Am. Midl. Nat. (2020) 184:129–148

Lessons Learned 5+ Years After Transplanting and Seeding Restoration Sites in the Sonoran Desert, U.S.A.

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Abstract.—Recovery of degraded lands in arid environments is especially challenging due to difficulty of matching ideal conditions to seed germination requirements and reduced native soil seed banks. Restoration practitioners try to overcome these challenges through seeding and site preparation treatments. In the McDowell Sonoran Preserve, Scottsdale, Arizona, the focus for restoring old roads was on seeding, cactus transplants, and soil treatments (either ripping or adding soil from nearby construction areas). Here we evaluated the success of these restoration sites 5–8 y after project completion. We compared vegetation and ground cover on eight roads that received a combination of these restoration treatments with adjacent reference areas. Plant cover was similar between the restoration and reference plots, but plant composition was different. The restoration plots contained more cacti due to cactus transplants, whereas the reference areas contained more shrub cover. The number of native plant species was greater in the reference areas than in the restoration plots. Seeding treatment had little effect, with only five of 11 seeded species appearing in plots, and only one species, *Bouteloua aristidoides*, appeared in both treatments that included seeding. Although cacti may have contributed to overall plant cover, they did not appear to aid establishment of other plants. Our findings suggest more interventions are likely required for the restoration and reference plant communities to converge in arid environments. We suggest considering multiple seeding treatments that will maximize the potential for ideal germination conditions and additional local interventions that may help accumulate litter and protect seeds.

Introduction

Restoration of degraded lands in arid environments can be challenging due to limited water resources and climatic variability. Natural regeneration may take more than 50 y (Lovich and Bainbridge, 1999; Bolling and Walker, 2002; Webb and Thomas, 2003), and some areas may never recover to predisturbance conditions due to changes in the seed bank, soil compaction, and other alterations in the system (Bekker *et al.*, 1997; Webb, 2002; Guo,

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2004). As a result identifying effective methods for active restoration is crucial, but determining appropriate treatments can be difficult.

Even with active restoration efforts, vegetation can take a long time to establish (Abella and Newton, 2009; Abella *et al.*, 2009). Generally, relatively few seeded species proliferate (Abella and Newton, 2009; Abella *et al.*, 2009; Defalco *et al.*, 2012), and species that establish within the short term may decline over time (Ott *et al.*, 2011). Similarly, treatments that work in one area may not be successful in another, because of differences in local factors, such as soil type, slope, and weather variability (Webb, 2002; Kulpa, 2010; Hall, 2013). Even under generally favorable circumstances and over long periods of time, successful restoration is not assured, and results may vary significantly (Lovich and Bainbridge, 1999; Snyman, 2003; Guo, 2004; Herrick *et al.*, 2006; Abella *et al.*, 2009; Ott *et al.*, 2011). Additionally, treatments that support native plant recovery also often support establishment of nonnative plants (Snyman, 2003; Banerjee *et al.*, 2006; Abella *et al.*, 2012; Woods *et al.*, 2012; Wells, 2013; Fick *et al.*, 2016; Abella and Chiquoine, 2019), negating restoration goals.

Restoration ecologists have identified practices to help overcome these challenges. Seeding is a common approach in active restoration. Because plant species have different germination requirements (Adondakis and Venable, 2004; Abella and Newton, 2009; Baskin and Baskin, 2014), site-specific conditions such as aspect should be considered to determine the correct seed mix and application technique for an area (Montalvo *et al.*, 2002; Kulpa, 2010). Applying seeds at higher densities (greater number of seeds per unit area) can result in greater diversity and biomass of seeded species due to the higher probability for establishment of each species (Wells, 2013). Planting early in the rainy season generally yields more germination than later in the rainy season (Turner *et al.*, 2006; Ruthrof *et al.*, 2013), but administering multiple applications of the seed mix throughout the year can help match species-specific needs with appropriate temperature and other environmental conditions (Defalco *et al.*, 2012). During drier times irrigation can help species establish, although it also may result in greater nonnative plant cover (Banerjee *et al.*, 2006; Bainbridge, 2007). A variety of seed enhancement technologies, such as coatings or extruded pellets, may help overcome common limiting factors in arid lands restoration by increasing water availability, controlling timing of seed germination, and offering protection from pre- emergent herbicide (Madsen *et al.*, 2016). Appropriately sourced seed is also important. Locally sourced seed can help maintain genetic diversity and local adaptations (McKay *et al.*, 2005; Herget *et al.*, 2015). However, using seeds from diverse sources may accommodate a changing environment (Broadhurst *et al.*, 2008).

As an alternative to or in combination with seeding, planting seedlings, transplants, or containerized plants can aid establishment. One of the greatest benefits of such planting is providing structure to an otherwise denuded area. Shrubs, cacti, and other planted species can stabilize the soil (Carrillo-Garcia *et al.*, 1999) and provide resource islands, trapping local seeds and litter (Bainbridge, 2007; Abella *et al.*, 2015). Transplants or outplanted individuals can also serve as nurse plants, protecting new seedlings from extreme weather conditions and herbivory (Padilla and Pugnaire, 2006; Souad *et al.*, 2013). At the McDowell Sonoran Preserve in Scottsdale, Arizona, U.S.A. (Preserve), managers have commonly used cactus transplants to readily recolonize bare areas while also keeping people from trampling restoration sites (C. Miller, pers. comm. 2020). In lieu of planting species, the use of barriers or connectivity modifiers (ConMods, 15 cm wire mesh barrier structures) can also serve these purposes (Fick *et al.*, 2016; Abella and Chiquoine, 2019). Other environmental conditioning treatments include surface modifications, such as ripping or tilling, which can increase water availability and the ability for plants to establish root systems (Bainbridge,

TABLE 1.—Mean annual precipitation (cm) data averaged from the four Flood Control District of Maricopa County (2018) weather stations closest to study sites in McDowell Sonoran Preserve, Scottsdale, Arizona, U.S.A. The long-term mean includes data from 1990–2018

Long-term mean (cm)	Mean annual precipitation (cm)									Mean precipitation of study period, 2010–2018 (cm)	Deviation of study period from long term mean
	2010	2011	2012	2013	2014	2015	2016	2017	2018		
25.4	24.3	23.0	19.3	27.7	29.9	25.3	18.4	25.1	14.8	23.1	−2.3

2007). These practices break up the soil surface, which is especially important in compacted areas, allowing moisture to infiltrate more rapidly and for plants to root more easily (Oh and Woo, 1992; Montalvo *et al.*, 2002; Snyman, 2003; Osunbitan *et al.*, 2005; Kinyua *et al.*, 2010; Ruthrof *et al.*, 2013).

