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Transplanting Native Plants to Revegetate Abandoned Farmland in the Western Mojave Desert

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ABSTRACT

Nursery-grown, native plant species have potential application for revegetating disturbed arid and semiarid lands. We evaluated nursery-grown fourwing saltbush [*Atriplex canescens* (Pursh) Nutt.], allscale saltbush [*A. polycarpa* (Torrey) S. Watson], bladderpod (*Isomeris arborea* Nutt.), honey mesquite [*Prosopis glandulosa* Torrey var. *torreyana* (L. Benson) M. Johnston], and rubber rabbitbrush [*Chrysothamnus nauseosus* (Pallas) Britton] transplanted to abandoned agricultural land throughout the western Mojave Desert. Two types of temporary plant enclosure for herbivory and environmental protection (plastic cones and wire cages) and three mulch treatments (straw, bark, and none) were tested at all six sites. Rubber rabbitbrush was difficult to propagate in the nursery and is not recommended for transplanting. Significant differences in plant performance occurred between sites with similar aerial environments but contrasting degrees of edaphic disturbance. Plastic cones were significantly superior to wire cages for plant vigor and survival but no differences were detected between mulch treatments. Fourwing saltbush was generally successful over all treatments and sites and is recommended for transplanting in this area. In a larger plot study, narrow augered holes led to superior survival of honey mesquite relative to wide, hand-dug holes, and plastic cones were superior to wire cages. Mortality of all species was high due to dry, but not atypical, weather during the 2 yr of the study. We conclude that transplanting without intensive irrigation does not guarantee survival of even the most successful species. Its greater cost relative to direct seeding may not be warranted for large-scale restoration of arid and semiarid environments.

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REVEGETATION of arid and semiarid sites that have been disturbed by agriculture, mining, livestock grazing, or recreation has become increasingly important in many areas of the western USA, and elsewhere in the world, as awareness of the process and consequences of desertification increases. In the cases of road cuts, mine spoils, and disrupted wetlands, regulatory action by U.S. Environmental Protection Agency (USEPA) has fostered restoration efforts that have contributed considerable empirical knowledge regarding revegetation practices. Extensive abandoned agricultural lands have not been subject to the same level of environmental regulation, and have been assumed to be capable of recovery without intervention (Jackson et al., 1991). This may be true in more humid environments, where abandoned land is usually colonized rapidly by annual and perennial herbs (Horn, 1974), but arid and semiarid regions pose more severe challenges.

Water availability is generally considered the single most limiting resource for plant growth (Boyer, 1985) particularly in arid or semiarid environments because rainfall is low, highly variable, and inherently unpredictable. Differences in moisture requirements between species result in seedling recruitment of some species nearly every year, but of others only every decade or longer (Allen, 1991). As with natural recruitment, desert revegetation through direct seeding fails in most years (Bainbridge et al., 1993; Jackson et al., 1991; Cox et al., 1982; Bleak et al., 1965), although direct seeding coupled with fortuitously timed rainfall may result in highly successful plant establishment in these areas (e.g., Grantz et al., 1998).

Establishing plants in arid areas is difficult without intensive irrigation. Methods of applying supplemental

Abbreviations: VAM, vesicular-arbuscular mycorrhizal; ANOVA, analysis of variance.

water include simple basin watering, deep pipes, buried clay pots, porous capsules, wicks, and drip systems (Bainbridge and Virginia, 1990). An alternative method increases retention of rainwater with microcatchments that reduce runoff and increase infiltration (Jackson et al., 1991; Virginia and Bainbridge, 1987; Shanan et al., 1970). In the case of formerly irrigated but abandoned agricultural lands, groundwater depletion and consequent reliance on rainfall and run-off may further constrain recruitment, potentially excluding formerly dominant phreatophytes.

Water availability is not the only factor controlling productivity of arid and semiarid lands (Allen, 1991; West, 1991). Spatial variability in shrub-dominated arid and semiarid sites is distinguished by "islands of fertility," characterized by enhanced soil nutrients and organic matter under existing plant canopies, relative to areas between plants (Allen, 1991). This concentration of resources by root scavenging and leaf litter deposition is a critical initiator of successional processes (Allen, 1988), improving soil tilth, moisture infiltration, and microbial activity (West, 1989).

Vesicular-arbuscular mycorrhizal (VAM) fungi form mutualistic associations with about 90% of species from arid and semiarid lands (Trappe, 1981). These symbiotic relationships increase the rooting volume via hyphal extension (Bainbridge et al., 1993), increasing access to nutrients, especially P, and water in exchange for carbohydrates (Harley and Smith, 1983; Allen and Boosalis, 1983). The VAM fungi and P are both concentrated within the drip line of established shrubs (Allen and MacMahon, 1985).

