursage
Atriplex canescens+	Fourwing saltbush
A. lentiformis	Quailbush
Cassia covesii+	Desert senna
Encelia farinosa	Brittlebush
Larrea tridentata+	Creosote bush
Native seeded grasses and forb	
Aristada purpurea	Purple three awn
Baileya multiradiata	Desert marigold
Bouteloua aristidoides+	Needle grama
Plantago insularis	Wooly Indian wheat
Volunteer forbs	
*Alyssum alyssoides**	Yellow alyssum
*Amaranthus retroflexus**	Amaranth
A. elegens (rosea)+	Wheelscale saltbush
*Brassica nigra**	Black mustard
*Chamaesyce maculata**+	Prostrate and spotted spurge
*Erodium cicutarium**	Redstem filaree
Euphorbia spp.	Spurge
*Malva neglecta**	Common mallow
Pectis angustifolia+	Fetid marigold
*Salsola iberica**+	Russian thistle
*Sisymbrium irio**	London rocket
*Solanum elaeagnifolium**+	Silverleaf nightshade
*Trianthema portulacas**+	Horse purslane
Volunteer grasses	
*Cyanodon dactylon**+	Bermuda grass
*Eleusine indica**	Crab grass
Schismus spp. *(arabicus and barbatus)**	Mediterranean grass
Volunteer tree	
Prosopis velutina	Velvet mesquite

*indicate non-native species; + indicate species present in density plots in October 2003.

Germination and survival of native plants was less than 1 plant/m^2; by contrast, annual, non-native weedy species dominated the plots. Figure 4 shows the response of the most abundant exotic and native species to irrigation treatment. Irrigation increased the number of *Salsola iberica* plants, but decreased the number of *Brassica nigra* plants. Hand weeding of plots to remove *S. iberica* was only partially effective. During the first season, *S. iberica* was less abundant in the irrigated and weeded plots than in the irrigated plots, as expected. However, sufficient seeds existed in the soil so that new plants emerged 30 days after weeding. Although not shown in Figure 4, *Schismus* spp. (non-native, cool season annual grasses) germinated readily in the winter. They formed a nearly complete cover less than 2 cm in height in both irrigated and unirrigated plots during winter. Plant densities were greater than 1,000 per unirrigated plot and greater than 3,000 per irrigated plot. Another exotic annual, *Solanum*

Table 3. Results of a split-plot ANOVA for seedling emergence and plant cover, all species combined, on a 1.2-ha test site on abandoned farmland in Arlington, Arizona.

	Soil Treatments		*Irrigation Treatments*	
	$F_{[15,30]}$	p	$F_{[2,60]}$	p
October 2002	1.31	0.21	5.09	0.008
January 2003	0.39	0.99	21.5	0.000
April 2003	0.82	0.65	78.5	0.000
July 2003	0.76	0.72	82.0	0.000
October 2003	0.42	0.97	38.8	0.000
Plant Cover	0.33	0.99	87.8	0.000

Plant cover was measured at the end of the experiment in October 2003.

elaeagnifolium (not shown in Fig. 4) was present in low numbers at all measurement periods and in all treatments.

The only native plants that germinated with any abundance were two annual grasses, Needle grama grass (*Bouteloua aristidoides*) and Wooly Indian wheat grass (*Plantago insularis*). *Bouteloua aristidoides* is a warm season grass that was most numerous in plots in October. At the last measurement period, significantly more *B. aristidoides* were present in the unirrigated than in the irrigated plots (0.12 plants/m^2 under irrigation, 0.25 plants/m^2 without irrigation). Removal of *S. iberica* did not have a significant effect on *B. aristidoides* germination. *Plantago insularis*, a winter annual grass, was most abundant in January 2003. Removal of *S. iberica* in the irrigated plots significantly increased *P. insularis* (0.19 plants/m^2 without irrigation, 0.11 plants/m^2 with irrigation, 0.54 plants/m^2 with irrigation and removal of *S. iberica*). *Bouteloua aristidoides* appeared in both 2002 and 2003, so it apparently reproduced successfully in the plots.