Our objective was to assess the efficacy of restoration efforts conducted 5–8 y ago in the Preserve. Specifically, we sought to: (1) compare treated roads and nearby reference plots to assess progress towards restoration, (2) assess success of seeding, cactus transplants, and soil treatments (ripping or soil additions and harrowing), and (3) evaluate whether cactus transplants expedite restoration. We predicted sites with more restoration inputs would result in fewer differences with their reference communities in terms of plant cover, species richness, and litter than would sites with fewer inputs. We also predicted that cactus transplants, vertical mulch, and woody debris will aid plant recruitment and result in increased plant cover compared to plots without these applications.

METHODS

STUDY SITE

The McDowell Sonoran Preserve (Preserve) encompasses 12,375 ha of Sonoran Desert Upland habitat (Brown *et al.*, 1979a) at the northeastern edge of the Phoenix metropolitan area in Scottsdale, Arizona (33°35′24″N, 111°45′36″W). During the years between the restoration treatments and the time of the study, from 2010–2018, January mean temperature was 12.5 C with a range of −6–27 C, and July mean temperature was 31.7 C with a range of 17–47 C at the two nearest weather stations (Flood Control District of Maricopa County, 2018). Precipitation means from the four nearest precipitation gauges indicated rainfall was below average for much of the study (2010–2012 and 2015–2018), but above average in 2013 and 2014 (Table 1). The Sonoran Desert climate includes two distinct rainy seasons: one in the winter (December–March) and one in the summer (June–September). At our study site, winter rains typically deliver more overall precipitation than summer monsoons (https://www.usclimatedata.com/climate/scottsdale/arizona/united-states/usaz0440).

The Preserve is topographically and biologically diverse, ranging in elevation from 515 to 1237 m above sea level. More than 1000 species have been found in the Preserve, including 416 plant and 243 vertebrate animal species. Jones and Hull (2014) identified 14 distinct plant associations distributed across the Preserve. Bedrock geology and soil types differ across the Preserve, with predominantly metamorphic rock in the south and decomposed granite in the north (Skotnicki, 2016).

The study sites were in the central region of the Preserve at elevations between 774–835 m and between 33°45′17″N, 111°48′14″W in the north and 33°14′39″N, 111°48′2″W in the south (Table 2). These areas were a flat granite pediment with very gravelly sandy loam soil.

TABLE 2.—List of study sites in McDowell Sonoran Preserve, Scottsdale, U.S.A., with year treated, associated plant communities, and treatments applied. The plant community codes represent the following: 154.123 *Simmondsia chinensis* – mixed scrub association, 154.120 *Senegalia greggi* – mixed scrub association, and 154.128 *Ericameria laricifolia – Parkinsonia microphylla* – mixed scrub association (Jones and Hull, 2014). Treatments included combinations of soil treatment (ST; ripping to at least 20–30 cm deep or soil addition of 30–50 cm depth and recontouring), transplanting cacti (T), and seeding (S)

Site code	Treatments initiated	Plant community code	Treatment	Treatment code
RS12	2013	154.123	soil treatment*+transplants+seed	ST/T/S
RS16	2013	154.123	soil treatment*+transplants+seed	ST/T/S
RS15	2013	154.123	soil treatment*+transplants	ST/T
RS13	2012	154.123	soil treatment**+seed	ST/S
RS24	2012	154.120	transplant only	T only
RS25	2012	154.120	transplant only	T only
RS100	2012	154.120	transplant only	T only
RS6	2010–2011	154.128	transplant only	T only

* soil treatment = soil addition and recontouring
** soil treatment = ripped only

The plant communities associated with the sites included 154.123 *Simmondsia chinensis* – mixed scrub association in the southernmost sites (RS12, RS13, RS15, RS16), 154.120 *Senegalia greggi* – mixed scrub association in the central area (RS24, RS25, RS100), and 154.128 *Ericameria laricifolia – Parkinsonia microphylla* – mixed scrub association in RS6, the northernmost site (Jones and Hull, 2014).

PRIORITIZING STUDY SITES

We selected sites using a database of past restoration projects across the Preserve, which included the following information: type of original disturbance/cause of degradation, date of restoration treatment, and treatments applied (*e.g.*, seed, transplants, soil treatments, deadfall). We mapped all projects with location data in Google Earth Pro (V7.3.2). From these we prioritized old roads that had a range of the most common treatments – seeding, cactus transplants, and soil treatments (ripping or soil additions and contouring) – and were large enough for sampling with multiple replicates. Therefore, all the sites were linear disturbances, although the width varied. Because we were working with past restoration sites not established for research, we were unable to find treatment combinations that enabled comparisons of individual treatments; therefore, we compared the available combination of treatments instead (Table 2).

TREATMENTS

In 2011–2012 the City of Scottsdale constructed a trailhead near Tom's Thumb in the Preserve (approximate trailhead location 33°41′39″N, 111°48′07″W). From 2010–2013 the city closed old roads and treated them with a combination of soil treatments, cactus transplants, and seeding. Soil treatments consisted of either ripping the old road area (mechanically digging the old road to a depth of 20–30 cm) or adding soil that was excavated during Tom's Thumb trailhead construction to a depth of 20–50 cm and contouring the soil to make it smooth and level (Table 2). For transplant treatments whole cacti of all sizes (*e.g.*, *Cylindropuntia acanthocarpa* (Engelm. & J.M. Bigelow) F.M. Knuth var.

coloradensis (L.D. Benson) Pinkava (Colorado buckhorn cholla), *Cylindropuntia bigelovii* var. *bigelovii* (Engelm.) F.M. Knuth (teddybear cholla), *Echinocereus engelmannii* (Parry ex Engelm.) Lem (Engelmann's hedgehog cactus) and cacti segments (*e.g.*, *Cylindropuntia* sp. and *Opuntia* sp) were salvaged from a power line construction area approximately 6 km away in the Preserve, transported to the site, and placed under shade, if available. Cacti were left as bare root, without covering. Within 2–3 d crews trimmed any dried out or scabbed over roots and planted the cacti or cacti segments into holes along the treated areas. No water was added. Transplant density at time of treatments was unknown. The seeding treatment included broadcast-seeding a commercial Sonoran Upland mix (Wild Seed, Tempe, Arizona) at the rate of 0.45 kg/186 m^2 (1 lb/2000 sq. ft) recommended on the label. The seed mixture included the following species: *Bouteloua aristidoides* (Kunth) Griseb. (needle grama), *Encelia farinosa* A. Gray ex Torr. (brittlebush), *Ambrosia dumosa* (A. Gray) Payne (burrobush), *Atriplex canescens* (Pursh) Nutt. (desert saltbush), *Atriplex lentiformis* (Torr.) S. Watson ssp. *breweri* (S. Watson) H.M. Hall and Clem. (quailbush), *Senna covesii* (A. Gray) Irwin and Barneby (desert senna), *Larrea tridentata* (DC.) Coville (creosote bush), *Simmondsia chinensis* (Link) C.K. Schneid. (jojoba), *Aristida purpurea* Nutt. var. *purpurea* (purple three awn), *Plantago ovata* Forssk. (desert indianwheat), *Sporobolus cryptandrus* (Torr.) A. Gray (sand dropseed). The proportion of each species in the mix is unknown. In addition to these distinct combinations of treatments, dead wood was sometimes planted into the ground as vertical mulch or laid onto the ground as mulch. Because this application was not consistent with one of the main treatments, it was measured during sampling and analyzed separately.