Transplanting of widely spaced individual shrubs of locally adapted species may initiate formation of these islands of fertility. Establishment of large, homogeneous shrub populations may not be necessary, and could be less cost effective than transplanting isolated individuals. Limited cover (e.g., 20–30%; Carpenter et al., 1986) is typical of these arid regions, and is sufficient to reduce fugitive dust emissions by up to 75% (Bilbro and Fryrear, 1995). The use of transplants for desert revegetation has received increased attention since the 1980s, and techniques for successful establishment have been evaluated (Bainbridge et al., 1995; Bainbridge et al., 1993; Bainbridge and Virginia, 1990; Romney et al., 1987).

Following transplanting, protection from herbivory, moisture stress, and wind damage has been found to be beneficial under some circumstances. Herbivory, in particular, may be a critical factor in plant establishment in arid and semiarid environments (Bainbridge and Virginia, 1990; Romney et al., 1987; McAuliffe, 1986), where grazing by blacktail jack rabbits (*Lepus californicus*) (Romney et al., 1987) and insects (e.g., grasshoppers; family Acrididae) are often a limiting factor in the Mojave Desert and Great Basin environments. A variety of plant protection techniques have been demonstrated, including use of the plastic, conical tree shelters and metal screens evaluated in the present study, as well as rock mulches, plant collars, animal repellents, straw stubble, and mulches of standing senescent biomass. Applicability of each is determined by cost and individual site requirements (Bainbridge et al., 1995).

Straw and bark mulches have been shown to enhance establishment of transplanted native plants on some disturbed sites where moisture is limiting (Zink, 1994). These have been used extensively in agricultural and horticultural contexts to conserve soil moisture, regulate soil temperature, and control weeds. In desert revegetation programs, recalcitrant C sources such as wood bark additionally serve to sequester N on disturbed sites through increased microbial biomass with subsequent slow release of N (Zink, 1994; Whitford et al., 1989). Nitrogen is an important regulator of production in arid ecosystems, once sufficient water is available (West, 1991). Unlike cultivated or forested systems in which a high C/N ratio is undesirable, in semiarid areas a high C/N ratio is favorable, excluding ephemeral nitrophilic species and fostering symbiotic mycorrhizal colonization.

In this paper we evaluate several native shrub species transplanted to various sites in the Antelope Valley of the western Mojave Desert, several different planting techniques, including contrasting methods of hole excavation, mulches, herbivory protection, and the role of site disturbance in predicting transplant survival. Interest in the use of transplants in this environment derived from earlier experiments that illustrated the risks associated with reliance on direct seeding for revegetation and suppression of wind erosion and fugitive dust emissions (Grantz et al., 1998).

MATERIALS AND METHODS

Plant Material

Five native plant species were chosen for evaluation. Honey mesquite, a deep-rooted, drought-resistant (avoiding and tolerant) leguminous species, is well adapted to drainages of both the high and low deserts of California. In some areas it has proven successful for stabilizing disturbed areas both by direct seeding and transplanting (Hickman, 1993; Bainbridge et al., 1993). Honey mesquite is considered endemic in this region but is now uncommon in the study area due to harvest for firewood and land clearing. Although capable of *Rhizobium* nodulation, this generally requires access to permanent fossil water tables for appreciable N_2 fixation (Rundel et al., 1982; Shearer et al., 1983), and is seldom observed on dry sites (Sprent, 1987) even following experimental irrigation (Virginia et al., 1989). The transplants used in this evaluation were not inoculated with *Rhizobium*.

Two saltbushes, fourwing saltbush and allscale saltbush, are well adapted to the study area and occur commonly throughout the western Mojave Desert. Fourwing saltbush was the most successful shrub in a direct seeding experiment carried out in this locale (Grantz et al., 1998).

Bladderpod is a highly branched shrub formerly common in the study area, and has shown some promise for use in stabilizing disturbed arid areas (Hickman, 1993). Rabbitbrush is widely adapted to diverse habitats from British Columbia to Baja California (Hickman, 1993) with numerous biotypes/subspecies. It is an early successional species in the western Mojave Desert, exhibiting vigorous colonization of abandoned, denuded, or burned areas which have not been subjected to extensive physical soil disturbance (e.g., by tillage;

Grantz et al., 1998). Following soil disturbance it is usually displaced by invasive annuals including Russian thistle (*Salsola pestifer* Nelson).

Seedlings of all species were grown by the California Department of Forestry in Davis, CA, in high aspect 5 by 5 by 35.5 cm containers (plant bands; Bainbridge et al., 1994), in an artificial soil mix comprised of (by volume) 40% sand, 45% perlite, 5% vermiculite, 5% fir bark, and 5% coarse peat (L. Lippett, 1997, personal communication). Fertilizer (38–45–0; N–P–K; 590 g m^{-3}) and gypsum (2950 g m^{-3}) were added prior to planting.

