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ABSTRACT

The Twist Hollow restoration site on BLM land near St. George, Utah, had been badly disturbed by sand mining, rock quarrying, dumping, off-road vehicles and target shooting prior to its closure and treatment. In December 1992 the site was sculpted and drill seeded with Indian ricegrass (Stipa hymenoides)*, sand dropseed* (Sporobolus cryptandrus*), galleta (*Hilaria jamesii*), gooseberryleaf globemallow (*Sphaeralcea grossulariifolia*) Palmer penstemon (*Penstemon palmeri*), fourwing saltbush (*Atriplex canescens*) and winterfat (*Krascheninnikovia lanata*) in an effort restore natural vegetation and desert tortoise habitat. Vegetation was sampled before and after treatment and subsequently monitored over a period of 14 years. With the exception of winterfat, all the seeded species established and increased in density and/or cover during the period 1993-1998. Cheatgrass (*Bromus tectorum*) also increased and became dominant during this period. Seeding was most successful on a rockier substrate where fourwing saltbush became a dominant shrub. Drought conditions after 1998 corresponded with declines in most seeded species while broom snakeweed (*Gutierrezia sarothrae*), hairy goldenaster (*Chrysopsis villosa*), desert globemallow (*Sphaeralcea ambigua*) and sandsage (*Artemisia filifolia) *increased through recruitment from surrounding vegetation. Sandsage was the dominant shrub of nearby undisturbed sandy sites and grew rapidly following establishment in a sandier portion of the treated area. Cheatgrass and other annuals fluctuated from year to year in the treated area but had lower density and cover than nearby untreated areas throughout the monitoring period. We conclude that the restoration project's objectives have been met to varying degrees despite the limited persistence of the seeded species. Further research into management techniques aimed at reducing annual grasses and enhancing high-quality desert tortoise forage is recommended.*

INTRODUCTION

The Red Cliffs area near St. George, Washington County, Utah, is valued for its striking scenery and its ecological significance as part of the Mojave Desert ecosystem providing habitat for the threatened desert tortoise (*Gopherus agassizi*). The area is characterized by Mojave Desert climate and vegetation superimposed on colorful geological strata typical of the nearby Colorado Plateau. Exposed sandstone formations have weathered and eroded to produce sandy soils punctuated by sandstone cliffs and outcrops (Mortensen and others 1977). Much of the area is public land administered by the Bureau of Land Management (BLM) where a variety of activities have taken place including livestock grazing, mining and off-road vehicle use (BLM, pers. comm.). Recently BLM management of the area has shifted pointedly toward habitat conservation in conjunction with (1) listing of the desert tortoise in this area as a threatened species on April 2, 1990 (USFWS 1990), (2) designating the area as critical habitat on February 8, 1994 (USFWS 1994) and (3) development of the Washington County, Utah Habitat Conservation Plan and the establishment of the 62,000-ac Red Cliffs Desert Reserve (BLM 2008; Smith and Rose 1996). Efforts are now underway to restore native vegetation on degraded lands resulting from earlier activities within the reserve (Rose and Duck 2001).

Restoration of native vegetation in the Mojave Desert ecosystem is complicated by a limited and fluctuating moisture supply for seed germination and establishment (Allen 1995; Bainbridge 2007; Stevens 2004). Cryptobiotic crusts, which provide soil stability, moisture retention and nutrient inputs to desert plants, are often deficient in disturbed sites where restoration is desired (Belnap 1995). Competition from non-native plants, especially invasive annuals such as brome grasses (*Bromus* spp.), is another factor that may limit restoration success in the Mojave Desert (Beatley 1966; Lovich and Bainbridge 1999). Although non-native annuals may contribute forage for the desert tortoise and other wildlife (Grover and DeFalco 1995; Schiffman 1994), their net effect on biodiversity and ecosystem functioning is typically negative because of their dominating effect and their production of fine fuel that facilitates the spread of damaging wildfires (Brooks and Berry 2006; Brooks and Matchett 2006; D'Antonio and Vitousek 1992).

Despite the challenge of the task, the BLM has carried out a series of restoration projects at the Red Cliffs Desert Reserve using reclamation technology (Bainbridge 2007; Thornburg 1982). An early project was initiated in 1992 with the goal of reclaiming and restoring two abandoned quarries. This paper reports the effects of this restoration project on vegetation establishment and subsequent vegetation development and dynamics over a period of 14 years following treatment, offering a longer-term view than a previous report spanning two years (McArthur and Sanderson 1996). Permanent plots provide the opportunity to assess vegetation changes and relate them to conditions during the monitoring period.

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MATERIALS AND METHODS

Study Area

The Twist Hollow restoration area (113^o 36' 10" W longitude, 37^o 09'13" N latitude) is located on the east side of Utah State Highway 18 three km north of St. George, Washington County, Utah at an elevation of about 1010 m. The average annual precipitation at St. George during the 30-year period preceding this study was 204 mm with 64 percent of that falling Oct. 1 to March 31 (NOAA 2008). In common with other Mojave Desert locations precipitation patterns are erratic but the July-Sept. period receives approximately twice as much precipitation as the Apr.-June period (NOAA 2008). The area is topographically diverse with Navajo Sandstone outcrops towering over washes and wind-blown deposits of loamy fine sand of the Pintura Series (McArthur and Sanderson 1994; Mortensen and others 1977).

The primary treated site for the Twist Hollow restoration project, the Sand Pit, covers ca. three ac of sand deposits stretching from sandstone cliffs to the east and north to Highway 18 on the west (figure 1). Sand was mined from this area prior to the 1990s and its accessibility also led to widespread refuse dumping, off-road vehicle use, and target shooting activities. A secondary treatment site, the Rock Quarry, is located ca. 200 m northeast of the Sand Pit in a half-ac hollow of a northeast-facing sandstone outcrop above the Twist Hollow arroyo (figure 1). Soil and vegetation in the Rock Quarry hollow were disturbed during a period of rock quarrying prior to its closure at the time of the restoration project (BLM, pers. comm.).

Treatment

Physical site preparation and seeding of the Sand Pit and Rock Quarry sites were performed by BLM field crews from the Cedar City District Office. Prior to seeding which took place on December 7-8, 1992, the sites were cleared of refuse, sculptured with a bladed tractor and, in the case of the Rock Quarry, explosives, to give the area a natural appearance. The sites were disked before seeding (BLM, pers. comm.).

