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CONSERVATION ISSUES

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Revegetating Disturbance in National Parks: Reestablishing Native Plants in Saguaro National Park, Sonoran Desert

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ABSTRACT: Habitat in national parks is periodically disturbed for road maintenance, and few revegetation protocols of known financial cost exist for this disturbance, especially in deserts where extreme environments constrain natural revegetation. In Saguaro National Park of the Arizona Upland Subdivision of the Sonoran Desert, we monitored survival of 1587 outplanted individuals of 33 native perennial species for revegetating a 2006 re-construction project of the park's Cactus Forest Drive. Outplants were caged to deter vertebrate herbivory and provided with supplemental water in the hot, dry part of summer. Overall plant survival was high – 84% (1340 of 1587 outplants) – one year after planting. Survival was generally consistent across species, with survival >50% for 32 of 33 (96%) species. Survival of two tree species (*Parkinsonia microphylla* (yellow paloverde) and *Prosopis velutina* (velvet mesquite)), monitored for two years, declined little or not at all from the first to the second year and was 55% and 67%, respectively, at two years. The project met management goals of reestablishing a 1:3 lost: restored ratio of tree density required for habitat restoration of an endangered owl species and of reestablishing a range of native species for aesthetic and vegetation structural restoration. Budget estimates indicated a cost per plant of $54 from grow-out in a nursery through plant maintenance in the field. This cost also included supporting activities of site preparation, exotic plant control, and effectiveness monitoring. The monitoring data, combined with longer term observations, suggest that the National Park Service's revegetation strategy effectively established a range of native plant growth forms and met habitat restoration targets.

Index terms: ecological restoration, outplanting, revegetation, road

INTRODUCTION

Effective protocols of known financial cost are often needed for revegetating planned and unplanned disturbances. In U.S. national parks, for example, roads need to be modified (e.g., widened or re-routed) for environmental concerns (e.g., improving water runoff management) or traffic safety (Peterson et al. 2004). These planned projects frequently require that post-construction disturbances are revegetated to curtail negative off-site impacts to surrounding natural areas, reestablish aesthetics, and promote habitat recovery (Tyser et al. 1998; Paschke et al. 2000). Reliable revegetation protocols are also important for supporting decisions about attempting revegetation of unplanned disturbances. Managers can make decisions based on considerations such as how effective active revegetation is compared to natural recovery and the resources and financial expenditures needed to achieve the revegetation (Bean et al. 2004).

Developing effective techniques for revegetation is especially challenging in arid lands, where low and variable precipitation, extreme temperatures, granivory, and herbivory limit both natural and active reestablishment of plant populations (Bainbridge 2007). In the Sonoran Desert of the American Southwest, for example, revegetation efforts reported in the literature have displayed mixed effectiveness. For revegetating highway borrow pits, Bainbridge and Virginia (1990) found that one-year survival of nursery-grown *Parkinsonia florida* (Benth. ex A. Gray) S. Watson (blue paloverde) outplants was 80% with active irrigation, whereas seeding did not successfully establish this species. On derelict farmland, Bean et al. (2004) reported that one-year survival exceeded 60% for outplants (all plants were irrigated) that had been greenhouse-grown in 3.8-L containers of some species such as *Ambrosia dumosa* (Gray) Payne (burrobush), *Larrea tridentata* (Sessé & Moc. ex DC.) Coville (creosote bush), *Pleuraphis rigida* Thurb (big galleta), and *Atriplex canescens* (Pursh) Nutt. (fourwing saltbush). On the other hand, Cox et al. (1987) found that survival of outplanted *Bouteloua curtipendula* (Michx.) Torr. (sideoats grama) and *Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths (blue grama) was low after 2.5 years, at only 18% and 28%, respectively. These and other studies indicate that revegetation effectiveness can sharply vary depending on method (seeding versus planting), species, and treatment (e.g., irrigation or cages to provide herbivory protection) used for revegetation (Roundy et al. 2001; Bean et al. 2004; Abella and Newton 2009). No well-established protocols exist for revegetating planned or unplanned disturbances in deserts, and financial cost projections for accomplishing revegetation are rare.

We monitored plant survival to assess outplanting effectiveness for revegetating disturbed roadsides in Saguaro National Park, Sonoran Desert. We also estimated a budget to quantify the resources and finances required to accomplish the revegetation.