Seeds of fourwing saltbush, allscale saltbush, and bladderpod were collected from plants growing near Gorman, CA, (118°40′ W, 34°50′ N, near the experimental area) and were obtained through a commercial supplier (S & S Seeds, Inc., Carpinteria, CA). Seed pretreatments varied for these species. The saltbush spp. received a 24-h running water rinse with a 4-wk naked (without substrate) chill, resulting in a 31.5% germination rate for fourwing saltbush and a 22.5% germination rate for allscale saltbush. Bladderpod received a 24-h soak followed by a 6-wk naked chill, yielding a 22% germ. Rubber rabbitbrush seed was hand collected and bulked from 30 individual plants selected throughout the study area. X-ray analysis revealed about 36% mature seed, with 19% germination. Mesquite seeds were collected in the western portion of the Coachella Valley of California and exhibited 93% germination. Differences in required stratification and growth led to differences in dates of transplanting to the field. This precluded direct species comparisons.

Rabbitbrush, excluded from disturbed sites in the field, proved difficult to establish from seed in the well-mixed potting soil. Several successive plantings produced only a few seedlings suitable for transplanting (from more than 1000 sown seeds). This species was excluded from further consideration and is not recommended for transplanting.

Weather Data

A micrometeorological station was operated at a secure site (118°35′15″ W, 34°51′00″ N) during these evaluations. Wind speed and direction were measured at 2 m above the surface with a Model 03001-5 Wind Sentry Set (R.M. Young Co., Traverse City, MI). Air temperature and relative humidity were measured at 2.0 m with Model 107 and 207 probes, respectively (Campbell Scientific Inc., Logan, UT). Solar radiation and rainfall were measured with a Model LI-200SB pyranometer sensor (Li-Cor Inc., Lincoln, NE) and a Model TE525 tipping bucket rain gauge (Campbell Scientific Inc., Logan, UT). All sensors were interrogated at 1 Hz and data recorded as 20 min averages with a data logger (Model 21X with SM192 solid state storage modules; Campbell Scientific Inc., Logan, UT).

Experiment I

This experiment was conducted on a site (Table 1; Site K) subjected to intensive farming over the last several decades but abandoned in 1989. Between 1954 and 1989 this land was cropped to alfalfa (*Medicago sativa*, 7–8 yr per cycle) in rotation with small grain grown for a single year between alfalfa plantings (P. Kindig, 1997, personal communication). Alfalfa was harvested five times annually with three flood irrigations between harvests. Commercial phosphate fertilizer was added annually for alfalfa, and N fertilizer was added for small grains.

Honey mesquite was planted on a large plot (183 m long by 91.5 m wide, ca. 1.7 ha) at this site as part of a concurrent project to evaluate the effect of shrubs on the emission of PM_{10} from desert lands (Farber et al., 1996). The site was disked and transplanted in September 1995, in rows 9 m apart with 2.3 m between plants in a row. The field contained 780 transplants in 19 rows.

Two planting methods were applied to transplanting locations pre-marked with wire flags. Several crews of range-fire fighters with revegetation experience moved across the field, equipped with a power-auger (excavating a 10 cm diam. by 36 cm deep hole; 370 plants) or a pickax (excavating a 40 by 40 by 40 cm deep hole; 410 plants). The resulting distribution of planting methods to experimental units was randomly determined by which crew arrived first at each flag. Two liters of water were added to each hole and allowed to drain before transplanting. Plants were placed in the hole and the plant band removed. The hole was back-filled and the soil lightly compacted. An additional 1 L of water was added after planting and another 2 L on eight subsequent occasions during the first dry season.

Two types of transplant protection were also randomly assigned. Four-hundred seventy-five plants were covered with plastic tree shelters (cones; base diameter 20 cm, top diameter 10 cm, height 61 cm; Tree-Pee, Baileys Inc., Laytonville, CA) and 305 plants were covered with cylindrical stucco wire cages (diameter 30 cm, height 91 cm) held in place with a metal rod threaded through the wire mesh and driven into the soil. The height of the honey mesquite transplants was 15 to 25 cm. Protective covers were removed in October 1996 when plants began to emerge from the shelters.

Seven additional individuals of honey mesquite were transplanted adjacent to this plot into augered holes, protected with wire cages. These plants received weekly irrigation.

Plants were scored for vigor (a continuum from 0 = dead

Table 1. Site, elevation, soil classification, and surface characteristics for six common garden plots (Exp. II).