The sites were seeded with native plants with a rangeland drill at the rate of 19.5 lbs of seed per ac. The seed mix contained 8.0 lbs/ac Indian ricegrass (*Stipa hymenoides*), 2.5 lbs/ac sand dropseed (*Sporobolus cryptandrus*), 1.0 lbs/ac Palmer penstemon (*Penstemon palmeri*) and 2.0 lbs/ac each of galleta (*Hilaria jamesii*), gooseberryleaf globemallow (*Sphaeralcea grossulariifolia*), winterfat (*Krascheninnikovia lanata*) and fourwing saltbush (*Atriplex canscens*) (BLM, pers. comm.).

Data Collection

On November 25, 1992, prior to seeding, representative study plot locations were identified, referenced in relation to nearby topographic features and marked with buried steel rebars. Following seeding we were able to relocate the plots with the aid of a metal detector and the rebars were then positioned above ground for ease of relocation. Two of the Sand Pit plots were located in intact vegetation that was not disturbed by sculpting or seeding and served as control plots (one of these was added following seeding in 1993). One of the original Rock Quarry plots became partially covered by rubble and was subsequently omitted from our analysis. Here we report the results from 12 plots in 3 treatments: 8 Sand Pit Seeding plots, 2 Sand Pit Control plots and 2 Rock Quarry Seeding plots (figure 1).

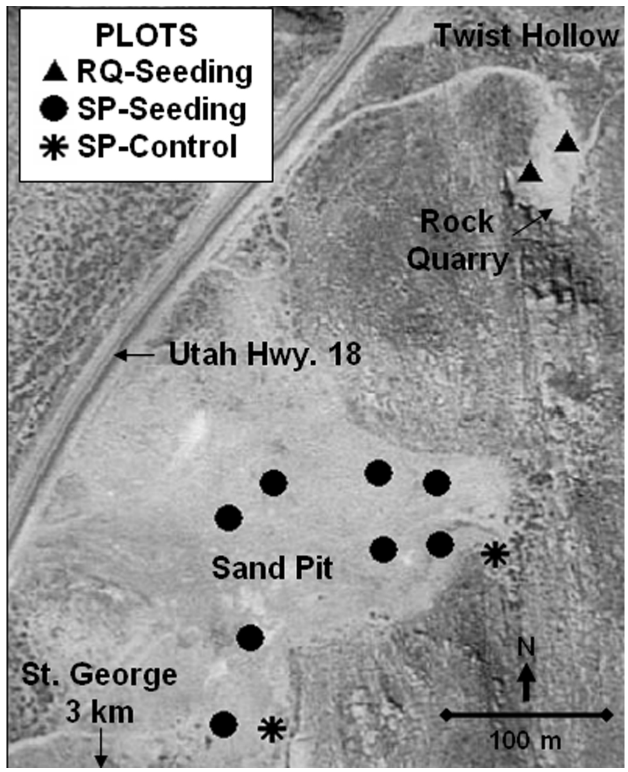

Figure 1—Aerial photograph (mid-1990s) of the Twist Hollow restoration site showing locations of the Sand Pit, Rock Quarry, and plots in each treatment. RQ=Rock Quarry, SP=Sand Pit. Source: Utah GIS Portal, http://gis.utah.gov.

Data were collected at the scale of a circular 100 m^2 plot and from eight systematically-located 1 m^2 subplots (figure 2). Vascular plant species composition was collected at each scale following the nomenclature of Welsh and others (1987), subsequently updated to Welsh and others (2003). At the 100 m^2 scale each species was assigned to one of the following percent cover classes: <1, 1 to 5, 6 to 25, 26 to 50, 51 to 75, 76 to 95, >95 (after Braun-Blanquet 1932). At the 8 m^2 scale direct estimates of percent cover were taken along with density counts for each species. Pre-treatment baseline data were collected on November 25 to 28, 1992, followed by repeated episodes of post-treatment spring-season data collection on April 8 to 14, 1993; May 2 to 3, 1994; April 11 to 12, 1995; April 15 to 16, 1997; April 21 to 23, 1998; April 22 to 23, 2002; April 26 to 28, 2005; and May 7 to 8, 2007.

Data Analysis

For each species detected during the course of the study we calculated tabular summary statistics (frequency and cover in 100 m^2 plots; cover and density in 8 m^2 plots) by treatment and year. Geometric means of cover classes were used to obtain percent cover values for the 100 m^2 plots.

The localized nature of the study and small sample sizes limited our use of formal statistical analysis; however the Sand Pit Seeding treatment had a sufficiently large sample size (n = 8 plots) to test the statistical significance of observed changes in cover and density between successive data collection dates using a binomial sign test (Crawley 2007). For each plot and species (or group), changes between successive dates were classified as an increase, decrease, or no change. Omitting plots where a species was absent on both the beginning and ending date, the ratio of increases or decreases relative to the total number of plots was used as a test statistic. The following ratios lying within the realm of the data are significant at alpha=0.05 according to a one-sided binomial sign test: 5:5, 6:6, 7:7, 7:8, and 8:8 (extracted from the binom.test function in R vers. 2.7.0; R Development Core Team 2008).

Additional insights into data patterns and environmental correlations were gained from exploratory analyses including hierarchical clustering and regression tree analysis (McCune and Grace 2002). These insights are described below although the results of these analyses are not explicitly presented.

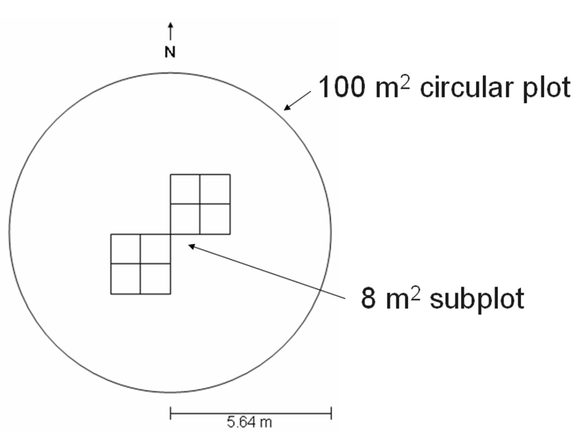

Figure 2—Vegetation Plot Layout used at Twist Hollow restoration site.

RESULTS

Different aspects of the Twist Hollow site vegetation and its variation over time are highlighted in tables 1 to 3. Table 1 lists each of the 105 vascular plant species recorded during the course of the study and its frequency (in 100 m^2 plots) by treatment and year. Mean cover values of species groups and selected species (seeded species and species with greater than 1 percent mean cover in any treatment/year/scale) are shown in table 2 for both 100 m^2 and 8 m^2 plot scales. Cover values mentioned in the text below are averages between the two scales unless otherwise indicated. Density estimates derived from the 8 m^2 plots are provided in table 3 for selected species (those recorded at least seven times in 8 m^2 plots of the seeded treatments over the course of the study). Figure 3 sets our data collection dates in the context of precipitation patterns over time at the nearby St. George weather station.