METHODS

Study Area

We conducted this study within the 37,006-ha Rincon Mountain District of Saguaro National Park, beginning 1 km east of the city boundary of Tucson, Arizona (Figure 1). The park lies within the Arizona Upland Subdivision of the Sonoran Desert, characterized by the columnar cactus saguaro (*Carnegiea gigantea* (Engelm.) Britton & Rose), and containing a scrubland or low woodland physiognomy with shrub-trees, cacti, forbs, and graminoids (Brown 1994). Climate consists of an average of 29 cm/yr of precipitation, average daily July high temperature of 37 °C, and an average daily January low temperature of 4 °C (Tucson Airport Weather Station, 787 m elevation, 1930–2011 records; WRCC (2012)). Rolling hills, alluvial fans, and concave drainageways are the principal topographic features. Soils are primarily derived from granite and classified as Torriorthents and Haplargids (Cochran and Richardson 2003). Livestock grazing has not been authorized in the park since 1976, but native herbivores such as *Lepus californicus* Gray (black-tailed jackrabbit) and *Sylvilagus audubonii* Baird (desert cottontail) are present. The park receives over 600,000 human visitors annually, including about 30,000 cars, 23,000 bicyclists, and 6000 walkers on the park's main road, Cactus Forest Drive (National Park Service, Public Use Statistics Office, https://irma.nps.gov/Stats/).

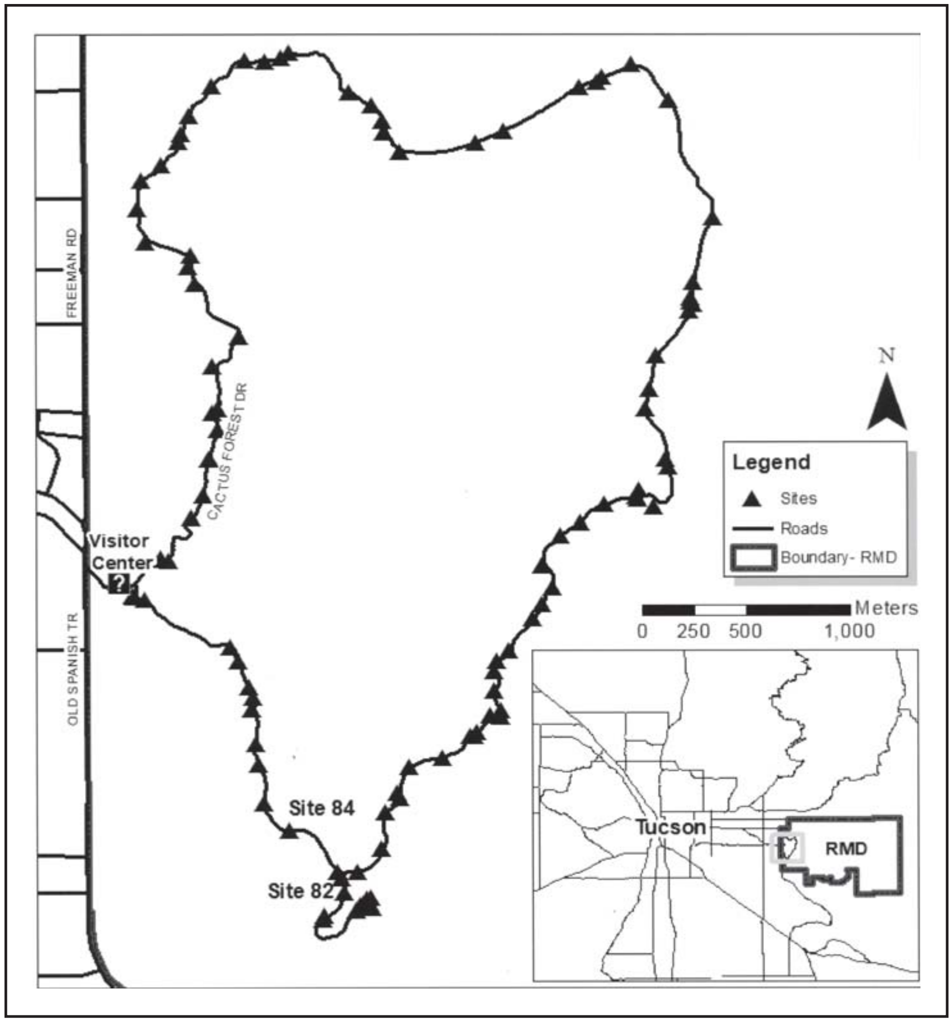

Figure 1. Location of revegetation sites (triangles) along Cactus Forest Drive of the Rincon Mountain District (RMD) of Saguaro National Park, Arizona, 2007. The inset map displays the location of the RMD and the Cactus Forest Drive in the western part of the RMD. Sites numbered as 82 and 84 in the main figure correspond with photos in Figure 2.

