ABSTRACT

We found that the most effective and economical method for establishing native shrubs on extensive areas of retired cropland in southern Arizona makes use of drip irrigation and 3.8-l (1-gal) transplants (outplants). In March 2001, we established a small (8 ha [20 ac]) field trial to test the effectiveness of different combinations of transplanting, seeding, drip irrigation, and furrow irrigation. Treatments utilizing transplants and drip irrigation had higher survival and lower densities of weed species than other treatments tested. Based on these results, we planted again in November 2001 using drip-irrigated transplants to examine the effectiveness of this method over a larger scale (85 ha [210 ac]). As a further refinement of this method, we tested various sizes of container stock and determined that transplants of 3.8-l (1-gal) size had superior growth and survival when compared to smaller-sized transplants. The total cost of this method is approximately US$ 4430/ha ($1790/ac), but it is more likely to succeed as compared with direct seedings, which is a commonly used approach to revegetation in southwestern ecosystems. Although a drastic effort, our technique holds promise for revegetating environments in the hottest and driest parts of the Sonoran Desert in southern Arizona.

KEY WORDS

Ambrosia dumosa, Atriplex polycarpa, drip irrigation, *Larrea tridentata,* Sonoran Desert, transplants

NOMENCLATURE

ITIS (2002)

Intensive revegetation in

ARIZONA'S HOT DESERT

The advantages of container stock

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Much of the unfarmed areas surrounding the retired cropland are dominated by creosotebush. The smaller shrub is white bursage. Our revegetation mix includes species from both the creotebush-dominated and saltbush-dominated (not pictured) plant communities (see pages 174–175 for an explanation of the species selected).
Photo by Martin M Karpiscak

Arizona has a long history of clearing natural vegetation for irrigated crop production in its low-elevation deserts. Changes in the economics of agriculture have caused about 50% of the agricultural land in the lower Santa Cruz and Gila River Valleys to be retired from cultivation (Jackson and Comus 1999) and simply abandoned following the final cropping season. Although some of this land was later developed or incorporated into cities, much of it remains idle. In many cases, several decades have passed since abandonment, but little recovery of vegetation has occurred (Figure 1), especially in areas with clay soils (Karpiscak 1980). Revegetation of these lands is complicated by limited economic incentives, low and variable precipitation (generally < 200 mm/y [< 8 in/y]) (WRCC 2000), extreme temperatures and evapotranspiration, few available propagules, presence of exotic invasive plants, altered hydrology and soil structure, and low soil fertility.

Photo by Martin M Karpiscak

Figure 1. Abandoned agricultural fields such as this one often suffer from a lack of vegetation recovery. Note the lack of topography (from land-leveling practices) and the old concrete irrigation ditch.

A COMMON SOLUTION

Dryland seeding is a common technique used in attempts to restore vegetation on disturbed sites in arid regions. Cox and others (1982) studied dryland seeding attempts on more than 400 sites in the Chihuahuan and Sonoran deserts and concluded that significant plant establishment could be expected only once out of every 10 attempts. Grantz and others (1998) investigated the effectiveness of seeding to mitigate dust on retired cropland in the Mojave Desert of California. They concluded that directly sowing seeds can lead to plant establishment in years with above average rainfall but is likely to fail in most years. Bainbridge and others (1995) state that seeding without supplemental irrigation is an ineffective restoration strategy in arid lands because of unpredictable and infrequent occurrence of conditions favorable for seed germination and seedling establishment.

HOW MUCH DOES IT COST?