Site	Location	Elevation	Soil classification	Surface characteristics
		m		
B	34° 51′ 00″ N 118° 37′ 45″ W	982	Greenfield gravelly coarse sandy loam; coarse-loamy, mixed, thermic Typic Haploxeralfs	Senescent annuals, low sparse cover
W	34° 48′ 45″ N 118° 35′ 25″ W	881	Hanford loamy sand, hummocky; coarse-loamy, mixed, nonacid, thermic Typic Xerorthents	Devoid of vegetation, overburden sand
K	34° 47′ 55″ N 118° 15′ 00″ W	730	Hesperia fine sandy loam; coarse loamy, mixed, nonacid, thermic Xeric Torriorthents	Senescent annuals, low dense cover
C100S	34° 47′ 28″ N 118° 18′ 45″ W	752	Rosamond loam; fine-loamy, mixed (calcareous) thermic Typic Torrifluvents	Dense senescent cover *Sisymbrium altissimum*
C100N	34° 47′ 30″ N 118° 18′ 45″ W	752	Rosamond loam; fine-loamy, mixed (calcareous) thermic Typic Torrifluvents	Native desert shrub, barren from wildfire
B120W	34° 48′ 17″ N 118° 20′ 24″ W	765	Rosamond loamy fine sand; fine-loamy, mixed (calcareous) thermic Typic Torrifluents	*Achnatherum hymenoides* (Roemer & Shultes) growing on overblown sand

to 8 = most vigorous) using defined criteria (Table 2), on six dates between planting and January 1997. Contingency analyses were performed on the survival data (score of 0 vs. sum of all other scores) on selected dates to determine the effect of the four planting methods on plant survival. A two-way analysis of variance (ANOVA) (hole type × protection type) was performed on the vigor data (General Linear Model; PROC GLM, SAS, 1988) on selected dates to determine the effect of the four planting methods on plant vigor. Mean separation of vigor scores was by Duncan's multiple range test.

Experiment II

A multi-species comparison was established at six sites (Table 1) throughout the western Mojave Desert. Sites were selected in October 1995 to incorporate the spatial variability observed in soil classification (USDA, 1970) and in the success of a previous revegetation by direct seeding (Grantz et al., 1998).

The difficulties with nursery propagation noted above led to elimination of rabbitbrush from the experiment and a range of planting dates for the remaining species (Table 3). All transplants were placed in power-augered holes and irrigated as above. There were no additional irrigations.

At each site (Table 1) the transplants were treated with one of three mulch treatments (straw, wood chips, and control) and one of two types of herbivory protection (plastic cones or wire cages), assigned randomly. The straw and wood chip mulches were applied to a depth of 8 to 10 cm in a circular pattern around the base of the plant (covering ca. 0.04 m^2). The straw mulch was crimped into the soil. There were five replicate blocks at each site (30 plants per species per site) with species assigned randomly between entire rows and mulches × protection applied randomly within rows. All transplants received either a cone or cage based on our previous experience in the study area. Protection was removed in October 1996 as above.

Plants were scored for vigor periodically after planting, using the 0 to 8 rating scale (Table 2). Three of the transplanted species (fourwing saltbush, allscale saltbush, and honey mesquite) were evaluated five times between April 1996 and April 1997. Bladderpod was evaluated four times. Differing planting dates prevented the planned complete factorial analysis. Therefore a within-species ANOVA of plant vigor was undertaken, using a General Linear Model (PROC GLM; SAS Institute, 1988) of site, protection, mulch, and interactions. Mean separation for significant site effects within each species was by Duncan's multiple range test. The simple effects of protection or mulch type within a site were evaluated only if main effects or interactions across all sites were significant.

Three randomly located soil samples (0–10 cm depth) were obtained from each of the six sites in April 1996 and analyzed for nitrate (NO_3) and ammonium (NH_4)–N levels (Keeney, 1982), and for bacterial and fungal populations (Anderson and Slinger, 1975; Trent, 1993; Conners and Zink, 1994). Soil data were analyzed by one-way ANOVA, and significant differences between site means were determined by Fisher's protected LSD.

Table 2. Vigor rating scale used to assess transplanted seedlings.

Vigor rating	Description
0	No leaves, stem brown, no green or purplish tissue evident
1	Stem partly green or purplish, no leaves present, no new growth
2	Stem partly green or purplish, no leaves present but new growth evident in axils
3	Stem wholly green or purplish, no leaves present, no new growth
4	Stem wholly green or purplish, no leaves present but new growth evidence in axils
5	Stem wholly green or purplish, <50% of old leaves present, no new growth
6	Stem wholly green or purplish, <50% of old leaves present, new growth evident
7	Stem wholly green or purplish, >50% of old leaves present, no new growth
8	Stem wholly green or purplish, >50% of old leaves present and new growth evident

RESULTS AND DISCUSSION

Rainfall was below normal in 1995 to 1996 (19% of the 20-yr average; Grantz et al., 1998), and in 1996 to 1997, (34% of the 20-yr average by late April) (Fig. 1A). The drought conditions over these 2 yr exerted a substantial impact on the outcome of these experiments.

Experiment I—Large Plot Evaluation of Honey Mesquite

Although hot dry conditions prevailed during and following transplanting of the honey mesquite plants at Site K, >85% survival was obtained during the first 2 mo. Although rainfall is unlikely during the warm season (May through September, Fig. 1B), seedlings were transplanted, with supplemental water, at this time to foster some root proliferation before the onset of cold weather and winter dormancy. By March, after five additional irrigations and at the beginning of the dry season, survival had decreased to <80%, a decline that continued through the summer of 1996. By early January of 1997 survival had fallen to near 40% (Fig. 2A).