Pre-treatment and Intact Vegetation

Prior to treatment in the fall of 1992 the disturbed portions of the Sand Pit and Rock Quarry had sparse but variable vegetation cover dominated by annuals (tables 1 to 3). Total cover in the 100 m^2 plots ranged from zero to 35 percent with annuals contributing ca. 70 percent of the total (table 2). The dominant annual species were the exotics cheatgrass (*Bromus tectorum*) and Russian thistle (*Salsola tragus*) and the natives bur ragweed (*Ambrosia acanthicarpa*), gray sandplant (*Dicoria canescens*) little twistflower (*Streptanthella longirostris*) and whitestem blazingstar (*Mentzelia albicaulis*). Russian thistle cover was especially high in the Rock Quarry, exceeding 5 percent in both plots. Some plots of the Sand Pit has 1-5 percent cover of native perennial species (table 2) including Indian ricegrass, sand dropseed, longbracted trefoil (*Lotus plebius*), hairy goldenaster (*Chrysopsis villosa*) and broom snakeweed (*Gutierrezia sarothrae*). Indian ricegrass, although variable in cover, had the highest frequency of any perennial in the disturbed areas.

Relative to vegetation in the disturbed areas, nearby intact vegetation of control plots was characterized by a well-developed shrub layer and a denser herbaceous layer concentrated under or near shrub canopies (tables 1 to 3). The 1992 Sand Pit Control plot, representing a shallow sand environment, had ca. 23 percent shrub cover dominated by sandsage (*Artemisia filifolia*) with lesser amounts of blackbrush (*Coleogyne ramosissima*), range ratany (*Krameria parvifolia*) Nevada ephedra (*Ephedra nevadensis*), burrobrush (*Ambrosia salsola*), bush encelia (*Encelia frutescens*) and broom snakeweed (tables 1 to 2). The herbaceous layer was dominated by cheatgrass with ca. 16 percent cover (table 2) and density of ca. 664 m^{-2}, many times higher than recorded in any disturbed plot (table 3). Indian ricegrass and Underwood spikemoss (*Selaginella underwoodii*) were the dominant herbaceous perennials with ca. 3 percent cover each, and sand dropseed was also present at ca. 1 percent cover (tables 1 to 2). The additional Sand Pit Control plot, added in 1993, captured a deeper sand environment that was also dominated by sandsage and cheatgrass. This plot contained fewer shrub species and the dominant perennial herbaceous species were Indian ricegrass, big galleta (*Hilaria rigida*), longbracted trefoil and Mojave croton (*Croton californicus*); and to a lesser extent sand verbena (*Abronia fragrans*), hyalineherb (*Hymenopappus filifolius*) hairy goldenaster and sand dropseed (tables 1 to 3).

General Treatment Effects

The sculpting and disking treatment had the effect of removing most of the existing vegetation from the Sand Pit and Rock Quarry although residual mature plants were detected in a few plots of the Sand Pit where shallow rocky soils limited the effectiveness of the treatment. Through residual re-growth and new seedlings most of the pre-treatment species had re-established by the spring of 1993. A few species that had been present in trace amounts in 1992, such as blackbrush, bush muhly (*Muhlenbergia porteri*), perennial milkvetch (*Astragalu*s spp.) and rattlesnake-weed (*Chamaesyce albomarginata*), did not reappear following treatment (table 1). Other species, mostly annuals, were first detected in 1993, including the exotic species red brome (*Bromus rubens*) and Mediterranean grass (*Schismus barbatus*) in the Sand Pit (tables 1 to 3). Seedling establishment of both annuals and perennials was likely enhanced by above-average precipitation during the winter of 1992 to 93 and additional periods of high precipitation lasting through 1998 (figure 3).

A ca. 5 percent reduction in mean vegetation cover following treatment between fall 1992 and spring 1993 belies cover decreases in some plots and increases in others resulting in less variance in cover within the treated area. Vegetation cover rebounded in subsequent years and exceeded pre-treatment levels by 1995 in the Sand Pit and 1997 in the Rock Quarry (table 2). These increases cannot be attributed entirely to treatment affects because cover increases were also observed in the control plots during this period (table 2).

Much of the new cover following treatment consisted of annuals, particularly cheatgrass. Cheatgrass densities declined in the Sand Pit following treatment but rose from ca. 8 to 87 m^{-2} between 1993 and 1995. By 1995 cheatgrass cover had reached ca. 9 percent in the sand pit and 5 percent in the Rock Quarry, then remained stable in the Rock Quarry through 1998 while declining to ca. 3 percent in the Sand Pit. In general, greater increases of cheatgrass cover and density were observed in plots with greater rock cover. Despite its expansion following treatment, mean cheatgrass cover and density in the treated plots remained lower than the control plots throughout the study (tables 2 to 3). Red brome remained subordinate to cheatgrass, reaching a maximum of 1 percent cover in the Rock Quarry in 1995 (table 2). Russian thistle cover in the Rock Quarry fell to ca. 1 percent following treatment and remained at or below this level in subsequent years, although this may be an artifact of the underdeveloped stage of this species in springtime when sampling took place. High densities of Russian thistle (for example, 17 m^{-2} in the Rock Quarry in 1993; table 3) suggest that this species likely remained dominant later in the season.

Seeded Species Establishment

Establishment success of seeded plants varied between species. Of the seeded grasses, Indian ricegrass had the greatest response following treatment, regaining pre-treatment levels of mean cover (in 100 m^2 plots) and density by the spring of 1993. By 1995, Indian ricegrass cover in the Sand Pit had risen to 2 percent and density to 1.1 m^{-2}; and by 1997 in the Rock Quarry, 1 percent and 2.2 m^{-2} (tables 2 to 3). Residual plants and/or seeds may be partially responsible for Indian ricegrass establishment, especially in the Sand Pit. Sand dropseed also appears to have persisted in some Sand Pit plots due to residual re-establishment following treatment, although it was lost from other plots between 1992 and 1993 (table 1). A flush of new sand dropseed seedlings then appeared in both the Sand Pit and Rock Quarry in 1994 (table 3), presumably originating largely from the seeding. However, sand dropseed cover remained below one percent in all treated plots and its frequency and density declined after 1994 (tables 1 to 3). Galleta initially became established in only one plot of the Rock Quarry where it persisted with less than 1 percent cover for several years. New galleta seedlings were later detected in three Sand Pit plots in 2005 (tables 1 to 2) but whether these are derived from the seeding is unknown.