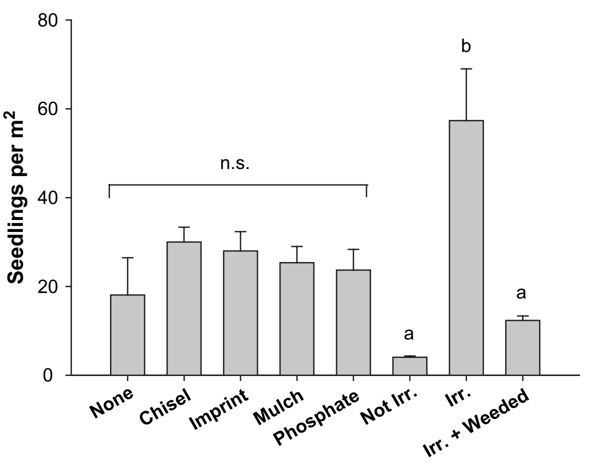

Figure 3. Seedling emergence in plots receiving soil and irrigation treatments on a 1.2-ha test site on abandoned farmland in Arlington, Arizona. Bars show means and standard errors of total seedlings in treatment plots averaged over all five sample dates ($n = 15$ replicates for control plots, $n = 48$ for treatment plots). Different letters over bars indicate means are significantly different at $p < 0.05$; n.s. = not significant.

Plant Cover in Plot Experiment

As with seedling density, the soil pretreatments did not have a significant effect on final plant cover, but the irrigation treatment was significant (Table 3). At the end of the experiment, native plants had less than 4% cover on the plots and nearly all the plant cover was due to *S. iberica* (Table 4). Weeding *S. iberica* from irrigated plots during the first season affected the final cover of *S. iberica* but not the other species. At the end of the experiment, unirrigated plots had 2% *S. iberica* cover, irrigated plots had 37% cover, and irrigated and weeded plots had 50% cover (all significantly different). Significantly fewer but larger *S. iberica* plants were on the irrigated and weeded plots (4 plants/m^2) compared to irrigated and unweeded plots (6 plants/m^2), whereas unirrigated plots averaged only 1 plant/m^2. *Bouteloua aristidoides* had significantly greater canopy coverage in plots without irrigation (3.5% cover) compared to irrigated plots (<0.1% cover).

Salinity and Moisture Content in Soils from the Replicated Plot Experiment

The salinity of the irrigation water was high, which contributed to soil salinity (Table 5). The irrigated soil was significantly more saline than the unirrigated soil. Soil moisture was higher in the irrigated plots than the unirrigated plots, but there was no significant difference in pH.

Seed Bank Experiment

The source of soil had a significant effect on total seedling emergence ($F_{[3,36]} = 30.0$, $p = 0.000$) and on emergence of 7 of the 27 species that germinated in trays (Table 6). The greatest number of seeds germinated in the unirrigated experimental soil (681 plants/kg soil) and irrigated experimental soil (415 plants/kg soil), whereas, at the low end, natural desert soil produced only 38 plants/kg soil. However, nearly all the seeds that germinated in the experimental soils were the non-native annuals that dominated the plots: *B. nigra*, *Schismus* spp., and *S. iberica*. Native plants germinated significantly more in the soil from untreated abandoned farmland taken from an area adjacent to the direct seeded experimental site ($\bar{X} = 23$ plants/kg soil) and the natural desert soil ($\bar{X} = 5$ plants/kg) than in either of the seeded experimental soils ($\bar{X}$s <1.0 plants/kg). *Salsola iberica* seeds germinated significantly more in the seeded soils than in the unseeded soils.