The specific study area was a 3.2-ha area corridor along the 13-km Cactus Forest Drive on the western side of the Rincon Mountain District (Figure 1). This road was scheduled for re-construction as part of periodic road maintenance activities conducted by the Federal Highway Administration in national park units (Tyser et al. 1998; Petersen et al. 2004). Construction activities were performed in summer 2006 and consisted of milling existing layers of chip seal to create a road base and adding a 5-cm thick layer of asphalt to create a new road surface. Additionally, approximately 100 informal roadside pullouts were to be closed and restored, some existing pullouts paved with designated parking spaces, and roadside natural history exhibits installed at nine pullouts.

The road project affected habitat for *Glaucidium brasilianum cactorum* Gmelin (cactus ferruginous pygmy-owl), which was listed as an endangered species at the time (US Fish and Wildlife Service 2011). As a result, the project Biological Assessment/Biological Opinion, approved by the US Fish and Wildlife Service, required replacing destroyed trees for habitat restoration at a ratio of three trees for every tree destroyed. A total of 38 trees of *Parkinsonia microphylla* Torr. (yellow paloverde) and *Prosopis velutina* Woot. (velvet mesquite) were removed by the project, so ≥114 restored trees were needed to survive for >2 years to meet habitat restoration targets.

Plant Grow Out

Beginning two years before construction, park staff collected seed from the two tree species and other native perennial species growing along the roadside to be reconstructed (Table 1). Seeds were cleaned and refrigerated until grow out in a nursery. In April 2006, seed was sown in pots, and reseeded as necessary to produce a seedling in each pot. Plants were grown in an outdoor nursery under shadecloth (open to rainfall) at the Natural Resources Conservation Service's Plant Materials Center (Tucson, Arizona). To encourage deep roots, which can be important for successful establishment of desert plants (Bainbridge 2007), "tall" pots were used for propagation. The taller-statured tree species (*Parkinsonia*, *Prosopis*, and *Acacia*) were grown in 33-cm tall pots that were 8 × 8 cm at the top and 10 × 10 cm at the bottom. The bottom consisted of a removable 0.5-cm mesh size hardware cloth panel that allowed full drainage, and when removed at the time of planting, allowed the plants and potting soil to slide into the planting hole. The other species were grown in pots of the same dimensions except that they were 23 cm tall. Pots were either plastic or paper, and because survival was high across outplants, pot types are not differentiated. The potting soil mixture consisted of 10 parts sand : 15 parts perlite : 30 parts potting soil (Sunshine Professional Growing Mix, Sun Gro Horticulture, Inc., Bellevue, Washington). Pots were regularly watered to soil moisture capacity during the 8-month growth period. Plants were moved to a shadecloth-covered holding area at the park in January 2007 where they were watered periodically and kept until outplanting during 6 weeks of revegetation activities.

Table 1. Survival of native plant species planted in 2007 along roadsides of Saguaro National Park, Arizona, one and two years after outplanting for tree species and one year after outplanting for other species.

Species[a]	No. planted	Survival (%)
Grass		
Aristida purpurea	34	94
Bothriochloa barbinodis	48	85
Bouteloua repens	77	92
Digitaria californica	29	100
Heteropogon contortus	43	98
Muhlenbergia porteri	32	97
Setaria macrostachya	31	90
Forb		
Baileya multiradiata	2	50
Dalea pringlei	16	75
Isocoma tenuisecta	112	86
Menodora scabra	44	75
Nicotiana obtusifolia	4	75
Psilostrophe cooperi	37	89
Senna covesii	30	60
Sphaeralcea ambigua	9	100
Zinnia acerosa	193	96
Shrub		
Calliandra eriophylla	26	88
Dalea pulchra	16	50
Encelia farinosa	94	93
Ephedra trifurca	13	15
Ericameria laricifolia	9	89
Fouquieria splendens	80	89
Jatropha cardiophylla	1	100
Larrea tridentata	85	80
Simmondsia chinensis	50	78
Trixis californica	49	90
Shrub-tree		
Acacia constricta	56	86
Acacia greggii	46	100
Celtis ehrenbergiana	30	93
Gossypium thurberi	31	94
Tree		
Parkinsonia florida	1	100 (100)[b]
Parkinsonia microphylla	123	62 (55)
Prosopis velutina	136	67 (67)
Total	**1587**	**84**

[a]Nomenclature follows NRCS (2012).