Seeded fourwing saltbush became established in both the Sand Pit and Rock Quarry by the spring of 1993 but subsequently followed different trajectories in these two areas. After emerging in six Sand Pit 100 m^2 plots with a density of 0.2 m^{-2} in 1993, fourwing saltbush declined to four plots and 0 m^{-2} in 1994 and remained insignificant in the Sand Pit for the remainder of the study (tables 1 to 3). In the Rock Quarry, on the other hand, frequency increased from 1 to 2 and density from 0.4 to 0.5 m^{-2} between 1993 and 1994 (tables 2 to 3). Density then declined to ca. 0.15 m^{-2} for the remainder of the 1990s in the Rock Quarry while cover of surviving individuals rose to ca. 1 to 2 percent (tables 2 to 3).

The seeded forb Palmer penstemon was most successful in the Rock Quarry where it attained a density of 2.7 m^{-2} and approached 1 percent cover in 1997 (tables 2 to 3). Palmer penstemon also became established in seven of the Sand Quarry plots by 1995 but declined in frequency in the Sand Pit thereafter (table 1).

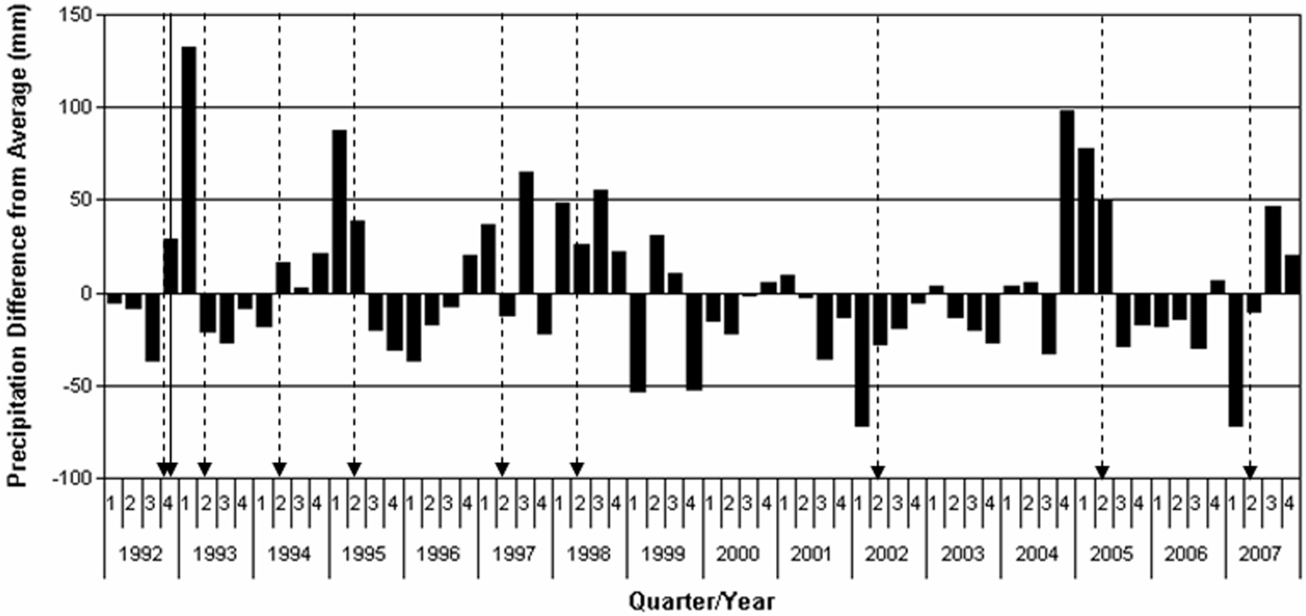

Figure 3—Precipitation patterns at the St. George weather station, Washington County, Utah, 1992-2007. Bars show total precipitation above or below average precipitation (30-year average, 1962 to 1992) calculated separately for each quarter. Dashed arrows are approximate dates of data collection at the Twist Hollow restoration site; solid arrow is treatment date. Source: NOAA (2008).

Emergence of seeded gooseberryleaf globemallow was delayed until 1994 in the Rock Quarry and 1995 in the Sand Pit. This species remained at low densities (less than 0.06 m^{-2}) with less than 1 percent cover before dropping out by the end of the study (tables 2 to 3), in contrast to the congener desert globemallow (*Sphaeralcea ambigua*) which, although not seeded, became established and increased in cover in some plots over the course of the study (tables 1 to 2). Desert globemallow was observed growing in nearby rock outcrops and likely recruited from these areas.

Winterfat was not detected in any plots following treatment and the reasons for its failure to establish are unknown. Other species appear to have seeded origin and may have been unintended components of the seed mix. The latter include the shrub rubber rabbitbrush (*Chrysothamnus nauseosus*), which gained prominence in the Rock Quarry, and the forbs alfalfa (*Medicago sativa*) and yellow sweetclover (*Melilotus officinalis*) which had an irregular and impermanent presence in both the Sand Pit and the Rock Quarry in the years following treatment (tables 1 to 3).

Multi-year Trends

As alluded to above, vegetation changes in the years following treatment can be related to precipitation patterns during this period (cf. Beatley 1974, 1980; Brooks and Berry 2006; Hereford and others 2006; Webb and others 1987). Seedling establishment and growth were favored by above-average precipitation during the winter immediately following seeding, and although the next winter was drier than normal, repeated periods of high precipitation (figure 3) led to increases in cover and density through 1998 (table 2). However, the strong El Nino event that brought high rainfall in 1998 was immediately followed by an strong La Nina event (WRCC 2008), initiating a period of drought that lasted through our next round of sampling in 2002 (figure 3). Cover and density of cheatgrass and other annuals declined dramatically between 1998 and 2002 in both treated and control plots, and many of the annuals that had been present in previous years were absent altogether (tables 1 to 3). In 2005 we captured an equally dramatic but opposite extreme of exceptionally high annual cover and density (tables 2 to3) in consequence of another El Nino event (WRCC 2008), followed by a return to drought conditions in 2007 (figure 3). The post-2005 drought impacted cheatgrass less in the Rock Quarry, where cover rose to ca. 9 percent and density 222 m^{-2} 2007, than in the Sand Pit where it dropped to ca. 2 percent and 41 m^{-2} (tables 2 to 3). Some annuals of earlier importance (red brome, bur ragweed, Russian thistle, gray sandplant, alfalfa, yellow sweetclover) were virtually absent at the conclusion of the study in 2007 (tables 1 to 3).