Discussion

The main finding of this study is that direct seeding, even with supplemental irrigation, may be an unreliable method to establish plant cover on abandoned arid agricultural land. Judging by the present results, abandoned farm soils can have a large reservoir of both summer and winter annual weed seeds in the topsoil, which readily germinate and outcompete native species for space and water

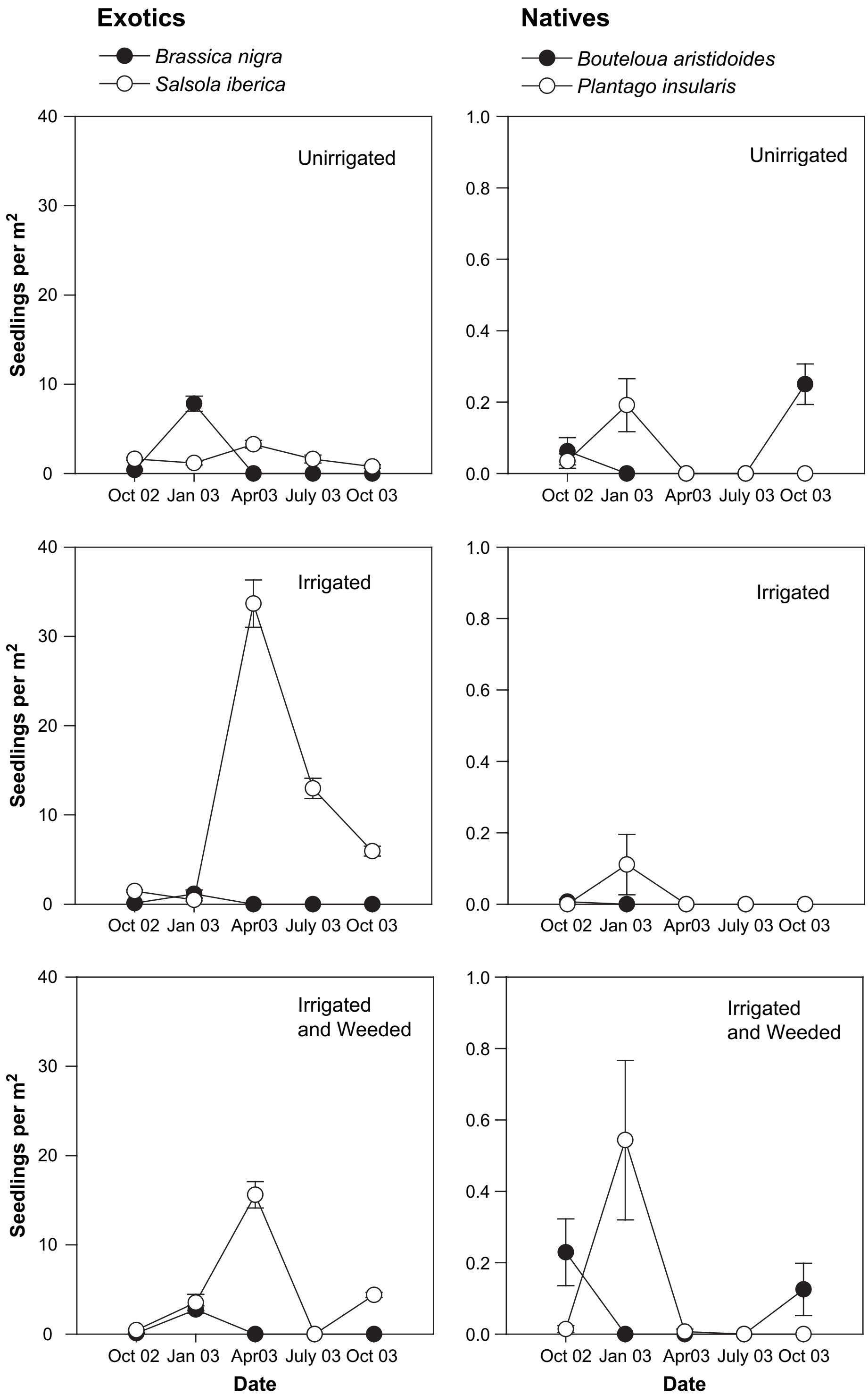

Figure 4. Time course of emergence and survival of non-native and native plants on a 1.2-ha test site on abandoned farmland in Arlington, Arizona. Results are for irrigated, unirrigated, and irrigated and weeded plots pooled across soil treatments at five sample dates ($n = 48$ replicates per treatment). Weeding was conducted in September 2002, to remove *S. iberica* plants. Bars show standard errors.

when irrigated. Irrigation in spring produced a cohort of *Salsola iberica* plants, which apparently outcompeted the native species in the seed mix. Similarly, winter irrigation produced a nearly complete cover of *Schismus* spp., which presumably also interfered with native seed germination. Another winter weed, *Brassica nigra*, germinated to a greater extent in unirrigated than in irrigated plots. Hence, native seeds faced competition from weeds under

Table 4. Ground cover (%) of plant species in unirrigated and irrigated plots on a 1.2-ha test site on abandoned farmland at Arlington, Arizona.