A contingency analysis of the survival data from four evaluation dates (Fig. 2A) indicated a significant effect of planting method on survival (χ^2 = 43.5, 68.7, 136.3, 129.8 for successive dates, all $P < 0.005$). In January 1997, 62% of plants in narrow deep holes with plastic cone protection survived, compared with only 10% in broad holes with wire cages (Fig. 2A).

Significant differences were also observed in plant vigor between these treatments within each date (Fig. 2B,C). Plants protected with plastic cones exhibited significantly greater vigor than those with wire cages (Fig. 2B; average vigor 1.28 vs. 0.60 in January 1997). We speculate that the plastic cones increased the relative humidity, decreased incident solar radiation and leaf temperature, and decreased wind velocity, relative to

Table 3. Planting dates for four species at six sites (Exp. II).

	Planting date by species			
Site	*Prosopis glandulosa*	*Atriplex canescens*	*Atriplex polycarpa*	*Isomeris arborea*†
B	25 Oct. 1995	11 Jan. 1996	24 Jan. 1996	2 May 1996
K	25 Oct. 1995	11 Jan. 1996	24 Jan. 1996	2 May 1996
W‡	31 Jan. 1996	11 Jan. 1996	24 Jan. 1996	2 May 1996
C100S	26 Oct. 1995	12 Jan. 1996	25 Jan. 1996	2 May 1996
C100N	26 Oct. 1995	12 Jan. 1996	25 Jan. 1996	2 May 1996
B120W	26 Oct. 1995	12 Jan. 1996	25 Jan. 1996	2 May 1996

† In May 1996 some *Isomeris* plantings were heavily grazed by *Orthoptera* spp. at some sites.

‡ Site W replaced an original site which was destroyed, resulting in a different planting date for *P. glandulosa*.

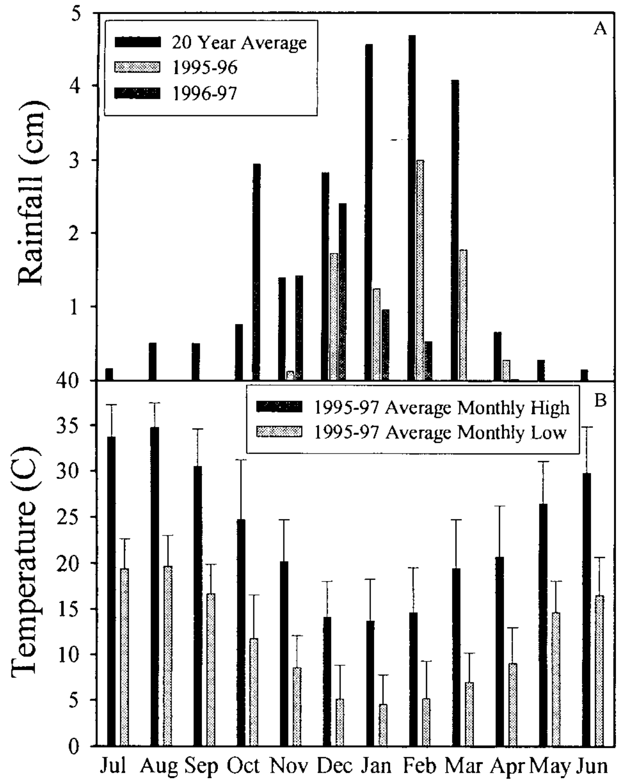

Fig. 1. Twenty-year average rainfall as measured at the Fox Field National Weather Service Station at Fox Field, Antelope Valley, and for the two years of transplant evaluations as measured by an on-site meteorological station (Panel A), and average monthly high and low temperatures from the same on-site station (Panel B). Error bars represent 1 SD.