Perennial grass cover also declined from 1998 to 2002 and did not rebound in 2005 or 2007 (table 2), despite slight increases in seedling density of Indian ricegrass in 2002 and sand dropseed in 2005 and 2007 (table 3). Other perennials varied in their responses during this period, with some declining such as rubber rabbitbrush and longbracted trefoil (*Lotus plebius*) and others increasing such as broom snakeweed (*Gutierrezia sarothrae*) and hairy goldenaster (*Chrysopsis villosa*) (tables 2 to 3). By 2007 the latter two species were co-dominant with fourwing saltbush at the

Rock Quarry, each having 1 to 2 percent cover (table 2). Broom snakeweed was the species with the highest mean cover (ca. 3 percent) in the Sand Pit Seeded treatment in 2007, and hairy goldenaster also became prominent in some of the rockier Sand Pit plots. In sandier plots, sandsage cover and density rose between 2002 and 2005, and cover remained high in 2007 despite a slight reduction in density (tables 2 to 3). In one deep-sand plot near the edge of the Sand Pit, sandsage attained ca. 10 percent cover by 2007, a value that approached sandsage cover values of the control plots.

(a)

(b)

Figure 4—Photographs of Rock Quarry (a) and Sand Pit (b) at the Twist Hollow restoration site in June 2008 after the conclusion of this study. Note large fourwing saltbush (*Atriplex canescens*) in treated area below quarry face in (a); abundance of broom snakeweed (*Gutierrezia sarothrae*) in (b). Fenceline shown in (b) restricts vehicular traffic from entering the site.

DISCUSSION

The objectives of the 1992 Twist Hollow treatment included aesthetic enhancement of the site, soil stabilization, wildlife (especially desert tortoise) habitat improvement, and native plant community restoration (BLM, pers. comm.). To varying degrees each of these objectives was realized over the course of 14 years following treatment although not necessarily in the manner anticipated. The role of the seeded plants in meeting these objectives differed depending on the time frame of observation. In our earlier assessment of the Twist Hollow treatment (McArthur and Sanderson 1996) we optimistically noted increasing trends in several seeded species on the treated substrate following periods of high precipitation. Because the early period of seed germination and plant establishment is typically considered the most sensitive and crucial period of growth (Stevens 2004), it was easy to conclude that established plants would persist over the long term. This conclusion proved partially correct inasmuch as some individuals of seeded species persisted through the duration of the study. However, with localized exceptions such as fourwing saltbush at the Rock Quarry, the seeded species were generally declining when viewed from the time frame of the latter years of the study when drought conditions prevailed.

In hindsight, the species selected for seeding might have been chosen differently, given the poor performance of some such as gooseberryleaf globemallow and galleta. Seed was obtained from commercially-available stock possibly derived from ecotypes poorly adapted to local conditions. However, the use of local seed sources may not have guaranteed greater seeded plant persistence. Local native populations were not immune to the effects of the harsh conditions of the post-1998 drought periods, as evidenced by declines in Indian ricegrass and other native species in the control plots (tables 1 to 3).

Those species that did establish and increase despite the drought, such as sandsage, broom snakeweed, hairy goldenaster and desert globemallow, might well be given greater attention in future restoration projects in the Red Cliffs environment. Colonization by these species was likely facilitated by the relatively small size of the quarrying disturbances and their proximity to intact vegetation. Assisting this colonization process through artificial seeding may be beneficial, especially where the disturbances are larger or local seed sources more limited. Sandsage is a good candidate for artificial seeding because it has been seeded elsewhere and its cultivation requirements are known (McArthur and Stevens 2004; McArthur and Taylor 2004); however, its natural range includes only the northeastern portion of the Mojave Desert (NRCS 2008) and it thus may not be suitable for many Mojave Desert sites.

In terms of site characteristics, species abundance and composition the intact vegetation we recorded at the Twist Hollow Sand Pit closely resembles sandsage communities of Washington County, Utah described by Rasmussen and Brotherson (1986). These authors noted that fourwing saltbush, blackbrush and creosote bush, though present in adjacent rocky, gravelly or clayey sites, where virtually absent from sandy sites where sandsage communities occurred (Rasmussen and Brotherson 1986). Of our two Sand Pit control plots, the deep sand plot was clearly aligned with these sandsage communities while the shallow sand plot had characteristics intermediate between sandsage and blackbrush communities. In the treated areas sandsage establishment was highest on deep sand of the Sand Pit, in contrast to fourwing saltbush on the rockier substrate of the Rock Quarry, suggesting different habitat preferences for each species related to substrate. Within sandsage communities, Rasmussen and Brotherson (1986) noted differences in species composition in the sandsage canopy zone relative to interspaces where Indian ricegrass was the dominant perennial. Sandsage and Indian ricegrass are apparently incompatible in close proximity but complement each other at the broader scale. Our results indicate that drought may play a role in determining the balance between these two species because sandsage appeared to be more drought-tolerant that Indian ricegrass. Elsewhere in its range, sandsage is commonly associated with drier and more overgrazed sites relative to grasses (Ramaley 1939; Sims and others 1976).

Perennial species are justifiably the focus of restoration projects in arid environments because of their stability and soil protection capacity. However, annuals are also important in terms of plant biodiversity in the Mojave Desert and are an important component of the desert tortoise diet (Grover and DeFalco 1995; Oftedal 2002). Of particular importance for desert tortoise nutrition are plant species rich in protein relative to potassium (Oftedal 2002, 2005). Many annuals have this property including several of the annual species and genera recorded following treatment at our study site such as desert globemallow, Pursh's plantain (*Plantago patigonica*), small-flowered milkvetch (*Astragalus nuttallianus*), storksbill (*Erodium cicutarium*), tansymustard (*Descurainia* spp.) and whitestem blazingstar (Ofedal 2002; Oftedal and Leuteritz 2006). The perennial forb longbracted trefoil, which was common at the Sand Pit before and after treatment during wet years, also likely has a high protein to potassium ratio by virtue of its nitrogen-fixing capacity. The exotic annual grasses (cheatgrass, red brome and Mediterranean grass), though readily eaten by desert tortoises, are nutritionally inferior because of their relatively low protein to potassium ratios (Oftedal 2002, 2005).

Cheatgrass re-establishment and dominance in the treated area was perhaps an unavoidable consequence of a residual seed bank and dense populations of this species in the surrounding vegetation. Nevertheless, the consistently lower density and cover of cheatgrass in the treated plots relative to the control plots suggests limitations on cheatgrass imposed by the treated substrate. The control plots had not only denser populations providing more seed, but also more litter and cryptobiotic crust cover than the treated plots. Litter is known to enhance cheatgrass by providing safe sites for seed germination (Evans and Young 1984), while cryptobiotic crusts enhance growth through nutrient inputs (Belnap 1995; Pendleton and others 2003). Vesicular-arbuscular mycorrizhae are also likely to have been more abundant in the undisturbed soils, benefiting both cheatgrass and perennial species (Bainbridge 2007; Knapp 1996). Our observation that cheatgrass establishment was higher on rockier portions of the treated area, such as the Rock Quarry, suggests that rocky microtopography may have partially compensated for litter in providing safe sites for cheatgrass germination. Mycorrhizal establishment over time may have contributed to the decline in the non-mycotrophic species Russian thistle that paralleled the increase of cheatgrass at the Rock Quarry (Allen and Allen 1988).