[b]Percent survival after two years is provided in parentheses after the first-year survival.

Revegetation Procedure

Outplanting occurred in January-February 2007 at 104 locations – roadside berms and decommissioned vehicle pullouts – along Cactus Forest Drive (Figure 1). Planting on soft soils was done by digging holes with a shovel and allowing the entire contents (potting soil and plant) of pots to empty out of pots into the holes. On hard-packed soils, holes were dug using a one-person auger or with a Poinjar rock drill. Planting holes were saturated with water prior to planting and were re-saturated once the plant was in place. The species mixture and density planted at each of the 104 locations were prescribed based on the species composition of adjacent undisturbed land, balanced with the available species of propagated plants. Tree species were placed at all of the larger sites and were planted at least 4 m from the edge of the road to eliminate the need for future pruning. In all, 1587 propagated plants of 33 species were outplanted on 3.2 ha, corresponding to a density of 496 plants/ha. After planting, small depressions ("saucers") were excavated to a depth of approximately 5 cm and a distance of approximately 25 cm beyond the root ball to catch and retain moisture around each outplant (Bainbridge 2007). Cages 0.7 m tall and 0.5 m in diameter and made of chicken wire (3-cm openings) were installed around each outplant, other than *Fouquieria splendens* Engelm. (ocotillo), to deter vertebrate herbivory. Vertical mulch, consisting of an *Opuntia* spp. pad or an approximately 5-cm diameter branch, was placed inside each cage to provide shade and microclimate amelioration.

Other associated activities with the revegetation included additional "vertical mulching" and salvaging and replanting 3000 *Mammillaria* spp. cacti and other cactus species across locations. Vertical mulch consisted of dead plant material collected on site: tree limbs, *Fouquieria splendens* pieces, *Opuntia* pads and stems, and other material that was "planted" in the ground. Vertical mulch can provide several functions by mimicking the surrounding desert (which has standing dead plant debris) to camouflage the restoration site, creating shade, providing wind breaks, and serving as a visual barrier that may reduce the possibility of anthropogenic disturbance (Bainbridge 2007).

Plant and Site Maintenance

Maintenance activities during the first two years after planting included watering plants, removing exotic plants, and removing herbivory cages at the end of the study two years after planting. Water was delivered using twenty 19-L water containers in the back of a pickup truck, and each outplant was hand watered from a 19-L container. Each outplant was watered six times during the hot, dry period of the summer (May–July) for each of the first two years after planting, with 3 L delivered to each outplant during each watering. The entire Cactus Forest Road was walked during October 2007 to map and treat exotic plants at the revegetated sites and within 1 m of the road. Fourteen species were removed through hand pulling, with the major species being *Eragrostis lehmanniana* Nees (Lehmann lovegrass).

Monitoring and Analysis

All outplants were inventoried in January 2008 to quantify one-year survival and trees were also inventoried in January 2009 to quantify two-year survival. While longer term monitoring is ideal, not all of the forbs have long life spans (some live <5 years); thus, park managers chose to invest the resources into monitoring the longer-lived trees for the additional year. Moreover, the goal of the revegetation project was to quickly provide plant cover in <2 years to these disturbed sites, so short-term monitoring was designed to quantify whether that objective was met. A rule of thumb for outplanting in deserts is that achieving a target of ≥50% survival is considered good (Abella and Newton 2009). An additional target for the project was to have ≥114 surviving trees to mitigate habitat loss for *Glaucidium brasilianum cactorum* from construction activities. We calculated the proportion surviving for each outplanted species.

To quantify resources and finances required for the project, we included each stage of the revegetation, starting with plant propagation through monitoring. We compiled costs for the plant grow out in the nursery, preparing sites and planting in the field, maintenance watering (e.g., fuel and water costs), and control of exotic plants. We also calculated the amount of water, time, and kilometers driven required to perform maintenance watering after planting.