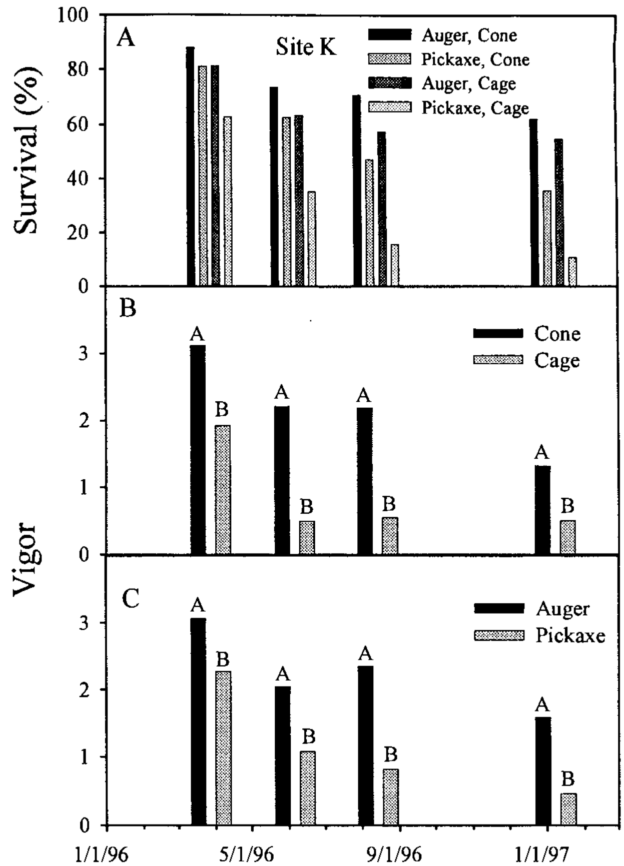

Fig. 2. Time course of survival (*A*) and vigor (*B*) of mesquite plants at Site K in the western Mojave Desert. Means associated with different letters within evaluation dates are different at $P = 0.05$.

plants in the more open wire cages. These beneficial changes in plant microenvironment were apparent to the eye and hand, but were not explicitly measured. In January 1997, plants in augered holes were significantly more vigorous than those in holes dug with a pickaxe (average vigor 1.58 vs. 0.47, $P < 0.001$). This may reflect concentration of water in the narrow augered hole and minimal disturbance of the root systems during planting, compared to the large hand dug holes. The combination of augered holes with plastic cones yielded significantly more vigorous plants on every evaluation date than any of the other three treatment combinations, and this protocol is to be recommended for transplanting native shrubs in this arid environment.

Though these differences reveal that planting methods and type of herbivory protection are important factors to consider, plant survival and vigor in this environment are primarily limited by water availability. The surviving mesquite plants within Site K (i.e., deleting all score = 0 individuals), despite five supplemental waterings, exhibited average vigor scores of only 0.99. Supplemental irrigation provided to the large plot was obviously insufficient. The seven additional honey mesquite transplants that received weekly irrigation exhibited 100% survival, substantial growth, and average vigor scores of 8.0 over this same period.

Herbivory protection was removed from all plants in October 1996 when many individuals had emerged from their shelters. Above-average rainfall initiated establishment of annual species such as filaree [*Erodium cicutarium* (L.) L'Hér] that could provide alternative forage for herbivores. Nonetheless, new leaves and shoots of honey mesquite were intensely grazed by indigenous herbivores with a subsequent decline in vigor in January 1997 (Fig. 2).

Experiment II—Test of Species by Site

The site main effect was significant for all species (Fig. 3), while the protection main effect was significant for allscale saltbush, attributed to the significant simple effect of cones observed at Site C100N (Fig. 3B). The site × protection interaction was significant for honey mesquite, attributed to the significant simple effect of the cones at Site B (Fig. 3C). Fourwing saltbush was very successful in these tests, performing well at four of the six sites (Fig. 3A). Allscale saltbush, although naturally occurring throughout the western Mojave, survived at only one site. Bladderpod survived at only two sites. At sites B and K this species was eliminated within 48 h of transplanting by grasshoppers (order Orthoptera, family Acrididae). At Sites B120W and C100S, though grasshopper herbivory was not a factor, all individuals of this species died from desiccation. Honey mesquite performed poorly at all sites.

Mulches had no significant effect in this experiment. Effects on water availability may have been minimal in the dry years of this study.

The negligible difference in vigor that was observed between plants grown under plastic cones or wire cages

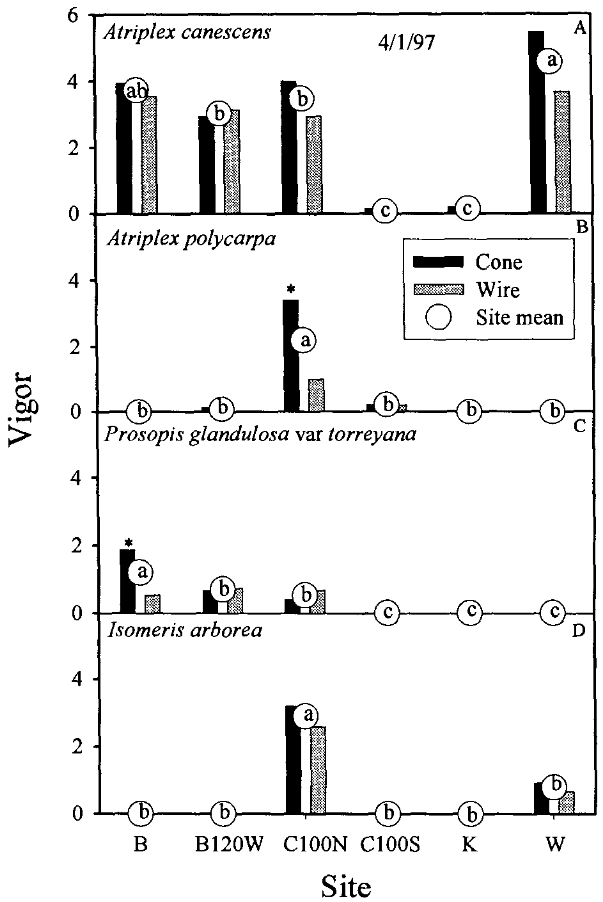

Fig. 3. Mean vigor of individual shrub species treated with plastic cones or wire cages for herbivory protection and species site means (bars and circles, respectively) on the April 1997 evaluation date. Site means associated with different letters are different at $P = 0.05$. Herbivory protection means within species and sites identified with asterisks are different at $P = 0.05$.