GENERATING RANDOM PLOT LOCATIONS

At each site we established five 2 m diameter circular plots at five randomly selected locations along the length of the old road, paired with five reference plots in the adjacent area. Plots on the roads were located at least 5 m apart (center point to center point) and at least 2 m from each end of the restoration area to avoid edge effects. If randomly selected points fell in washes or if a plot had more than 25% large rock, another random point along the length of the road was selected. Because the restored roads were different widths, we used a random number generator to select the distance from the road edge, ensuring that the edge of the plot was at least 0.5 m from the edge of the treatment area. For each restoration plot, a reference plot was selected at least 5 m from the edge of the disturbed area, perpendicular to the plot on the higher elevation side. If the 5 m mark fell in a disturbed area or wash or had more than 25% large rock, plots were moved 1 m farther or to the opposite side of the road using the same approach.

PLANT SAMPLING

Plant sampling occurred in October–November 2018 and was conducted using visual estimates within the 2 m diameter plots. Plant cover by species and ground cover (litter, woody debris, bare ground) were estimated using the following cover classes: 0%, 0–0.1%, 0.1–1%, 1–2%, 2–5%, 5–10%, 10–25%, 25–50%, 50–75%, 75–95%, >95% (NCVS protocol, *see* Peet *et al.*, 1998). Because it was not always possible to distinguish between plants that had died and those that had been intentionally added as dead vertical mulch, we estimated cover of all standing dead plants. For analysis cover classes were converted to the midpoint. We also counted the number of living and standing dead cactus in each plot.

TABLE 3.—Generalized linear mixed analysis results for percent cover and total species richness by functional type. Treatments refer to the following: soil treatment+transplants+seed (ST/T/S), soil treatment+transplants (ST/T), soil treatment+seed (ST/S), and transplant (T only). Type (Treatment) refers to reference or restoration nested within treatment. Degrees of freedom (df) columns include numerator df followed by denominator df. Study sites were located in McDowell Sonoran Preserve, Scottsdale, Arizona, U.S.A.

	Treatment		Type (treatment)	
Response variable	df	F value	df	F value
Native plant cover (%)				
Total native plant cover	3,37	1.4	4,37	0.51
Grass	3,37	11.98***	4,37	1.89
Forb	3,37	4.77**	4,37	0.73
Shrub	3,37	74.31***	4,37	4.97**
Cactus	3,37	0.52	4,37	3.89**
Perennial plant	3,37	2.09	4,37	0.69
Annual plant	3,37	7.38***	4,37	0.17
Total seeded species	3,36	7.90***	4,36	0.62
Nonnative cover	3,37	7.37***	4,37	2.06
Native plant richness (#/plot)				
Total native plant richness	3,37	0.69	4,37	3.62**
Grass	3,37	2.64	4,37	5.92***
Forb	3,37	3.28*	4,37	3.57**
Shrub	3,37	0.33	4,37	1.63
Cactus	3,37	0.43	4,37	4.03**
Perennial plant	3,37	1.2	4,37	2.94*
Annual plant	3,37	1.02	4,37	2.2
Nonnative plant richness	3,37	12.77***	4,37	0.81
Ground cover (%)				
Litter	3,37	1.89	4,37	5.84***
Woody debris	3,37	3.27	4,37	4.54**
Bare ground	3,37	5.85**	4,70	5.91***

* $P < 0.05$ level; ** $P < 0.01$ level; *** $P < 0.001$

ANALYSIS

We analyzed the data in a nested mixed model design with two fixed factors – treatment (four levels: soil treatment+transplants+seed [ST/T/S], soil treatment+transplants [ST/T], soil treatment+seed [ST/S], and transplant [T only]) and type (restoration or reference plot) within each treatment. The mixed model explicitly accounts for the variability between and within each site by estimating a random intercept for each site and covariance between the paired restoration and reference plot measurements. Response variables were cover and richness of native plants in each functional group, nonnative cover and richness, ground cover, and seeded species cover (Table 3). All statistical analyses were performed using SAS (version 9.6, SAS Institute, Inc., Cary, NC) software except where noted. Figures 1–4 were created in Tableau (Version 2019.4.5, Tableau Software, Inc., Seattle, WA). Each model was checked to meet standard assumptions. Data for ground cover variables bare ground and woody debris were normal, and litter was transformed with square root to normalize the data and stabilize variance. Because plant response variables did not meet standard assumptions, we used a generalized Poisson mixed model adjusted for over-dispersion within the cover