RESULTS

Effectiveness of Revegetation

All of the 33 species except *Ephedra trifurca* Torr. ex S. Watson (longleaf jointfir) met the target of ≥50% survival after one year (Table 1). Moreover, survival was generally consistent among species, with 15 of the species exhibiting ≥90% survival and 23 of the species exhibiting ≥80% survival. Overall survival was 84% (1,340 of 1587 total outplants). Survival decreased little or not at all from one to two years for the trees monitored for two years. While quantitative data were not collected after the second year, longer term photographic documentation to six years after treatment (January 2013) suggested continued visual blending of the revegetated areas with their undisturbed surroundings (Figure 2).

Resources Required

The approximate estimated cost for the revegetation project totaled $85,870 (Table 2). This translated to approximately $54/plant that was outplanted and also included the supporting activities of general site preparation (e.g., contouring planting sites using hand tools), installation of vertical mulch, treatments to control exotic plants, and effectiveness monitoring.

DISCUSSION

Considering the high plant survival, exceeding required tree replacement ratios for habitat restoration, and the fact that the project can be viewed by approximately 600,000 human visitors/year, managers believed the project successfully met goals. The project exceeded the targets of ≥50% survival and ≥114 trees surviving for owl habitat mitigation. Park managers considered the project to have accomplished the goal of rapid revegetation of the disturbed roadside. Moreover, the project is among the most effective revegetation projects in the Sonoran Desert reported to date and resulted in the greatest number of established species compared to any planting or seeding study. For example, Abella et al. (2009) included 28 species in their seed mix, with 14 species established by one year after seeding and only five species occupying ≥50% of 10-m^2 plots three years after seeding. Other seeding studies in the Sonoran Desert have reported no (Bainbridge and Virginia 1990; Woods et