Treatment	*Unirrigated*	*Irrigated*
Native species		
Bouteloua aristidoides	3.51 (0.89) a	0.07 (0.07) b
Pectis angustifolia	0.27 (0.12) a	0 b
Cassia covesii	0.04 (0.04)	0
Allionia incarnata	0.16 (0.11)	0
Baileya multiradiata	0	0.02 (0.02)
Total natives	3.98 (0.95) a	0.028 (0.022) b
Non-native species		
Salsola iberica	2.01 (0.75) a	36.6 (3.15) b
Solanum elaeagnifolium	0.10 (0.06)	0.33 (0.16)
Cyanodon dactylon	0	0.07 (0.05)
Chamaesyce maculata	0.05 (0.05)	0
Trianthema portulacas	0	0.22 (0.22)
Total non-natives	2.15 (0.75) a	43.5 (3.1) b
Total Cover	6.1 (1.2) a	43.5 (3.1) b

Values are means of 10 replicates and standard errors. When results of an ANOVA were significant, means were separated with the Tukey HSD test; different letters after means denote a significant difference between unirrigated and irrigated plots at $p < 0.05$.

both irrigated and unirrigated plots and at all times of year.

Several factors may have contributed to the failure of native seeds to establish at this site, including high salinity, low soil moisture in the absence of irrigation, competition from weeds, and perhaps chemical and microbial factors. Native seed establishment may have been inhibited by the high soil salinity in both unirrigated and irrigated plots, equivalent to 6 g/kg soil and 13 g/kg soil on a dry weight basis, respectively. Moisture content was higher in irrigated than in unirrigated plots but was still well below field capacity for this soil (circa 0.15 g/g) and may have been yet another factor inhibiting native seed establishment. Furthermore, disturbing the soil in our seeded plots by disking may have aided the germination and establishment of weedy species. The soil microbial community, which presumably was altered by farming practices before the field was abandoned, may also have favored the establishment of weedy species over the natives. For example, desert plants often rely on mycorrhizal associations in the roots to aid in nutrient uptake and drought tolerance (He et al. 2002; Caravaca et al. 2005), and the fungal populations might have been disrupted by years of crop production followed by soil salinization (Atkinson et al. 2005).

Table 5. Average gravimetric moisture content, pH, and EC (dS/m) in soil samples from a 1.2-ha test site on abandoned farmland in Arlington, Arizona.

Constituent	*Unirrigated Plots*	*Irrigated Plots*
Moisture (g H_2O/g soil)	0.013 (0.0014) a	0.035 (0.003) b
pH	8.7 (0.5)	8.7 (0.5)
EC (dS/m)	1.99 (0.66) a	3.72 (0.65) b

EC and pH were determined in triplicate 1:5 soil:water extracts. Numbers in parentheses are standard errors of estimates ($n = 4$). Means followed by different letters within a row are significantly different at $p < 0.05$ by the Tukey HSD test.

Bouteloua aristidoides was the only native species that appeared to have successfully reproduced in the plots, but even for this species plant density was less than 1 m^2 and plant cover was less than 4%. Anderson and Ostler (2002) set a target value of 10 to 25 seedlings/m^2 1 year after seeding and plant cover of approximately 25% as the criteria for success in revegetating denuded military land in the Mojave Desert because seedlings suffered high attrition rates in subsequent years. By that criteria, none of the strategies tested in this study resulted in adequate establishment of native plants on this experimental test site. On the other hand, weed species density was up to 100 plants/m^2 and weeds composed up to 50% of the soil cover in irrigated treatments.