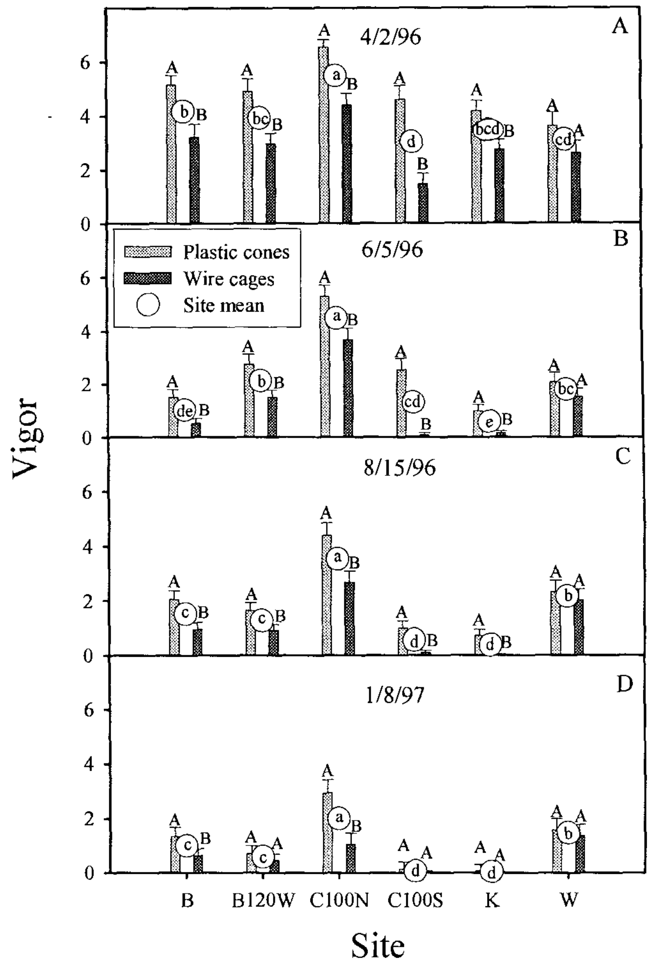

Fig. 4. Mean vigor of the four shrub species in Fig. 3, treated with plastic cones or wire cages for herbivory protection and site means (*bars* and *circles*, respectively) on four dates at six sites in the Antelope Valley. Means associated with different letters within a site and date are different at $P = 0.05$.

in April 1997 (Fig. 3) contrasts with the greater vigor of plants in cones that existed at all sites except W on previous evaluation dates, when the devices were still in place (Fig. 4A, B, C). A factorial analysis of these data (Fig. 4) revealed large and highly significant ($P < 0.001$) date, site, and protection main effects, as well as highly significant two-way interactions. Average plant vigor decreased from 3.8 to 1.6 between April (Fig. 4A) and August (Fig. 4C) of 1996, followed by a further decrease to 0.86 in January of 1997 (Fig. 4D) following removal of the protective devices in October 1996. Increased herbivory following removal of both forms of herbivory protection in October 1996 resulted in greater grazing on the succulent cone-protected plants, and therefore fewer significant differences between the methods observed in January 1997 (Fig. 4D).

The six sites represented a range of soil types (Table 1) and land use history. Sites B120 W and C100S had land use histories similar to Site K, with alfalfa in rotation with small grains and sugar beet (*Beta vulgaris* L.) (J. Santos, 1997, personal communication). Site B was used for strip cropping of dryland barley (*Hordeum vulgare* L.) between 1948 and 1989 (B. Barnes, 1997, personal communication). Soil amendments, other than grain stubble, were not added at this site. Site C100N had not been subjected to agriculture in recent decades as mature saltbush scrub existed here prior to a natural wildfire in the winter of 1995 to 1996. The significant site differences in plant vigor (Fig. 3) are attributed largely to edaphic factors associated with disturbance arising from contrasting agriculture practices. The proximity of the sites suggests similar aerial environmental conditions.