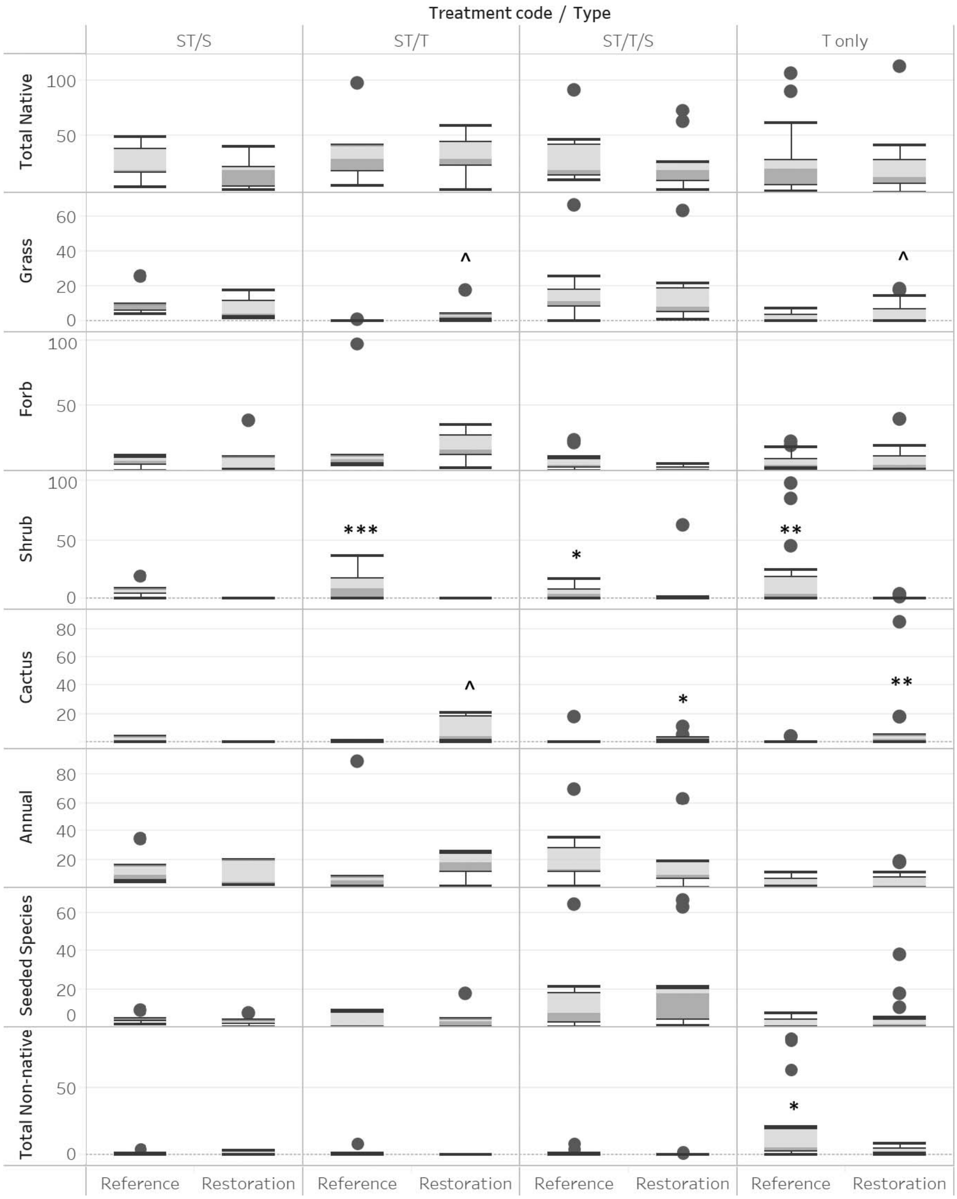

FIG. 1.—Percent cover of functional groups by plot type (restoration or reference) and treatment (soil treatment+seed [ST/S], soil treatment+transplants [ST/T], soil treatment+transplants+seed [ST/T/S], and transplant [T only]). Box plots display distribution of the data such that the shaded box areas and whiskers each represent one quartile of the data. Dots indicate outliers in excess of 1.5 x IQR (inner quartile range). Symbols denote differences within treatment between plot types (restoration and reference) using adjusted P as follows: ^ $P < 0.1$ level; * $P < 0.05$ level; ** $P < 0.01$ level; *** $P < 0.001$. Symbols are placed over the box with the higher mean. Only functional groups with significant effects are shown

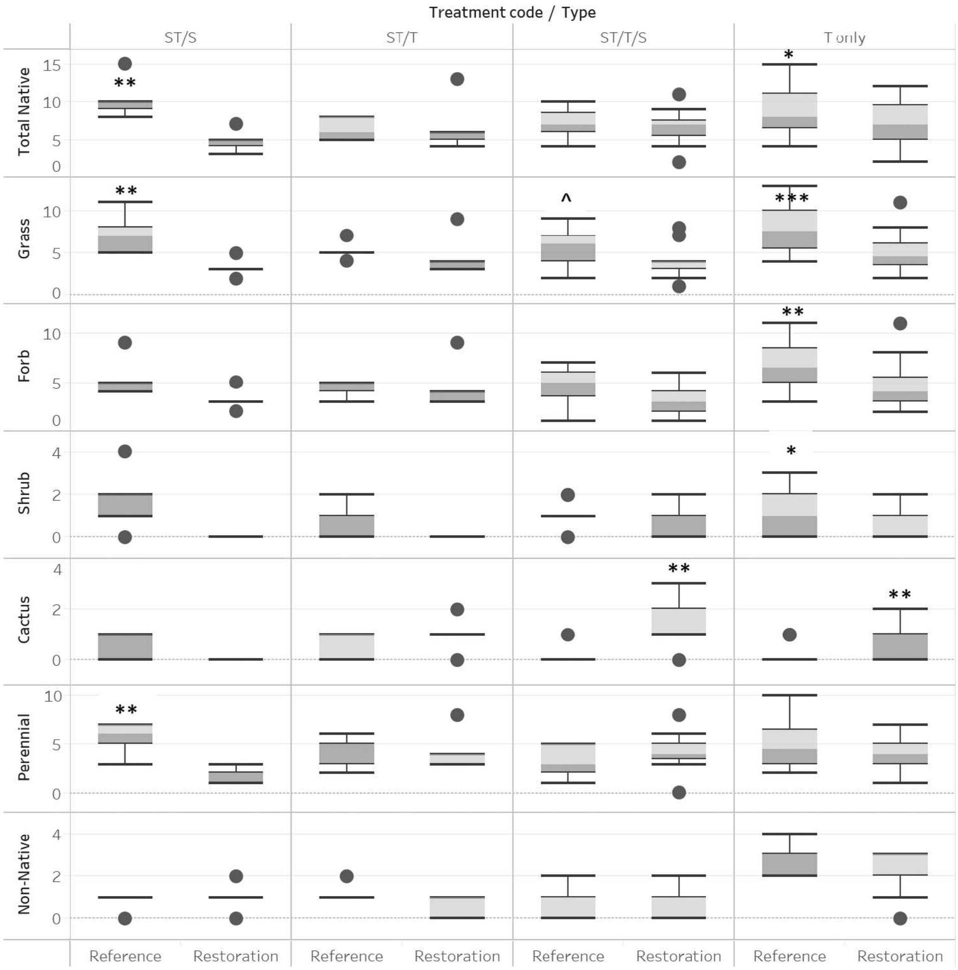

FIG. 2.—Richness (number of plants per 2 m diameter plot) of functional groups by plot type (restoration or reference) and treatment (soil treatment+seed [ST/S], soil treatment+transplants [ST/T], soil treatment+transplants+seed [ST/T/S], and transplant [T only]). Box plots display distribution of the data such that the shaded box areas and whiskers each represent one quartile of the data. Symbols denote differences within treatment between plot types (restoration and reference) using adjusted P as follows: ^ $P < 0.1$ level; * $P < 0.05$ level; ** $P < 0.01$ level; *** $P < 0.001$. Symbols are placed over the box with the higher mean. Only functional groups with significant effects are shown

data to account for the large number of zeros (SAS Institute, 2016) and a generalized Poisson mixed model for the richness count data. The models for forbs and cactus cover and richness and nonnative richness could not include site as a random factor because the estimated effects were too close to zero, resulting in an inestimable model. When interpreting results we considered differences between restoration and reference plots, nested within treatment, to determine restoration success; functional group plant cover or richness that showed no difference between restoration and reference plots indicated