Cost estimates for large-scale restoration projects are rare. Seeding cost estimates are highly variable, ranging from US$ 50 to $3700/ha ($20 to $1500/ac) (Bainbridge and Virginia 1990). Recent seeding efforts on retired cropland near Tucson, Arizona, cost between US$ 250 and $1000/ha ($100 and $400/ac) for seeds alone (Phillips 2003). The USDA Natural Resources Conservation Service (NRCS) estimates a cost of US$ 125/ha ($50/ac) to revegetate degraded rangelands in Arizona by means of seeding, though it is unclear what costs (that is, seed, land preparation, management, and so on) are included in this figure (NRCS 2000). Slayback and others (1995) seeded native shrubs onto 1000 ha (2500 ac) of retired cropland in the Mojave Desert of California in 1992. They estimated the project cost exceeded US$ 750/ha ($300/ac), which apparently only included the cost of the seeds and their aerial application. This suggests that some estimates may greatly undervalue actual revegetation costs, especially when irrigation or seedbed modification is used. Additional estimates of the cost of various revegetation procedures are needed because selection of revegetation methodology may depend almost entirely on economic considerations.

MATERIALS AND METHODS

Our Revegetation Site

Our revegetation site is 80 km (50 mi) southwest of Phoenix, Arizona, on retired cropland that was last farmed in the late 1970s through the early 1980s. Soils are aridisols with loam and clay loam surface textures. Mean annual precipitation for the nearest long-term weather station in Buckeye, Arizona, is 194 mm (7.6 in) and occurs about equally in the summer (Jul–Sep) and winter (Nov–Feb) rain seasons (WRCC 2000). Summer rains usually are brief and intense convective storms while winter rains are usually from broad frontal storms of long duration and low intensity. Mean monthly maximum temperatures range from 45 °C (113 °F) in July to 20 °C (69 °F) in January (WRCC 2000). Vegetation on unfarmed lands adjacent to our site is dominated by creosotebush (*Larrea tridentata* (Sessé & Moc. ex DC.) Coville [Zygophyllaceae]), white bursage (*Ambrosia dumosa* (Gray) Payne [Asteraceae]), and desert saltbush (*Atriplex polycarpa* (Torr.) S. Wats. [Chenopodiaceae]).

The "Target" Plant Community

One challenge in revegetation of retired croplands in this region is determining the predisturbance (target) plant community. Reliable personal accounts are rare as much of the land was cleared more than 30 y ago, and any aerial photographs are of an inappropriate scale to accurately determine the plant species present. Often, the only clues that remain are the plant communities on lands adjacent to the cropland, although croplands in the Southwest typically are located adjacent to ephemeral watercourses (washes) and are lower in elevation and probably of a slightly different soil type than the areas that remain unfarmed. Early research by Shantz and Piemeisel (1924) in central Arizona supports this observation, stating that the best lands for agriculture were the desert saltbush-dominated shrub communities adjacent to washes, which transitioned into creosotebush-dominated communities as distance from a wash and elevation increased.

As a bet-hedging strategy, we decided to select common species from both communities in composing the species list for our revegetation project. All species planted were natives and were documented to occur naturally within 1.6 km (1 mi) of the planting area. The origin of the plant materials used in our plantings is unknown. However, because conditions on-site are very different from those that existed prior to cultivation, local ecotypes may not have any adaptive advantage over nonlocal ecotypes.

The Trial Planting

An 8-ha (20-ac) planting was made in March 2001 to compare effectiveness of different combinations of transplanting (outplanting), seeding, furrow irrigation, and drip irrigation. Treatments were randomly assigned to 335-m-long (1100-ft-long) rows, 3 m (10 ft) apart, in each of 4 blocks. There were a total of 64 rows with 16 rows per block. Each row was assigned 1 of 4 treatment combinations: 1) seeding with furrow irrigation; 2) seeding with drip; 3) transplants with furrow irrigation; and 4) transplants with drip. Other treatments were also tested in additional rows but were later thrown out of the data analysis because of confounding factors.

Transplant survival and seedling emergence were estimated on a monthly basis under furrow and drip irrigation using 4 randomly located 100-m (330-ft) transects within single rows of each block. Seedlings of each species were counted in each of the seeded rows and seedling emergence was estimated as the average number of seedlings that had emerged per 100-m (330-ft) transect.

All plants were irrigated in sets lasting 12 h once per week by means of drip or furrow irrigation during April to September and twice per month during the remainder of the first year. Delivery rates for the drip emitters were roughly 2.1 l/h (0.6 gal/h), but delivery rates for furrow-irrigated rows were not measured.