The contrast in plant survival and vigor between sites C100N and C100S (Fig. 3 and 4) is notable since these two sites are adjacent, separated only by a narrow roadway that divides fields with different apparent use histories. These two sites were chosen to explore the visible contrast in revegetation success following the earlier direct seeding efforts in 1992 (Grantz et al., 1998). Site C100N had not been disturbed for decades and was covered with mature saltbush scrub. It was contiguous with an area in which all previuosly seeded species established well.

Plant growth was most vigorous of all sites at the minimally disturbed Site C100N. The significantly lower vigor rating for mesquite compared to the other three species at this site is due to high mortality shortly after transplanting. By June of 1996, only about 20% of the transplanted mesquite plants remained viable. This area had been subjected to an uncontrolled range fire in late

Table 4. Mean ammonium (NH_4) and nitrate (NO_3), bacterial counts, and hyphae fungal lengths (g soil^{-1}) for the soil surface layer (0–10 cm) on 19 Apr. 1996 (Exp. II).

Site	Mean NH_4	Mean NO_3	Bacteria	Fungal hyphae
	mg kg^{-1}		10^6 g^{-1}	m g^{-1}
C100S	1.23ab	7.76a	34a	0.65c
K	1.62ab	4.16b	87a	0.39c
B	0.79ab	0.41c	75a	0.72c
C100N	1.92a	1.54bc	95a	2.66a
W	0.22b	0.35c	94a	1.06bc
B120W	0.66ab	0.60c	92a	0.70c

* Means with the same letter are not significantly different at $P = 0.05$.

1995 prior to transplanting, and exhibited the highest concentration of NH_4–N, with low NO_3–N (Table 4) in the upper soil profile. This site also exhibited the most abundant fungal hyphae and bacterial populations of the six locations (Table 4). These soil samples were taken from areas between the plants where no mulch was applied. Plant vigor was not affected by mulch treatment at this site on any evaluation date.

Site C100S was imbedded in an area that had undergone decades of agriculture (flood irrigated alfalfa/small grain). No seeded shrubs had become established in the earlier experiments, and the area had subsequently become covered with the invasive annual species, tumble mustard (*Sisymbrium altissimum* L.). This site exhibited the highest NO_3–N concentrations and low bacterial populations, with few fungal hyphae present (Table 4). Survival and vigor of all transplanted species at this site declined steadily. By April 1997 evaluation, there were only two surviving individuals (of the 30 initial) of all-scale saltbush and one of fourwing saltbush.

Plant survival and vigor at Site K (small plot) was as poor as at Site C100S (Fig. 3). This site, adjacent to site K (Exp. I), had been cropped to alfalfa and in 1994 volunteer alfalfa plants emerged. The higher NH_4 concentration observed at this site (Table 4) may reflect remnant root biomass, though as at Site C100S, the soil had relatively high concentrations of NO_3–N and little fungal hyphae. The average NO_3 concentration at these two sites was 5.96 mg kg^{-1}, compared with an average of 0.73 mg kg^{-1} over the other four sites. High N availability is often conducive to establishment of invasive, fast-growing, nitrophilic species (West, 1991) such as *S. altissimum*, a vigorous competitor that does not form mycorrhizal associations (E.B. Allen, 1997, personal communication).

Accelerated microbial activity and N cycling because of disturbance (West, 1981), and loss of soil microorganisms that are currently difficult to reintroduce (Allen, 1988), are probably associated with the overall poor plant performance on the most disturbed sites. Populations of VAM fungi are reduced by agricultural (Allen and Boosalis, 1983) or erosive (Powell, 1980) soil disturbances, promoting invasion by weedy annuals that may not form VAM associations (Allen, 1991).

CONCLUSIONS

The high rate of plant mortality observed over two consecutive years of low but not atypical precipitation, suggests that the additional expense of transplanting native desert shrub species may not be warranted relative to the faster and more economical method of direct seeding, particularly over extensive areas where abundant supplemental irrigation is not available. Survival of transplants is maximized by introducing into narrow, deep planting holes that concentrate supplemental water and foster root-soil contact rather than into wide, hand-dug holes. While frequent irrigation results in vigorous plant growth and excellent survival, modest supplemental irrigations may not be sufficient to assure plant survival. Plastic cones placed over the transplants further maximized survival, providing excellent herbivory protection and beneficial microenvironmental effects. However grazing following removal of the cones may be catastrophic and difficult to predict. Adaptation to this high desert environment and feasibility of nursery production suggest that fourwing saltbush is highly recommended for transplanting in this area, while rabbitbrush is not. Mesquite did not perform as well as expected in these experiments and was highly susceptible to herbivory following removal of protection. It is not recommended but may warrant further study. Soil nutrients and microorganisms may reflect the level of soil disturbance. High available N and low soil inoculum encouraged invasion by nitrophilic annual species and reduced survival of transplanted native shrubs. Amending the soil to reduce N may be beneficial. Site preparation and selection of suitable species, along with proper planting procedures may optimize the chances of successful revegetation using transplants, but in highly variable arid and semiarid environments these protocols do not guarantee plant establishment in any given year.

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