Since this site was abandoned 15 years before revegetation was attempted, yet lacked a significant native plant community at the start of the experiment, we can presume that the weedy plant community observed in this study persists for many years after farming is discontinued and becomes the dominant plant association. *Salsola iberica* outcompetes native plants when there is a limiting resource, such as water (Allen 1982; McKell 1986). By removing *S. iberica* by hand in one treatment, we hoped to reduce competition to allow native species to germinate. On a large scale, this could be accomplished by cultivating the land or applying herbicides to kill *S. iberica* prior to sowing native seeds. However, sufficient *S. iberica* seeds existed in the seed bank or were replenished by nearby plants for reemergence to occur during the second growing season, even after the standing crop was removed. By the end of the study, *S. iberica* constituted more of the canopy cover in the plots where it was removed than in the plots where it was not. Disturbance caused by *S. iberica* removal may have facilitated further *S. iberica* germination and growth (Allen 1982; Schillinger & Young 2000).

Few viable, native seeds were present in the seed bank of soil collected 18 months after sowing. As in the field, *B. nigra*, *Schismus* spp., and *S. iberica* were the main plants that emerged in the seed bank experiment, despite the addition of native seeds to the soil. Native seeds may have germinated in the plots but not survived. Some may also have been removed by wind after sowing as we observed that mulch applied to the soil surface was removed by wind. By contrast, the initial disking would have mixed the weedy species into the surface, improving their conditions for germination.

In some studies, native plants have successfully been established on disturbed desert land with direct seeding and irrigation, even with low-quality water as was used here (Ries et al. 1988; Hall & Anderson 1999). Anderson and Ostler (2002) reported good results in establishing plants on disturbed, nonagricultural soil in Mojave Desert

Table 6. Mean number of viable seeds per kg soil in samples taken from abandoned farmland and from adjacent undisturbed desert soil in Arlington, Arizona.

Treatments	*Irrigated*	*Unirrigated*	*Ag*	*Desert*
Seeded species				
Ambrosia dumosa	0	0.07 (0.07)	0	0
Baileya multiradiata	0	0.07 (0.07)	0	0
Larrea tridentata	0	0.27 (0.20)	0	0.27
Plantago insularis	0 a	0.13 (0.09) a	23.3 (7.7) b	4.3 (2.1) a
Mean no. of seeded plants/kg soil	0 a	0.53 (0.28) a	23.3 (7.7) b	4.6 (2.0) a
Volunteer species				
Allionia incarnata	0	0	0.07 (0.07)	0
Bouteloua barbata	3.6 (2.4)	1.07 (0.45)	0.07 (0.07)	0
*Brassica nigra**	69.7 (12.2) a	57.6 (13.0) a	9.87 (3.58) b	0.20 (0.14) b
Camissonia spp.	0.04 (0.04)	0	0.13 (0.13)	0
*Chamaesyce maculata**	0.07 (0.07)	0	0	0
*Erodium cicutarium**	0.07 (0.07) a	0.07 (0.07) a	3.13 (1.10) b	0.53 (0.24) a
Euphorbia polycarpa	0.47 (0.14)	0.33 (0.21)	3.07 (2.42)	0
Lesquerella gordoni	0	0	0	0.07 (0.07)
*Malva neglecta**	0	0	0	0.07 (0.07)
Monolepis nuttaliana	0.07 (0.07)	0	0.13 (0.09)	0
Nama hispidium	0 a	0 a	0 a	10.13 (2.7) b
Oenoethera spp.	0.07 (0.07)	0	0	0
*Oligomeris linifolia**	0.20 (0.14)	0.07 (0.07)	5.07 (3.91)	2.47 (2.25)
*Oxalis corniculata**	4.73 (0.98)	1.00 (0.65)	2.73 (0.82)	1.73 (0.73)
Pectis papposa		0	0.53 (0.40)	0
P. angustifolia	0.07 (0.07)	0	0.07 (0.07)	0.07 (0.07)
*Salsola iberica**	10.20 (2.69) a	21.40 (5.82) a	0.67 (0.30) b	0 b
Schismus spp.*	325 (13) a	598 (57) b	414 (60) a	15 (3) c
*Solanum elaeagnifolium**	0	0.27 (0.27)	0	0
Sonchus spp.	0	0.13 (0.09)	0.67 (0.60)	0.07 (0.07)
*Tamarisk ramosissima**	0.07 (0.07) a	0 a	1.53 (0.88) b	2.80 (0.72) b
*Trianthema portulacas**	0	0	1.93 (1.93)	0
Unknowns	0.27 (0.15)	0.40 (0.18)	1.45 (0.62)	1.00 (0.32)
Mean volunteer plants/kg soil	415 (22) a	680 (69) b	443 (64) a	33.4 (3.5) c
Mean no. of plants/kg soil	415 (22) a	681 (69) b	467 (65) a	38.0 (5.0) c