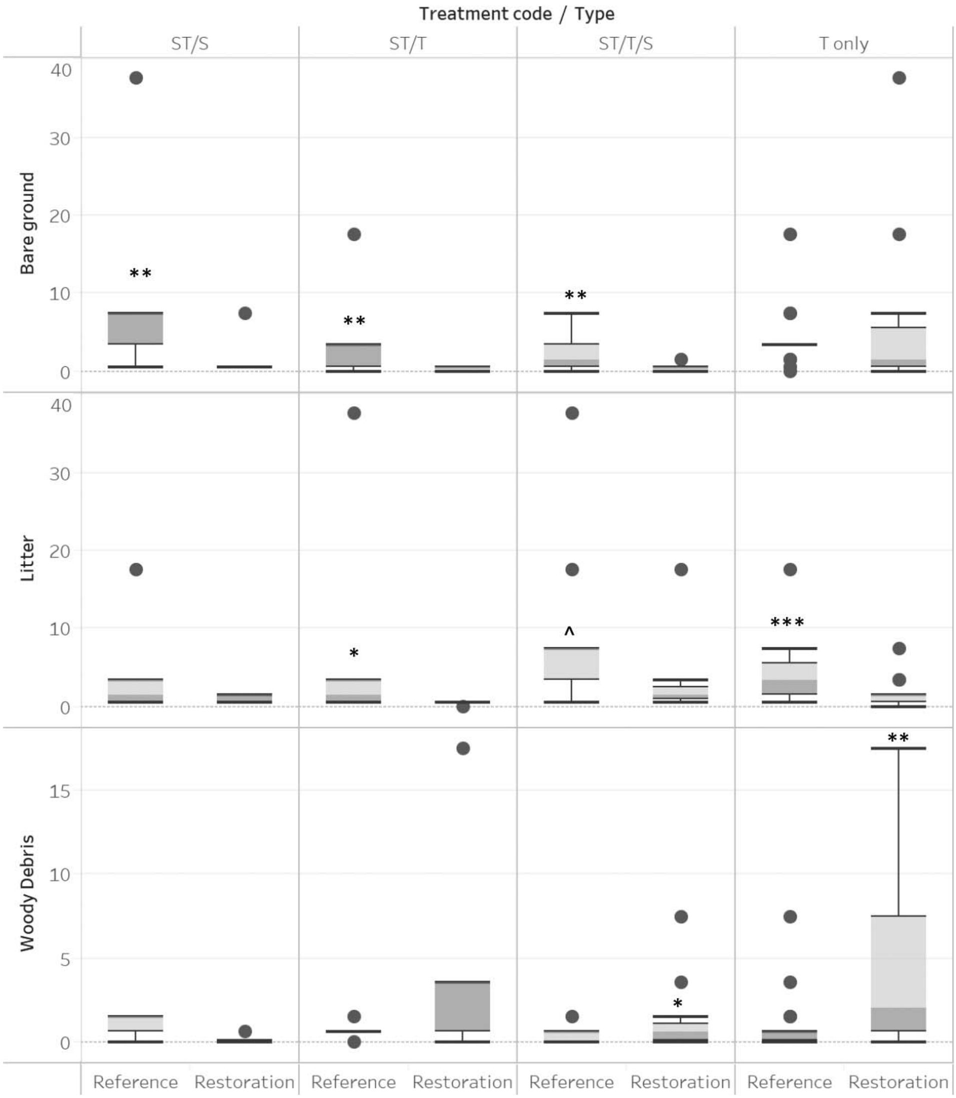

FIG. 3.—Percent of ground cover by plot type (restoration and reference) and treatment (soil treatment+seed [ST/S], soil treatment+transplants [ST/T], soil treatment+transplants+seed [ST/T/S], and transplant [T only]). Box plots display distribution of the data such that the shaded box areas and whiskers each represent one quartile of the data. Dots indicate outliers in excess of 1.5 x IQR (inner quartile range). Symbols denote differences within treatment between plot types (restoration and reference) using adjusted P as follows: ^ $P < 0.1$ level; * $P < 0.05$ level; ** $P < 0.01$ level; *** $P < 0.001$. Symbols are placed over the box plot with the higher mean

FIG. 4.—Distribution of seeded species as an average proportion of total seeded species cover by plot type (restoration and reference) and treatment (soil treatment+seed [ST/S], soil treatment+transplants [ST/T], soil treatment+transplants+seed [ST/T/S], and transplant [T only]) plots. Each line is the average proportional contribution across each treatment of each species to total seeded species cover. Species names are as follows: ARPUP5 = *Aristida purpurea;* BOAR = *Bouteloua aristidoides;* ENFA = *Encelia farinosa;* LATR2 = *Larrea tridentata;* SECO10 = *Senna covesii*

restoration recovery. There were too few tree species in plots to analyze this group separately. Likewise, there were too few data points for the individual seeded species for statistical analysis; therefore, we used histograms to show the relative influence of individual seeded species on the total seeded species cover.

To test the hypothesis that transplanted cacti, vertical mulch, or woody debris aided recruitment of other plants and resulted in more overall plant cover than sites without this treatment, we used a Wilcoxon rank sums test to compare medians of restoration treatment plots, excluding reference treatment plot data. All standing dead cacti and standing dead shrubs were considered to be vertical mulch. Because the majority of the vertical mulch was standing dead cactus, we analyzed both standing dead cactus and vertical mulch (standing dead cactus and standing dead shrubs). We conducted one-way analyses with one fixed factor (presence/absence of live cacti only, dead cacti only, vertical mulch only, live cacti and vertical mulch, and woody debris) to determine if the presence of the fixed factor in a plot increased plant response variables compared with plots without the fixed factor, respectively (JMP version 14.0, Institute, Inc., Cary, NC). The following were used as response variables: all plant cover (with cacti removed), native plant cover (with cacti removed), perennial cover (with cacti removed), annual cover (forbs and grasses), and nonnative cover. Finally, using only restoration plot data, we used the Wilcoxon rank sums for a one-way analysis to compare the density of cacti across treatments and the nonparametric Dunn Method for joint ranking for multiple comparisons (JMP version 14.0, Institute, Inc., Cary, NC)

RESULTS

OVERALL RECOVERY

Native plant cover was not significantly different between the restoration and reference plots, but representation of plant functional groups and native plant richness were different (Table 3, Figs. 1, 2, Appendix A). We did not detect a difference between restored plot total native living cover and the nearby reference plots, nested within treatments; however, total native plant richness was higher in reference compared with restoration plots in the ST/S and T only treatments (Table 3, Figs. 1, 2). In terms of functional groups, reference plots had higher native shrub cover (ST/T/S, ST/T, and T only treatments) and richness of forbs (T only treatment), grasses (ST/S, T only, and marginally in ST/T/S treatments), and perennials (ST/S treatment; Table 3, Figs. 1, 2). Restoration plots had marginally higher

TABLE 4.—Total number of living and dead cactus individuals by species rooted in restoration and reference plots at time of sampling, 2018. Study sites were located in McDowell Sonoran Preserve, Scottsdale, Arizona, U.S.A.