We used a native seed mix (a bulk mixture containing seeds of 22 species) applied with a range drill at 1.1 g/m or 670 pure live seeds per m (200 seeds/ft). Although the range drill was equipped to plant multiple rows at once, we disabled the extra seed-delivery tubes so as to plant only a single row at a time. Rose pot transplants (also known as "liners") measure 5 x 5 x 8 cm (2 x 2 x 3 in) and come in flats of 56 to 64 plants. Most of the rose pot transplants were mechanically planted using a tobacco planter. The 3.8-l (1-gal) containers measure 15 cm (6 in) in diameter by 20 cm (8 in) tall and are a commonly used container size in retail nurseries. Species in 3.8-l (1-gal) containers were 6 to 9 mo old while species in rose pot containers (creosotebush) were approximately 4 mo old. Species were placed randomly within each transplanted row.

Some representative species transplanted or seeded included creosotebush, white bursage, desert saltbush, fourwing saltbush (*Atriplex canescens* (Pursh) Nutt. [Chenopodiaceae]), velvet mesquite (*Prosopis velutina* Woot. [Fabaceae]), and catclaw acacia (*Acacia greggii* Gray [Fabaceae]) (Table 1). These species were selected largely on the basis of availability from commercial nurseries, as many of the desired species were not available at the time of the initial planting.

The Scaled-up Planting

An 83-ha (210-ac) planting was made at the same site as the initial planting in November 2001. The term "field" is used here to refer to those areas at this site that were irrigated as a single unit when the land was still under cultivation. Fields are easy to identify because they are often bounded by irrigation structures (canals, earthen borders) and can have noticeable differences in elevation. Fields ranged in size from 8 to 16 ha (20 to 40 ac). Different container sizes were randomly assigned to fields, with roughly 60 ha (150 ac) assigned to plants from rose pot containers, 16 ha (40 ac) assigned to plants from paper pot containers, and 16 ha (40 ac) assigned to plants from 3.8-l (1-gal) containers. Transplant survival was estimated using five 300-m (980-ft) transects, each within a single row, in fields with each of the 3 container sizes (Table 2).

All fields were irrigated using a drip irrigation system buried 15 cm (6 in) below the soil surface, with rows spaced 6 m (20 ft) apart and emitters spaced 6 m (20 ft) apart within rows (approximately 250 plants/ha [100 plants/ac]). The emitters have flow rates of 2.1 l/h (0.6 gal/h) at 70 kPa (10 psi). Plants were irrigated in 12-h sets by means of drip-irrigation approximately once every week during April to September, then twice a month during October to March. After the first year, plants were monitored for signs of drought stress and additional irrigation was deemed unnecessary. Total amounts of water used to irrigate the November 2001 planting for 1 y were estimated at 226 000 l/ha (24 000 gal/ac).

In addition to the 2 previously mentioned container sizes (rose pot and 3.8-l [1-gal]), we used a paper-pot container that measured 7 cm (3 in) in diameter x 20 cm (8 in) in height for certain species (Table 2) in this planting. The paper pots were constructed of rolled tubes of biodegradable paper that were open on the bottom. The advantage of this container type is that it can be planted in the ground without having to remove the plant from the container, which potentially reduces transplant shock. White bursage, fourwing saltbush, quailbush (*Atriplex lentiformis* (Torr.) S. Wats. [Chenopodiaceae]), desert

TABLE 1

One-year survival [a] of selected species planted by propagule type, container size, and irrigation method during the initial experimental planting in March 2001.