Treatments were (1) irrigated soil from experimental plots (Irrigated); (2) unirrigated soil from experimental plots (Unirrigated); (3) soil from untreated abandoned farmland taken from an area adjacent to the experimental site (Ag); and (4) surrounding natural desert soil (Desert). Standard errors are in parentheses following means. Results for each species were subjected to one-way ANOVA with soil source as the independent variable; when the ANOVA was significant at $p < 0.05$, individual means were separated by Tukey HSD test. Means of 10 replicates followed by different letters are different at $p < 0.05$.
*Non-native species.

sites either with or without supplemental irrigation. Roundy et al. (2001) concluded that native plants could be established in summer with as little as 210 mm of irrigation plus precipitation in the Sonoran Desert. However, those studies were not conducted on abandoned farmland.

In other studies, direct seeding has been unsuccessful in areas with less than 250 mm/yr of annual rainfall. Grantz et al. (1998), working in the Mojave Desert, concluded that direct seeding without irrigation might be successful in favorable years but that in any given year it is likely to fail. Furthermore, plant establishment does not always increase with supplemental irrigation, even though seedling germination may increase initially (Ries et al. 1988; Gutiérrez 1992; Padgett et al. 2000). If only low-quality water is available, irrigation can contribute to increased soil salinity (Ries et al. 1988). Similar to our results, irrigation may also stimulate germination of weeds, such as *S. iberica* and *Schismus* spp., which dominate many disturbed sites (Allen 1982; Young 1991; Schillinger & Young 2000). Glenn et al. (2001) failed to establish adequate stands of native seeds on disturbed soil at a former uranium mill site in the Great Basin Desert using direct seeding with and without supplemental irrigation.

Soil pretreatments are often applied to increase the rate of germination and establishment in desert soils (Anderson & Ostler 2002). However, these treatments can be expensive, and in our study they did not increase seed germination, either in irrigated or in unirrigated plots. Soil pretreatments are as likely to stimulate weed germination as to enhance native seed germination (e.g., Brooks 2003).

Based on the present results and a review of the literature, direct seeding even with supplemental irrigation does not appear to be a reliable strategy for revegetating abandoned farmland in arid climates. A different combination of seeding and soil preparation methods, additional irrigation water, or higher quality water, might have stimulated more native seed germination in our study. However, strategies other than direct seeding should also be investigated for revegetating this type of land. For example, several studies have shown that transplanting and individually irrigating seedlings or rooted cuttings can reliably establish native shrubs through the first summer (McKell 1986; Call & Roundy 1991; Lash et al. 1999; Glenn et al. 2001; McKeon et al. 2005). At the Redhawk site, drip-irrigated *Atriplex canescens*, *A. polycarpa*, and *A. lentiformis* plants had high rates of survival and growth over 3 years (Gerhart 2005).

Water-concentrating techniques such as microcatchments and contour furrows have also been effective in establishing vegetation in arid climates (Eldridge et al. 2002; Gerhart 2005). Other innovative methods for improving native plant establishment include taking advantage of facilitative interactions among plants (Maestre et al. 2001), inoculating soil with mycorrhiza (Caravaca et al. 2002, 2005), planting drought-preconditioned seedlings (Vilagrosa et al. 2003), and protecting transplanted seedlings with treeshelters (Bellot et al. 2002). We recommend that pilot studies be conducted on a site before attempting large-scale revegetation and that the common practice of applying soil pretreatments followed by direct seeding of native species should be replaced or supplemented by more innovative methods for plant establishment on abandoned farmland in arid climates.

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