		Restoration plots		Reference plots	
Latin name	Common name	# live	# dead	# live	# dead
Cylindropuntia acanthocarpa var. coloradensis	Colorado buckhorn cholla	12	5	5	1
Cylindropuntia bigelovii var. bigelovii	Teddybear cholla	10	1	0	0
Cylindropuntia fulgida	Chain-fruit cholla	8	0	0	0
Echinocereus engelmannii	Engelmann's hedgehog cactus	5	3	0	0
Opuntia phaeacantha	Tulip pricklypear	3	1	0	0
Opuntia engelmannii	Cactus apple	3	0	0	0
Mammillaria grahamii	Graham's nipple cactus	1	0	0	0

native grass cover (ST/T and T only, Fig. 1). The T only treatment had significantly less nonnative cover than the reference community (Table 3, Fig. 1). Nonnatives in our plots included two annual forbs (*Portulaca oleracea* L. [little hogweed] and *Erodium cicutarium* [L.] L'Hér. ex Aiton [storksbill]) and two annual grasses (*Bromus rubens* L. [red brome] and *Schismus barbatus* [Loefl. ex L.] Thell. [common Mediterranean grass]). The latter three are widespread throughout the Preserve.

In terms of treatments success, T only and ST/T/S treatments showed the strongest differences in cactus and shrub cover and richness between restoration and reference (Fig. 1). The ST/T treatment also had marginally higher cactus and grass cover (Fig. 1). We detected no plant cover differences between restoration and reference plots for ST/S treatment, but richness was significantly lower in the restoration plots for total native, native grass, and native perennial plants (Fig. 1). There were no tree species in restoration plots and only three individual trees in reference plots. Reference plots had greater percentages of bare ground (ST/S, ST/T, and ST/T/S treatments) and litter (ST/T, T only, and marginally in ST/T/S treatments), whereas woody debris was higher in restoration plots in the T only and ST/T/S treatments (Table 3, Fig. 3).

SEEDING

Of the 11 species seeded, the following species were found in at least one study plot: *A. purpurea, B. aristidoides, E. farinosa, S. covesii, and L. tridentata* (Fig. 4). For these species combined, the total seeded species cover was not different between restoration and reference plots (Table 3, Fig. 1). *B. aristidoides* appeared more in the seeded treatments (ST/T/S and ST/S) than in unseeded (Fig. 4). *A. purpurea* and *L. tridentata* appeared in only one seeded treatment (ST/T/S) but also occurred in transplant-only plots that did not receive seeding (Fig. 4). All of the five seeded species that established appeared in both seeded and unseeded treatments, although *E. farinosa* appeared only in the reference plot of one seeded treatment (Fig. 4).

EFFECT OF CACTUS TRANSPLANTS

We found seven species of cacti in our plots with only one of those species found in the reference plots (Table 4). The mean density of cacti individuals was 1.02 (SE = 0.29) live and

TABLE 5.—Results of analysis comparing vegetation in plots with or without cacti, vertical mulch, combined cacti and vertical mulch, and woody debris using a Wilcoxon rank sums test to compare medians of response variables using only restoration treatment plots, excluding reference plot data. Presence or absence indicates the number of restoration plots with or without the independent variable, respectively. Cactus (living and dead) individuals include only those that were rooted in plot; cover includes species with presence in plot regardless if rooted in plot. Sites are in the McDowell Sonoran Preserve, Scottsdale, Arizona, U.S.A.

				Response variable				
Independent variable (binomials)	Presence (n)	Absence (n)	Wilcoxon statistic	Total cover (native and nonnative, excluding succulent cover)	Total native cover (excluding succulent cover)	Total native perennial cover (excluding succulent cover)	Total native annual cover	Total nonnative cover
Cactus individuals	21	20	Z	0.72	0.74	0.25	0.22	−0.54
Dead cactus individuals	9	32	Z	0.09	0.27	−1.15	0.72	0
Vertical mulch cover (includes dead cacti and dead shrub cover)	12	29	Z	0.62	0.64	−0.04	0.014	0.93
Cactus individuals + vertical mulch cover (includes dead cacti and dead shrub cover)	26	15	Z	−0.06	−0.2	0	−0.42	0.15
Woody debris cover > 2%	15	26	Z	−0.07	−0.07	2.24*+	−0.93	0.73
Woody debris cover > 5%	8	33	Z	1.27	1.33	1.75	0.56	0.35

* indicates significant at $P < 0.05$, + indicates a positive relationship between the response variable and presence of the independent variable

0.24 (SE = 0.08) dead cactus individuals rooted in each 2 m diameter (3.14 m^2) restoration plot, but the density differed significantly by treatment ($\chi^2 = 8.94$, df = 3, $P = 0.03$). The ST/T/S treatment had the highest density of cacti with a mean of 2.36 (SE = 0.93) per plot, which was significantly higher than the no transplant treatment (ST/S), which contained no cacti ($z = 2.88$, $P = 0.02$). The ST/T and T only treatments had 0.6 (SE = 0.4) and 0.65 (SE = 0.17) cacti per plot, respectively, and were not significantly different from the other treatments. Cactus cover and richness were higher in restoration plots (Table 3, Figs. 1&2). Compared to reference sites, restoration plots displayed higher cactus cover in all treatments with cactus transplants: T only, ST/T/S, and marginally in ST/T (Table 3, Fig. 1). Contrary to our prediction, we did not detect an effect of cactus transplants or combined transplants and vertical mulch on changes in native or nonnative plant cover (Table 5). In plots with more than 2% woody debris there was more native perennial cover (excluding cacti); however, when including only plots with more than 5% woody debris, the significant difference disappeared (Table 5).