Because the factors that favor establishment of desired Mojave Desert plant species generally also favor invasive annual grasses such as cheatgrass and red brome, successful restoration of native vegetation remains a complicated challenge. The beneficial effects of high rainfall years as a boon for native plant establishment and productivity can be outweighed by detrimental effects of explosive increases of these grasses. In 2005, for example, dense brome grass resulting from high precipitation fueled catastrophic fires throughout the Mojave Desert (Matchett 2006), including 14,741 ac that burned in the Red Cliffs Desert Reserve (McLuckie and others 2006). Innovative new strategies may be necessary to conserve the integrity of Mojave Desert vegetation from the threats of invasive species and wildfire (cf. BLM 2006).

Complete vegetation recovery on disturbed sites in arid regions is generally expected to take much longer than the 14-year timespan of this study (Bainbridge 2007). In light of the slowness of the process and the potential for setbacks, the Twist Hollow restoration project can be viewed as relatively successful. The seeded species successfully established and provided perennial cover in the early years following treatment while other species expanded into this role in the later years. Desert tortoises in areas adjacent to the treated areas currently appear to be thriving (BLM, pers. comm.). From an aesthetic standpoint the treated areas now blend reasonably well with their surroundings (figure 4). Fences constructed to restrict vehicular access (figure 4b) appear to have played an important role in reducing human disturbance and allowing recovery to take place. The site now contributes to the image of the Red Cliffs reserve as a scenic natural area, and with proper management may continue to do so.

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Table 1—Frequency (number of occurrences in 100 m^2 plots) by treatment and data collection year for species recorded at the Twist Hollow restoration site.

	Rock Quarry Seeded (2 plots)									Sand Pit Seeded (8 plots)									Sand Pit Control (2 plots)								
	2[d]	3	4	5	7	8	2	5	7	2	3	4	5	7	8	2	5	7	2	3	4	5	7	8	2	5	7
Shrubs																											
Ambrosia salsola																			1	2	2	2	2	1			1
Artemisia filifolia										1	1	2	2	2	2	2	3	2	1	2	2	2	2	2	2	2	2
Atriplex canescens (s)[a]		1	2	2	2	2	2	2	2		6	4	3	3	3	3	3	3									
Bassia prostrata[b] (s?)				1	1	1																					
Chrysothamnus nauseosus (s?)			2	2	2	2	2	1																			
Coleogyne ramosissima						1			1	1						1	1	1	1	1	1	1	1	1	1	1	1
Encelia frutescens										2	1	1	1	1	1				1	1	1	1	1	1	1	1	1
Ephedra nevadensis																			1	2	2	2	2	2	2	2	2
Ephedra viridis					2	1	2	2	2														1		1	1	1
Eriogonum fasciculatum				1	1									1						2	1	1	1	1	1	1	1
Fraxinus anomala						1																					
Gutierrezia sarothrae			2	1	1	1	2	1	1	3	4	4	6	7	7	8	7	7	1	1	1	1	1	1	1	1	1
Krameria erecta																			1	1	1	1	1	1	1	1	1
Opuntia erinacea														1													
Opuntia polyacantha						1									1	1											
Prunus fasciculata						1				1		1	2	1	1	1	1	1		1	1	1	1	1	1	1	1
Rhus aromatica																						1					
Perennial Grasses																											
Agropyron cristatum[b] (s?)				1																							
Aristida purpurea									1		1	1		1		2	2	2	1								
Bouteloua gracilis													1														
Elymus elymoides												1															
Elymus spp.[c] (s?)			1	1	2								3														
Hilaria jamesii (s)			1	1	1	1	1										3	2									
Hilaria rigida																				1	1	1	1	1	1	1	1
Muhlenbergia porteri										1																	
Sporobolus cryptandrus (s)			1			1	2		2	4	2	7	5	5	6	5	1	5	1	2	2	2	2	2	2	2	2
Stipa comata													1														
Stipa hymenoides (s)	1	2	2	2	2	2	2	2	2	7	8	8	8	8	8	8	8	8	1	2	2	2	2	2	2	2	1
Perennial Forbs																											
Abronia fragrans										1	1	5	3	3	2	1	2	2		1	1	1	1	1	1	1	1
Allium nevadense								1			1	1		1	1								1	1		1	
Androstephium breviflorum																										1	
Astragalus spp.										2																	
Baileya multiradiata													1		1	3	6	5						1		1	1
Calochortus flexuosus																						1					
Chamaesyce albomarginata										2									1								

Table 1 (Continued)—Frequency by treatment and data collection year.

	Rock Quarry Seeded (2 plots)									Sand Pit Seeded (8 plots)									Sand Pit Control (2 plots)								
	2[d]	**3**	**4**	**5**	**7**	**8**	**2**	**5**	**7**	**2**	**3**	**4**	**5**	**7**	**8**	**2**	**5**	**7**	**2**	**3**	**4**	**5**	**7**	**8**	**2**	**5**	**7**
Chrysopsis villosa	2	1	2	2	2	2	2	2	2	2	3	5	5	6	5	6	6	6		1	1	1	1	1	1		
Convolvulus arvensis[b]											1																
Croton californicus			1	1	1	1	1	1		3	4	5	4	4	4	4	4	4	1	1	2	1	1	1	1	1	1
Cynanchum utahense																		1			1		1	1		1	2
Dichelostemma pulchellum														1								1		1	1		
Eriogonum inflatum															1	1	3	3									
Erioneuron pilosum										1	1	1	2		1	1											
Hymenopappus filifolius																				1	1	1	1	1	1	1	1
Linum perenne												1	1														
Lotus plebeius						1		1		5	5	6	7	8	7	3	7	4	1	1	1	1	1	1		1	
Mirabilis multiflora											2																
Oenothera pallida													1	1	1	1											
Penstemon eatonii													1				2										
Penstemon palmeri (s)			1	1	1	1	1	1	1			5	7	6	5	1	4	1									
Sanguisorba minor[b] (s?)											1	1	1														
Selaginella underwoodii																			1								
Senecio douglasii							1	1	1																		
Sphaeralcea ambigua						1	1	1	1			6	3	2	1	3	3	1									
Sphaeralcea grossulariifolia(s)			1	1	2	2	1						4	5	5	3	2							1			
Stephanomeria pauciflora			1	1	1	1	1	1	1		1	2	3	5	5	5	5	5									
------Annual Grasses------																											
Bromus diandrus[b]								2				1	1				2					1				1	
Bromus rubens[b]			1	1	2		1	2			6	6	3	8	8	1	8				1	2	2		1	1	
Bromus tectorum[b]	2	2	2	2	2	2	2	2	2	6	8	8	8	8	8	7	8	8	1	2	2	2	2	2	2	2	2
Festuca octoflora					2	1		2			1	3	5	6	6	3	8			1	1	1	1	1		1	1
Hordeum spp.[c]											1	2	1	2	1												
Schismus barbatus[b]								1			2	5	7	7	7	2	8	8					1	2		2	2
------Annual Forbs------																											
Ambrosia acanthicarpa	1	2	2	2	2	2		1		6	8	8	8	8	8	5	8		1	1	1				1	1	
Amsinckia intermedia													1														
Astragalus nuttalianus			1	2	2	2		2						3	4		6	2			1						
Bassia scoparia[b]																											
Chamaesyce spp.															1												
Chorispora tenella[b]					2						4			1									1				
Cryptantha barbigera																	2										
Cryptantha circumscissa												4			1					2	2		1	1			
Cryptantha crassisepala								1																			
Cryptantha micrantha											2		5	7	6	4	6	3		2	1	2	2	2	2	2	2
Cryptantha pterocarya			1		2			2			1	3	3	4	5		4			1	2	2	2	2		2	