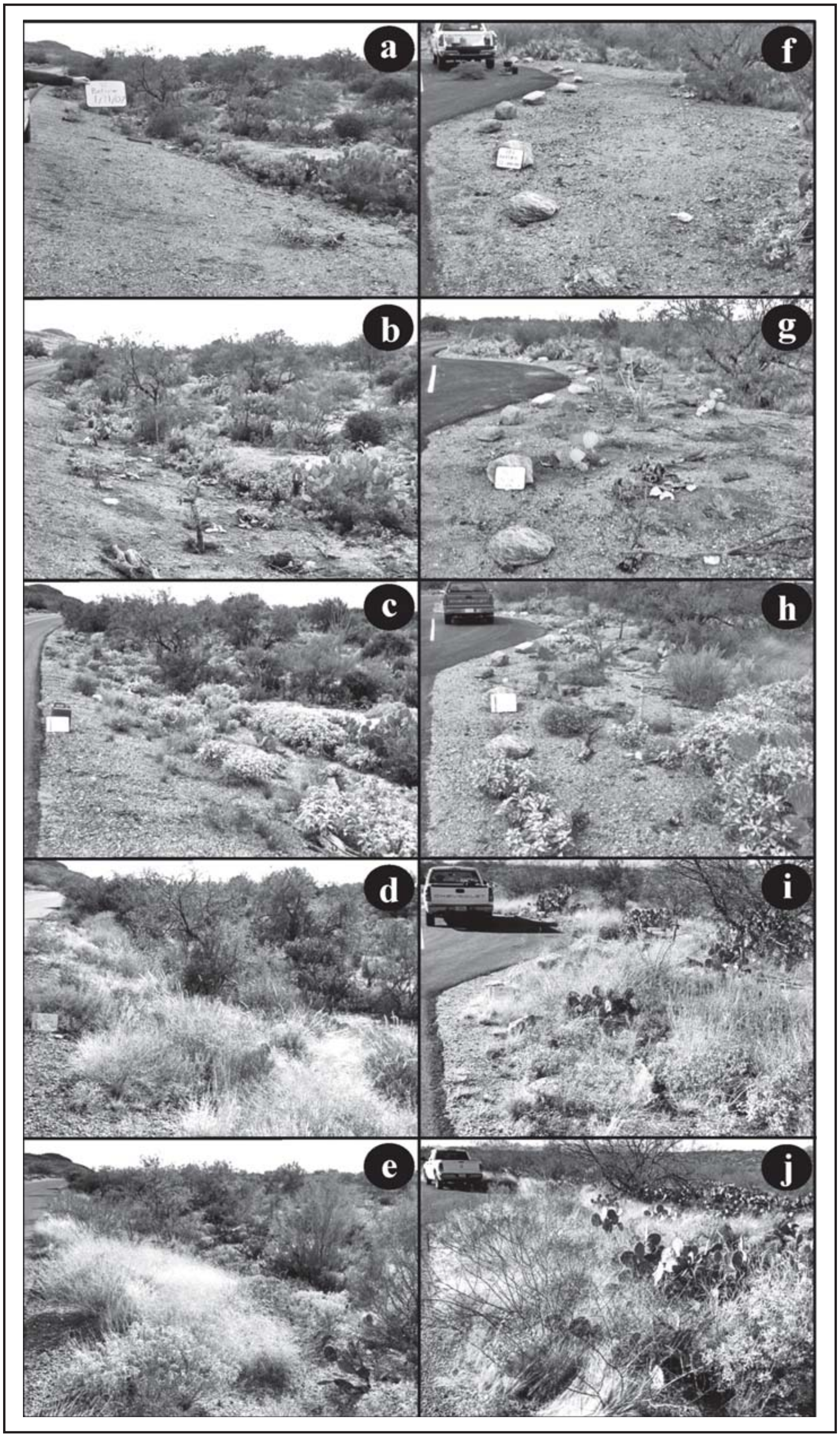

Figure 2. Repeat photographs of revegetation sites in Saguaro National Park, Arizona. The left panel shows site 82 and the right panel shows site 84, corresponding to Figure 1. Site 82: a) before restoration in January 2007, and after restoration in b) January 2007, c) September 2007, d) January 2009, and e) January 2013. Site 84: f) before restoration in January 2007, and after restoration in g) January 2007, h) September 2007, i) January 2009, and j) January 2013. Photos by K.L. O'Brien except for January 2007 by Kate Smith Connor.

al. 2012) or minimal plant establishment (Bean et al. 2004), or have noted limited establishment based on retrospectively measuring plant community composition of seeded sites (Judd and Judd 1976; Jackson et al. 1991; Banerjee et al. 2006). The next most species-rich outplanting study in the Sonoran Desert, Bean et al. (2004), reported that at least six species of shrubs and grasses exhibited ≥69% one-year survival on derelict farmland. Outplants in their study were grown in 3.8-L pots and were also irrigated, and the study site was much drier (19 cm/year average rainfall) than our site (29 cm/year average rainfall). In reviewing other outplanting studies, we found that *Parkinsonia florida*, *Prosopis glandulosa* Torr. (honey mesquite), *Fouquieria splendens*, *Ambrosia dumosa*, *Atriplex canescens*, and *Larrea tridentata* constituted some species of our study that also were successfully established in other studies (Bainbridge and Virginia 1990; Bainbridge 1994; Bainbridge et al. 2001).

Our results of reasonably consistent survival across species differ from other studies that have found species-specific outplant survival (Abella and Newton 2009). We suspect that intensive care of plants in the nursery and caging and irrigation might have tempered variation among species in our study, but other possibilities cannot be dismissed.

While monitoring was conducted only for first-year survival of all outplants and for first- and second-year survival for trees, we found that survival declined little (<5%) from the first to the second year for the trees. These results supported those of Abella et al.'s (2012) outplanting of 10 species (including forbs, grasses, and shrubs) in the Mojave Desert, where survival declined <10% from the first year to the third year.

Several factors are important to consider when evaluating if the revegetation technique reported here would be effective elsewhere. Precipitation in 2006, the year before outplanting, was 30 cm, near (104%) the long-term average (WRCC 2012). Precipitation in 2007 (25 cm, 86% of average) and 2008 (22 cm, 76% of average), the

Table 2. Summary of estimated financial cost, resources required, and labor for a revegetation project implemented in 2006–2008 along roadsides of Saguaro National Park, Arizona.

Item	Cost ($)	Description
Nursery grow out [a]	4,600	Propagate 1587 outplants
Revegetation [b]	76,300	Prepare sites, vertical mulch, install plants and cages
Maintenance watering [c]		
Water	43	53,753 L of water at $0.0008/L
Fuel	274	1891 km driven (24 km/3.8 L fuel at $3.50/3.8 L)
Labor	3,875	(310 hrs at $12.50/hr)
Weeding		
Fuel	28	193 km driven (24 km/3.8 L fuel at $3.50/3.8 L)
Labor	750	(60 hrs at $12.50/hr)
Total cost	85,870	

[a] Seed-collection costs are not included. Seed collection was done by Saguaro National Park staff when working at sites prior to implementation of the project. The nursery grow out was done at the Natural Resources Conservation Service's Plant Materials Center (Tucson, Arizona) and included supplies (e.g., potting soil), watering, and performing plant care.