Species	Seed		Rose pot transplants		3.8-l transplants	
	Drip irrigation	*Furrow irrigation*	*Drip irrigation*	*Furrow irrigation*	*Drip irrigation*	*Furrow irrigation*
	%					
Acacia greggii	2	2	NP [b]	NP	87	93
Ambrosia deltoidea	<1	<1	14	1	NP	NP
Atriplex polycarpa	<1	<1	NP	NP	60	60
Larrea tridentata	<1	<1	30	3	NP	NP
Lycium exsertum	<1	<1	NP	NP	67	80
Prosopis velutina	2	1	NP	NP	100	87
Mean survival [c]	**<1**	**<1**	**25**	**2**	**83**	**82**

Propagule type, container size, and irrigation

[a] Survival in seeded treatments ignores viable but ungerminated seed possibly remaining in the soil.
[b] NP = Not planted.
[c] Mean survival was calculated as the quotient of the total number of surviving individuals divided by the total number of individuals planted. This does not equal the average of the mean survivals for all species because they were planted in different proportions.

TABLE 2

One-year survival by container size of selected species planted during the large-scale experimental planting in November 2001.

Species	Rose pots	Paper pots	3.8-l transplants
		%	
Ambrosia dumosa	25	42	76
Atriplex canescens	90	72	69
Atriplex lentiformis	100	80	96
Atriplex polycarpa	42	58	85
Larrea tridentata	20	42	89
Pleuraphis rigida	55	50	95
Mean survival [a]	49	55	80

Container size

[a] Mean survival was calculated as the quotient of the total number of surviving individuals divided by the total number of individuals planted. This does not equal the average of the mean survivals for all species because they were planted in different proportions.

saltbush, creosotebush, and big galleta (*Pleuraphis rigida* Thurb. [Poaceae]) were planted by hand from rose pot, paper pot, and 3.8-l (1-gal) containers at each emitter into pre-irrigated soil.

RESULTS

In the initial experimental planting we found that seedling emergence and survival were low, with similar results for both drip- and furrow-irrigated treatments for all species evaluated (Table 1). Only 3 of the 17 perennial species included in the seed mixture were observed to emerge and persist after 1 y under furrow irrigation. Drip-irrigated rose pot transplants had higher survival than seedlings or furrow-irrigated rose pot transplants. Although not directly comparable because each contained a different suite of species, transplants of the 3.8-l size had higher survival than rows that were seeded or which contained rose pot transplants. Survival was similar for drip- and furrow-irrigated 3.8-1 (1-gal) transplants. Casual observations throughout the year after planting consistently showed that agricultural weed densities were higher in furrow-irrigated rows than in drip-irrigated rows.

In the large-scale experimental planting we found that 3.8-1 transplants had higher survival 1 y after transplanting than rose pot or paper-pot transplants for most species (Table 2). Survival was similar for all container sizes of fourwing saltbush, quailbush, or big galleta. The survival of 3.8-l (1-gal) transplants was compa-

TABLE 3

Three-year budget for the revegetation of a native plant community using drip irrigation in Maricopa County, Arizona. All rates and costs in US$.

Operation	Rate	Materials		Labor		Cost per hectare [a]
		Type	*Cost*	*Hours*	*Cost*	
LAND PREPARATION						
Scrape field [b]	52					52
Burn residue				2.5	69	69
Install drip irrigation		Drip system and tape	1235	29.6	230	1465
Apply pre-emergent herbicide [c]		Pendimethalin	29	0.7	32	61
Pre-irrigate [d,e]		Water (12000 l) [d]	3			3
PLANTING						
Plants [f]		3.8-l plants	783			783
Unload delivery truck [g]				2.5	19	19
Deliver inside field, hand plant, and stack containers				59.3	459	459
MAINTENANCE						
Irrigate [h]		Water (740 000 l) [i]	179			179
Hand weeding [j] (3X)	556					556
Drip system maintenance [k] (3X)		Chemicals (chlorine)	185			185
Subtotal						**3965**
15% Contingency [l]						**595**
Total						**4426**

[a] Costs per acre can be obtained using a multiplier of 0.4.

[b] Removes any existing weed or crop residue.

[c] Minimizes competition from agricultural weeds.

[d] Minimizes transplant shock and marks spot for planting.