Table 1 (Continued)—Frequency by treatment and data collection year.

	Rock Quarry Seeded (2 plots)									Sand Pit Seeded (8 plots)									Sand Pit Control (2 plots)								
	2[d]	**3**	**4**	**5**	**7**	**8**	**2**	**5**	**7**	**2**	**3**	**4**	**5**	**7**	**8**	**2**	**5**	**7**	**2**	**3**	**4**	**5**	**7**	**8**	**2**	**5**	**7**
Datura wrightii	1		1	1		1	2	1																			
Descurainia spp.[c]		1		1	1	1		1			3	1	5	3			3			1	1	1					
Dicoria canescens										2	7	4	6	3	3	1	3			1	1		1				
Dithyrea wislizenii												1	1		1			1		2	1	1		2		1	2
Draba verna								1									2										
Eriastrum spp.								1				4	3	5	4		8	7	1	2	2	2	2	2	1	2	1
Eriogonum spp.		1						1						2	1	3	3										
Eriophyllum lanosum								1									1										
Eriophyllum wallacei								1			1	1	2	3	1		6	1		2	1	2	2	2	2	2	1
Erodium cicutarium[b]	1	1	2	2	2	2		2	2	1	2	8	8	8	8	2	8	7	1	2	1	2	2	2		2	2
Gilia spp.		1	2	1	2	2		2	1				2	1	2		3						1	1		1	
Lepidium densiflorum													1				2				1						
Linanthus bigelovii													1	2	2	1					1	1	1	1			
Linanthus demissus																	8							1		2	
Lupinus concinnus										1	4	2	5	4	4		7	4		1	1	1	2			1	
Malcolmia africana[b]													1														
Medicago sativa[b] (s?)			1	1	1						1	1	2	1	1	1	1										
Melilotus officinalis[b] (s?)		1	1			1					1	1	1		1		1										
Mentzelia albicaulis	2	1	2	2	2	2	1	1	1									1									
Microseris lindleyi								1							1		3			1		1	2	2		1	
Oenothera primiveris			1							1									1								
Palafoxia arida												3	1								1						1
Pectocarya setosa																	4										
Phacelia ambigua													1														
Plantago patagonica																	4	1		1	1	1	1	1		1	1
Polygonum aviculare											1																
Salsola tragus[b]	2	2	2	2	2	2				7	7	8	7	8	5	1		1	1				1				
Sisymbrium spp.[b]		1	1	1		1		2		1	4	7	6	6	2		6		1					1			
Streptanthella longirostris										4	7	8	7	7	6		5	5	1	1	2	2	2	2		1	1
Stylocline micropoides																	3										
Tragopogon dubius[b]																										1	
Tripterocalyx micranthus					2																						

[a](s) indicates seeded species; (s?) were probably also introduced through the seed mix though not reported. [b]non-native species. [c]native and/or non-native species. [d]numbers indicate last digit of data collection years in following sequence: 2=1992, 3=1993, 4=1994, 5=1995, 7=1997, 8=1998, 2=2002, 5=2005, 7=2007.

Table 2—Mean cover of selected vascular plant species and functional groups by treatment and data collection year at the Twist Hollow restoration site. Leading cover values are for 100 m^2 plots; values in parentheses are for 8 m^2 subplots. Values are rounded to the nearest digit; "+" indicates values less than 0.5 and blank values are zeros. An asterisk denotes values significantly higher or lower than the corresponding value of the previous data collection year according to a one-sided binomial sign test at alpha=0.05 (see text for details). Treatment RQ-Seeded=X, SP-Seeded=Y, and SP-Control=Z.