DISCUSSION

Overall, native plant recovery seemed to be occurring on treated roads in the Preserve. However, native plant richness and functional group cover, especially cacti and shrubs, on the restored roads were not representative of the adjacent natural community. Although

FIG. 5.—Photo of study site RS16 with the treatment combination of soil treatment (ripping to at least 20–30 cm deep or soil addition of 30–50 cm depth and re-contouring), transplanting cacti, and seeding in McDowell Sonoran Preserve, Scottsdale, Arizona. The surrounding plant community is *Simmondsia chinensis* – mixed scrub association. Photo credit: Debbie Langenfeld, 2018

cacti were over-represented in the restoration treatments that included transplants, shrub cover and native grass, forb, and shrub richness lagged behind in the restoration sites, and the old roads remained obvious on the landscape (Fig. 5).

The transplant, soil, and seed treatments showed mixed success. Cactus transplants had a high success rate demonstrated by the higher cover of cacti in all of the restoration treatments that included transplants. Seeding was much less successful, with only 45% of the species (five of 11) appearing at the sites with little evidence that these species grew as a result of seeding. Further, in comparing the two treatment combinations that included seeding to the two that did not, no patterns emerged that indicate that seeding advanced restoration. Similarly, no patterns emerged when comparing the three treatments that included soil treatments to the one that did not. Our findings do not support our predictions that multiple inputs would increase similarity between restoration and reference areas. Rather, there appears to be a recovery lag in shrub cover, grass richness, and, in some cases, forb and shrub richness in these restoration sites, which the restoration inputs of soil, transplant, or seed treatments have not yet overcome.

As in other arid regions, recovery of degraded lands in the Sonoran Desert requires a long time, regardless of disturbance type. In the Tucson, Arizona, area, species density, cover, and diversity increased over 50–60 y since protection from grazing, until these indices reached a plateau (Guo, 2004). In a study at a site proximal to ours, 12 y after a 2005 wildfire in the Sonoran Desert, plant composition was still dissimilar between burned and unburned plots. Although there were no differences in overall perennial plant cover, succulent and shrub cover were greatest in unburned areas, and subshrub cover was highest in reseeded plots (Barron, 2018). In a study of the natural recovery of old roads after 88 y, soil nutrients beneath and between shrubs did not recover to levels of reference Mojave fertile shrub islands (Bolling and Walker, 2002). The type and severity of disturbance can affect the direction of succession and whether it is possible for a site to recover sufficiently to resemble reference conditions (McLendon and Redente, 1990; Bolling and Walker, 2002). These long recovery lags have many causes, including recovery of soil nutrients and soil nutrient patterns (Bolling and Walker, 2002), divergent seed banks in disturbed areas (Bekker *et al.*, 1997), the difficulty in matching germination requirements to field conditions (Adondakis and Venable, 2004), as well as granivory that can significantly reduce seed banks (Brown *et al.*, 1979b). Based on these lessons and the current trajectory, these Preserve sites will likely continue to recover slowly yet may never converge completely with the surrounding natural landscape.

Although native species may not recover quickly in arid lands, invasive species commonly thrive in restoration sites due to the treatments applied, dominance of weed species in the seed bank, or nonnative propagule pressure from nearby sites (Banerjee *et al.*, 2006; Rowe *et al.*, 2013; Fick *et al.*, 2016; Abella and Chiquoine, 2019). Disturbed areas also typically have less competition for light and space, creating opportunities for invasion (Hobbs and Huenneke, 1992). However, in our study, nonnative cover was low overall and predominantly found only in one treatment type, but it was higher in reference areas than on the restored roads. We could not determine if this was an effect of the restoration treatment or due to other causes.

Seeding is a common restoration practice for increasing native plant diversity and suppressing nonnative plants. Although purchasing and sowing seeds may seem relatively inexpensive, the success rate in arid lands is chronically low due to a combination of drought, wind, and granivory (Bainbridge, 2007), as well as environmental site conditions, seeding timing, species selection, genetic stock and germinability of seed, and associated restoration treatments (Abella *et al.*, 2009). Despite these constraints, we can continue to build our knowledge of which arid species establish well from seed and which treatments promote establishment (Abella and Newton, 2009; Abella *et al.*, 2009) as well as explore ways of protecting seeds through coatings, different planting techniques, agglomeration, and pellets (Madsen *et al.*, 2016). In our study there was little evidence that the seeded species established from the seeding treatments. Only five of the 11 species in the seed mix were present in any of our plots, and annual grass *B. aristidoides* contributed most to seeded species cover. However, the lack of differences between the restoration and reference plots made it difficult to link causality back to the seeding treatment. *B. aristidoides* could have established in the restoration plots and spread to the reference area. Alternatively, it is possible that *B. aristidoides* naturally occurred in the areas with the seed treatments and spread into the restoration areas. Because of the length of time since the restoration treatments and lack of available baseline data, we were not able to distinguish among these scenarios.

Creating vertical structure is another important tool that can aid with native plant establishment. In arid environments some perennial plants create "resource islands" that provide shelter, improve soil characteristics, and increase nutrients, symbionts, and organisms that promote establishment of new plants (Burns and Davies, 1986; Garner and Steinberger, 1989; Armbrust and Bilbro, 1997; Carrillo-Garcia *et al.*, 1999). Vertical mulch (standing dead material) has been shown to increase plant recruitment (Abella and Chiquoine, 2019) and ConMods serve the same purpose (Fick *et al.*, 2016). We had hypothesized that cactus transplants, vertical mulch, and woody debris would increase plant cover, but we did not detect an increase in plant recruitment associated with cacti transplants or vertical mulch. We did find that perennial plant cover was higher in plots with >2% woody debris, but that may have been an artifact of the shrubs and other perennial vegetation. Abella and Chiquoine (2019) found that vertical mulch increases recruitment of native and nonnative species at a small (0.25 m^2) scale but not at a larger (40 m^2) scale; therefore, we may have detected an effect had we sampled at a smaller scale. Other studies have found cactus improve site conditions and can lead to increased plant recruitment. In Mediterranean areas of North Africa, Italy, and Spain, *Opuntia ficus-indica* (L.) Mill. (prickly pear) is often planted as defensive hedges, which control erosion, particularly when planted along contours of slopes, and have shown improved soil physical and organic matter content under and directly adjacent to the hedges (Le Houérou, 1994). In a study of different aged plantations (<5 y, >20 y, and unplanted plots) of *O. ficus-indica* in arid Northeast Algeria, researchers found significant increases in vegetation cover and abundance with the prickly pear plantations (Neffar *et al.*, 2013). Although we did not detect an increase in plant recruitment, the cacti transplants could serve other restoration purposes, including deterring people from continuing to use the site or serving nurse plant functions (*e.g.,* improved soil characteristics and associations). In fact Abella and Chiquoine (2019) suggest, due to potential increase in nonnative species associated with vertical mulch, it may be better to use plant species that can provide the benefits of nurse plants (*e.g.,* soil cover, litter, wildlife forage) without supporting plant establishment.