[e] Area watered by drip system is 0.004 ha (0.01 ac): 250 emitters/ha (100 emitters/ac), each emitter wets an area of approximately 0.3 m^2 (3.2 ft^2).

[f] Includes the cost of replacements (in our case, 63 plants/ha at US$ 2.50 each) to achieve a density of 250 plants/ha (100 plants/ac).

[g] Includes sorting to mix up species.

[h] Water costs vary dramatically depending on location and source.

[i] Although we only irrigated for 1 y and used 226 000 l/ha (about 0.2 ac-ft), our budget includes water for three years in the event of a drought.

[j] Prevents the establishment of perennial weeds not controlled by the pre-emergent herbicide.

[k] Prevents algae from clogging emitters.

[l] Management fee, insurance, plant replacement, drip tape repair.

rable between the initial (82%) and large-scale experimental plantings (80%), but rose pot transplant survival was higher in the large-scale (49%) than in the initial planting (25%) (Tables 1 and 2). Because of weed problems associated with furrow irrigation and the higher survival of the 3.8-l (1-gal) transplants, we decided to use drip-irrigated 3.8-l transplants in future plantings. As of April 2004, we have planted an additional 340 ha (850 ac) using this method. Transplant survival remains high (see Figure 2) and we have not seen weed densities comparable to those experienced in the furrow-irrigated portion of the March 2001 planting, with the exception of a few fields that were recently retired (< 1 y) from agriculture.

The minimum cost of successfully establishing native plant species on retired cropland using our chosen technique in southern Arizona is estimated to be approximately US$ 4430/ha ($1790/ac) (Table 3). This estimate includes costs of installation, maintenance, and operation of the drip-irrigation system; irrigation water; nursery-grown plants; plant delivery and the sorting of these plants before transplanting (outplanting); hand-planting of 250 transplants/ha (100 transplants/ac) (3.8-l [1-gal] container size); hand-weeding; an application of a pre-emergent herbicide to control perennial weeds; and a 15% management fee. The drip-irrigation system has an estimated life span of 5 y, though it may last much longer with proper maintenance. Our plan at this site is to provide irrigation for the first year, and thereafter in years 2 or 3 only if absolutely necessary to ensure plant survival. This has decreased chances of invasive exotic plants becoming established and also minimized salt buildup around emitters in the irrigation line. Established plants continue to flower and produce seed following the cessation of irrigation and additional transplant mortality has been minimal.

DISCUSSION

Although seedling survival between drip- and furrow-irrigated treatments was similar for the initial planting, most species failed to germinate and persist after 1 y under furrow-irrigated conditions. Problems with prolonged inundation or an inability to withstand the erosion from flowing water within the furrows may account for the higher mortality of the furrow-irrigated seeds. Leguminous tree species, such as velvet mesquite and catclaw acacia, were able to germinate and establish under furrow irrigation, possibly because of their relatively larger seeds and seedling size or high growth rates. Species that dominate in unfarmed areas adjacent to the research site, such as creosotebush, white bursage, and desert saltbush, failed to establish in most seeded treatments.

Rose pot transplants were unable to withstand furrow irrigation. Triangleleaf bursage rose pot transplants had very low survival in all treatments and is likely not suited for planting at

Photo by Travis M Bean

Figure 2. The fields planted in November 2001 ten months after planting. Note the large plant sizes, some of which approximate or exceed average sizes found in natural communities. Also note the low weed densities.

this site using our methods. This species was included in the initial planting as a substitute for white bursage, which was unavailable at the time of planting. Triangleleaf bursage is more characteristic of the more mesic Arizona Upland Subdivision of the Sonoran Desert, while white bursage is more characteristic of the more xeric Lower Colorado River Valley Subdivision (Shreve 1951) where our revegetation site is located. For other species, the apparent differences in survival among drip-irrigated plants from rose pots in the initial versus the large-scale plantings may be due to the method of planting. A mechanical transplanter was used for most of the rose pot transplants in the initial planting, while rose pot transplants were hand-planted in the large-scale planting. Regardless, because plantings were made at different times and in different fields, caution should be exercised in comparing the results between the initial and large-scale plantings. Based on our observations, the root systems of plants that were hand-planted appeared to remain more intact during planting than did those of mechanically planted transplants. The hand-planted transplants from rose pots, however, experienced an episode of prolonged inundation that was the likely cause of their nearly complete mortality by November 2001.