[b] Revegetation activities were performed by contract and included laying out sites, collecting and installing vertical mulch, acquiring and constructing cages, installing the 1587 outplants, performing the initial watering, conducting initial exotic plant control treatments, and general site care until the project entered the maintenance phase.

[c] Quantity of water used was recorded for each trip. City of Tucson 2012 commercial potable water rates were used. Approximately 3 L of water was provided to each outplant on each visit, with 133 round-trips on the full 13-km Cactus Forest Drive and 22 round-trips on the two-way traffic portion of the drive (8 km each round trip). Labor included hourly salary. For efficiency, monitoring of plant survival and photo documentation were performed during maintenance site visits.

first two years survival was monitored, was less than average. While precipitation following outplanting was below average, average precipitation is still greater at 29 cm/yr in the study area (typical of Sonoran Desert Uplands) than in many other North American desert areas that have <20 cm/yr of precipitation (Brown 1994). Monsen et al. (2004) suggested that revegetation through seeding is difficult to achieve when precipitation averages <20 cm but did not provide lower limits for outplants, which are more frequently irrigated. The roadside environment also could have influenced results. On one hand, roadsides can accumulate moisture because of runoff from the road (Brooks and Lair 2009). On the other hand, exotic plants can be more troublesome along roadsides, though not always (Craig et al. 2010). Exotic plants were treated in this project.

It is typical for costs per plant to be in the range of tens of dollars for desert revegetation projects because a series of steps ranging from seed collection through grow out and maintenance in the field are required to provide field outplants (Bainbridge 2007). The project costs reported here further include several supporting activities such as exotic plant control and documenting effectiveness of the project. Several actions were performed to efficiently use the project budget, such as conducting monitoring and assessment activities during the course of other activities (e.g., exotic plant control). Use of volunteers or youth conservation corps can also help reduce costs on these types of projects, while engaging a range of people, and were used in other aspects (e.g., salvaging plants) of the overall road project.

Many of the resources required for revegetation projects such as this one are fixed (e.g., plant grow out). The major areas where managers might have flexibility for reducing resource inputs likely are grazing protection and irrigation (Table 2). Research in the Mojave and Sonoran Deserts suggests that influences of grazing protection on outplant survival are species- and site-specific, likely a function of palatability of the outplant species and intensity of herbivory (Bainbridge 1994). Grazing protection was provided to all outplants in our project, and future research that assesses which plants most require protection might help reduce the number of cages installed and removed. Effectiveness of irrigation also has been situational specific in southwestern deserts (Abella and Newton 2009). This is likely a function of drought tolerance of the species, precipitation during the project, and interactions of water with other factors (e.g., herbivory). Additional research, such as Roundy et al.'s (2001) study, which assessed moisture requirements for early survival of a range of native species, might help to focus irrigation on those species most requiring it. Moreover, drought-tolerant species that least require irrigation could be favored in projects where extensive irrigation is not feasible (Newton 2001). General ecological literature might provide some expectations as to the most drought-tolerant species (Smith et al. 1997), which could then be tested for suitability in revegetation.

While the data revealed that revegetation targets were met, further work is needed to understand what functional benefits might accrue from revegetation. Monitoring beyond establishment of the revegetation individuals themselves is rare, with Grantz et al.'s (1998) study for how revegetation reduced fugitive dust in the Mojave Desert being one of the few in southwestern deserts. Monitoring whether the outplants themselves produce seed to facilitate recruitment of their own populations, or whether revegetation facilitates recruitment of other species, could be informative for designing revegetation treatments that maximize benefits. A limitation of outplanting, for instance, is that often it is not feasible to revegetate large areas. However, if establishing revegetated "islands" can initiate or speed succession, the area positively influenced by outplanting would be much greater than suggested by just the planted area (Reever Morghan et al. 2005).

This study reports a protocol effective for meeting revegetation targets even in relatively dry years in a desert ecosystem. Considerable investment in plant materials development, planting effort, and maintenance were required to achieve this success. Future work could explore ways to reduce costs and identify potential functional benefits of revegetation.

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Scott Abella has founded Natural Resource Conservation LLC, dedicated to providing applied science support for resource and biodiversity conservation. He has an applied ecological science focus across the disciplines of restoration ecology, invasive species management, fire ecology, and plant community ecology in desert and forest ecosystems.

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