SUMMARY AND IMPLICATIONS FOR MANAGEMENT

Five to 8 y since restoration treatments were applied in this Sonoran Desert ecosystem, neither of our predictions of recovery were fully supported. The number of restoration treatments applied did not improve restoration success, and, although many transplanted cacti survived, cacti, vertical mulch, or larger woody debris did not aid plant colonization. No clear patterns emerged about the soil treatments, and, with the exception of one species, seeded species did not establish. Given the difficulties associated with seeding in arid lands, we should consider a combination of informed seed mix selection; interventions and technology to protect seed from wind, desiccation, and granivory; and monitoring and reseeding as needed until conditions align with germination requirements. One of the most important considerations for any restoration project is protection from continued degradation (Bainbridge, 2007; Abdullah, 2015). This study provides further support indicating prevention of additional disturbance alone allows for re- establishment of some plant cover and species richness in degraded areas over time. In some situations, this may be the most cost-effective approach to restoration, although the result may be slow.

Acknowledgments.—We thank the City of Scottsdale for funding support, the McDowell Sonoran Conservancy Citizen Scientists who helped collect data, Steve Jones for his botany expertise, and Claire Miller, Scott Hamilton, and Leona Weinstein for sharing and compiling information on past restoration treatments critical to this manuscript.

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SUBMITTED 4 FEBURARY 2020 ACCEPTED 9 JULY 2020

APPENDIX A.—Plant species observed in restoration and reference plots ordered by prevalence across plots. Numbers indicate in how many restoration and reference plots that species was observed live. The code (nn) indicates nonnative

Species	Common name	Restoration plots (n)	Reference plots (n)
Chamaesyce polycarpa	Smallseed sandmat	32	28
Bouteloua aristidoides	Needle grama	24	16
Bromus rubens (nn)	Red brome (nn)	23	32
Pectocarya sp.		20	25
Erodium cicutarium (nn)	Redstem stork's bill (nn)	17	16
Cylindropuntia acanthocarpa var. coloradensis	Colorado buckhorn cholla	17	9
Schismus barbatus (nn)	Common Mediterranean grass (nn)	15	20
Sphaeralcea ambigua	Apricot globemallow	12	22
Aristida adscensionis	Sixweeks threeawn	12	8
Chamaesyce melanadenia	Red-gland spurge	12	7
Senna covesii	Coues' senna	11	20
Ambrosia confertiflora	Slimleaf bursage	11	5
Bouteloua barbata	Sixweeks grama	8	14
Eriogonum wrightii	Bastardsage	6	6
Lotus humistratus	Foothill deervetch	6	4
Echinocereus engelmannii	Engelmann's hedgehog cactus	6	0
Amsinckia sp.		5	19
Boerhavia intermedia	Fivewing spiderling	5	13
Lepidium lasiocarpum	Shaggyfruit pepperweed	5	9
Euphorbia sp.		5	8
Encelia virginensis	Virgin River brittlebush	5	4
Chamaesyce setiloba	Yuma sandmat	5	2
Daucus pusillus	American wild carrot	5	2
Ericameria laricifolia	Turpentine bush	4	8
Baileya multiradiata	Desert marigold	4	3
Cylindropuntia bigelovii var. bigelovii	Teddybear cholla	4	0
Opuntia phaeacantha	Tulip pricklypear	4	0
Portulaca oleracea (nn)	Little hogweed (nn)	3	5
Lotus strigosus var. tomentellus	Strigose bird's-foot trefoil	3	3
Aristida purpurea var. parishii	Parish's threeawn	3	2
Opuntia engelmannii	Cactus apple	3	0
Calliandra eriophylla	Fairyduster	2	6
Lotus rigidus	Shrubby deervetch	2	5
Plantago patagonica	Woolly plantain	2	5
Amsinckia menziesii var. intermedia	Common fiddleneck	2	4
Plagiobothrys arizonicus	Arizona popcornflower	2	4
Porophyllum gracile	Slender poreleaf	2	4
Chamaesyce capitellata	Head sandmat	2	2
Larrea tridentate	Creosote bush	2	2
Marina parryi	Parry's false prairie-clover	2	2
Opuntia engelmannii	Cactus apple	2	0
Senegalia greggii	Catclaw acacia	1	10
Mirabilis laevis var. villosa	Wishbone-bush	1	9
Encelia farinosa var. farinosa	Brittlebush	1	3
Bothriochloa barbinodis	Cane bluestem	1	2

APPENDIX A.—Continued

Species	Common name	Restoration plots (n)	Reference plots (n)
Dasyochloa pulchella	Low woollygrass	1	1
Draba cuneifolia var. integrifolia	Wedgeleaf draba	1	1
Euphorbia abramsiana	Abrams' sandmat	1	1
Gutierrezia sarothrae	Broom snakeweed	1	1
Lotus sp.		1	1
Stephanomeria pauciflora	Brownplume wirelettuce	1	1
Cylindropuntia fulgida	Chain-fruit cholla	1	0
Lupinus sparsiflorus	Coulter's lupine	1	0
Mammillaria grahamii	Graham's nipple cactus	1	0
Argythamnia neomexicana	New Mexico silverbush	0	9
Lycium exsertum	Arizona desert-thorn	0	5
Physalis hederifolia	Ivyleaf groundcherry	0	3
Adenophyllum porophylloides	San Felipe dogweed	0	2
Amaranthus fimbriatus	Fringed amaranth	0	2
Astragalus nuttallianus	Smallflowered milkvetch	0	2
Phacelia distans	Distant phacelia	0	2
Bowlesia incana	Hoary bowlesia	0	1
Brickellia coulteri	Coulter's brickellbush	0	1
Calandrinia ciliate	Fringed redmaids	0	1
Chamaesyce pediculifera	Carrizo Mountain sandmat	0	1
Cryptantha sp.		0	1
Kallstroemia grandiflora	Arizona poppy	0	1
Muhlenbergia porter	Bush muhly	0	1
Parkinsonia florida	Blue paloverde	0	1
Parkinsonia microphylla	Yellow paloverde	0	1
Parkinsonia sp.		0	1
Pholistoma auritum var. arizonicum	Arizona fiestaflower	0	1
Sonchus sp.		0	1
Stylocline sp.		0	1
Tidestromia lanuginosa	Woolly tidestromia	0	1
Vachellia constricta	Whitethorn acacia	0	1
Ziziphus obtusifolia var. canescens	Lotebush	0	1