The larger 3.8-l (1-gal) transplants had higher survival than did other transplants in both the initial and large-scale planting regardless of irrigation treatment, most likely becasue of their larger root systems and greater ability to withstand transplanting stress. The greater amount of soil in the 3.8-l (1-g) containers may have also provided a buffer against the field soil with its lower water-holding capacity. Some species did well in the large-scale planting regardless of container size. If immediate visual impact or uniformity of transplant container size for efficient plant handling are not issues, then these species (fourwing saltbush, quailbush, and big galleta) might be transplanted from smaller container sizes to lower plant material costs. In general, rose pot and paper-pot transplants were similar in their survival. Paper-pot transplants are not recommended, however, because of the great difficulty in removing them from the trays in which they were delivered.

It is important to note the unique circumstances of these plantings in which this research was conducted. The property owners are committed to successfully and rapidly revegetating these lands while supporting restoration research. We have found that the most effective way to revegetate retired cropland in southern Arizona is to transplant native species of at least a 3.8-l (1-gal) container size (6 to 9 mo old) at appropriate densities (250 plants/ha [100 plants/ac] in our situation) into fields that are drip irrigated for the first year following planting, while minimizing soil disturbance as much as possible. This technique virtually guarantees success by mitigating two of the most important constraints to vegetation recovery in arid lands: low and variable precipitation and limited propagule availability.

By excluding drip irrigation and transplant-related costs from our budget (Table 3), we estimate that seeding with furrow irrigation might cost as little as US$ 1300/ha ($530/ac), assuming that the NRCS cost estimate for seeding is reasonable. Although more susceptible to invasion by exotics than drip-irrigated transplants, seeding with furrow irrigation may represent the most cost-effective method of achieving some native plant establishment on retired cropland in southern Arizona. Furthermore, it is a method familiar to most conventional farmers in the area as it mimics the methods they use in irrigated crop production. However, even under irrigation the resulting species compositions might be unpredictable with lower richness and diversity than in stands established with transplanting. Certain species that were included in the seed mix were able to germinate but were not present in established stands, possibly reflecting the vulnerability of seedlings to pre-establishment mortality.

Revegetation of severely disturbed sites in hyperarid environments involves considerable time, effort, and expense. Given the relatively invariant population dynamics of many desert plant communities and very infrequent (>50 y for many species) natural establishment of perennial desert species (Minnick and Coffin 1999; Cody 2000), seeding in the absence of supplemental irrigation cannot be expected to succeed in most years. Based on this information, the only plausible—but likely very expensive—method of successfully seeding without supplemental irrigation is to repeatedly seed until a year or series of years with above average precipitation occurs. Using the recent seed-only cost estimates for seeding retired cropland near Tucson (US$ 250 and $1000/ha [$100 and $400/ac]) and assuming that years favorable to germination and establishment occur roughly every 10 y (Cox and others 1982), it would cost an average of approximately US$ 2500 to

$10 000/ha ($1000 to $4000/ac) to successfully establish plants using the dryland seeding approach. This approach, however, still does not guarantee success and actual costs of a successful dryland seeding might be much higher depending on seed costs, seeding method, soil preparations, and climate. Though potentially more expensive, our approach virtually guarantees establishment in the first year, allows for precise control of plant densities and species composition, and provides very economical use of seeds to establish plants.

ACKNOWLEDGMENTS

We thank the Duke Energy North America Arlington Valley Energy Project for funding this research. We also thank Randy Lanford, Leon Hardison, and Jason Hardison, local farmers in Palo Verde, Arizona, for their efforts in implementing and maintaining the project, and N Gene Wright for his assistance in developing the budget.

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