Treament[c]		1992		1993		1994		1995		1997		1998		2002		2005		2007	
Shrubs																			
Artemisia filifolia	Y	+		+		+		+	(+)	+		+	(+)	+	(+)	1	(1)	1	(1)
	Z	11[d]	(16)[d]	11	(10)	11	(9)	23	(6)	11	(5)	11	(8)	11	(6)	7	(8)	11	(9)
Atriplex canescens (s)[a]	X			+	(+)	+	(+)	+	(+)	2	(1)	2	(1)	2	(1)	1	(+)	2	
	Y			+*	(+)	+		+		+		+		+		+		+	
Chrysothamnus nauseosus (s?)	X					+	(+)	+	(+)	+	(2)	+	(2)	1	(5)	+			
Gutierrezia sarothrae	X					+	(+)	+	(+)	+	(+)	+	(1)	+	(3)	1	(1)	1	(2)
	Y	+	(2)	1	(+)	1	(1)	2	(1)	2	(1)	2	(1)	3	(2)	2	(2)	3	(3)
	Z	+[d]		+		+		+		+		+		+		+		+	
Total Shrubs	X			+	(+)	+	(+)	+	(+)	2	(3)	2	(4)	3	(9)	2	(1)	3	(2)
	Y	+	(2)	1	(+)	1	(1)	2	(1)	2	(1)	2	(1)	3	(2)	3	(3)	4	(4)
	Z	18[d]	(30)[d]	16	(15)	17	(19)	28	(13)	16	(11)	15	(14)	17	(10)	9	(13)	12	(9)
Perennial Grasses																			
Hilaria jamesii (s)	X					+	(+)	+	(+)	+		+	(+)	+	(+)				
	Y															+		+	
Sporobolus cryptandrus (s)	X					+	(+)					+		+				+	
	Y	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+		+		+	(+)
	Z	+[d]	(2)[d]	+	(1)	1	(1)	+	(+)	1	(+)	1	(2)	1	(+)	+	(+)	+	(+)
Stipa hymenoides (s)	X	+		+	(+)	+	(+)	+	(1)	1	(1)	1	(2)	1	(1)	1	(1)	1	(+)
	Y	1	(2)	1	(+)	1	(1)*	2	(2)	2	(1)	2	(1)	1	(1)	+	(+)	+	(+)
	Z	2[d]	(4)[d]	2	(3)	2	(6)	2	(4)	2	(1)	2	(2)	+	(+)	+	(+)	+	
Total Perennial Grasses	X	+		+	(+)	+	(+)	+	(1)	1	(1)	1	(2)	1	(1)	1	(1)	1	(+)
	Y	1	(2)	1	(+)	1	(1)*	2	(2)	2	(1)	2	(1)	1	(1)	+	(+)	+	(+)
	Z	2[d]	(6)[d]	3	(4)	4	(7)	2	(4)	3	(1)	3	(4)	1	(+)	+	(+)	+	(+)
Perennial Forbs																			
Chrysopsis villosa	X	+		+	(+)	+	(+)	+	(1)	1	(2)	1	(2)	1	(1)	2	(1)	2	(1)
	Y	+	(+)	+	(+)	+	(+)	1	(+)	1	(+)	+	(+)	1	(1)	1	(1)	1	(1)
	Z	0[d]	(0)[d]	+	(+)	+	(1)	+	(+)	+	(+)	+	(+)	+					
Lotus plebeius	X											+				+	(+)		
	Y	2	(1)	2	(1)	1	(1)	1	(1)	+	(1)	1	(2)	+	(+)*	+	(+)	+	(+)
	Z	+[d]	(+)[d]	1	(+)	+		1	(+)	+	(+)	1	(+)			+	(+)		
Penstemon palmeri (s)	X					+	(+)	+	(+)	+	(1)	+	(+)	+	(+)	+	(+)	+	
	Y					+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)
Sphaeralcea ambigua	X											+	(+)	+	(+)	1	(+)	1	
	Y					+	(+)*	+	(+)	+	(+)	+		+	(+)	+	(+)	+	(+)
Sphaeralcea grossulariifolia (s)	X					+		+		+		+		+					
	Y							+	(+)	+		+	(+)	+	(+)	+			
	Z											+							
Total Perennial Forbs	X	+		+	(+)	+	(+)	+	(1)	1	(4)	1	(2)	1	(1)	3	(1)	4	(1)
	Y	2	(1)	2	(1)	1*	(1)	2	(1)	2	(1)	1	(2)	1	(1)	1	(2)	2	(1)*
	Z	2[d]	(5)[d]	2	(1)	2	(3)	2	(2)	+	(1)	1	(1)	+	(+)	+	(+)	+	(+)
Annual Grasses																			
Bromus rubens[b]	X					+		1		1	(1)			+	(+)	+	(+)		
	Y			+*	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+		+	(1)*		(0)*
	Z	0[d]	(0)[d]			+		+		+	(+)			+		+			
Bromus tectorum[b]	X	1	(+)	1	(1)	7	(2)	7	(2)	6	(2)	7	(2)	+	(+)	2	(17)	7	(11)
	Y	2	(1)	2	(1)	6	(3)*	12	(5)	9	(4)	5	(2)	+	(+)*	3	(5)*	2	(2)*
	Z	11[d]	(21)[d]	11	(24)	11	(26)	48	(29)	48	(29)	23	(22)	+	(3)	2	(47)	23	(28)

Table 2 (Continued)—Mean cover of selected vascular plant species and functional groups by treatment and data collection year.

Treament[c]		1992		1993		1994		1995		1997		1998		2002		2005		2007	
Total Annual Grasses	X	1	(+)	1	(1)	7	(2)	8	(2)	7	(3)	7	(2)	+	(+)	2	(17)	7	(11)
	Y	2	(1)	2	(1)	6	(3)*	12	(5)	9	(4)	5	(2)	+	(+)*	3	(8)*	2	(3)*
	Z	11[d]	(21)[d]	11	(25)	11	(26)	48	(29)	48	(29)	23	(22)	+	(3)	2	(47)	23	(28)
Annual Forbs																			
Ambrosia acanthicarpa	X	1	(+)	1		1	(1)	1	(1)	+	(1)	+	(1)		(0)*	+	(+)		(0)*
	Y	3	(2)	3	(1)	+	(1)	+	(1)	+	(1)	+	(1)	+	(+)	+	(+)		
	Z	+[d]	(+)[d]	+	(+)	+	(+)							+	(+)	+	(+)		
Dicoria canescens	Y	3	(1)	1	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)		
	Z	0[d]	(0)[d]	+	(+)	+	(+)			+	(+)								
Eriophyllum wallacei	X															+			
	Y			+		+		+		+		+	(+)			+*	(+)	+	
	Z	0[d]	(0)[d]	1	(1)	+	(+)	+	(2)	1	(5)	1	(2)	+	(+)	1	(1)	+	(+)
Erodium cicutarium[b]	X	+	(+)	+	(+)	+	(1)	+	(1)	1	(2)	+	(1)			+	(1)	2	(1)
	Y	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)
	Z	+[d]	(1)[d]	+	(+)	+	(+)	+	(1)	1	(1)	1	(2)			+	(+)	+	(+)
Medicago sativa[b] (s?)	X					+		+	(+)	+	(+)								
	Y			+	(+)	+		+		+		+	(+)	+		+	(+)		
Melilotus officinalis[b] (s?)	X			+		+	(+)					+							
	Y			+		1	(1)	+	(1)			+	(1)			+	(+)		
Mentzelia albicaulis	X	1		+		1	(1)	1	(1)	1	(1)	1	(1)	1	(+)	+	(+)	+	
	Y																	+	(+)
Salsola tragus[b]	X	11	(1)	1	(1)	+	(1)	1	(+)	+	(1)	+	(+)						
	Y	1	(1)	1	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)			+	(+)
	Z	+[d]								+	(+)								
Sisymbrium spp.[b]	X			+	(+)	+	(+)	+				+				+	(+)		
	Y	+		+	(+)	+	(+)	+	(+)	+	(+)	+	(+)			+*	(+)*	0*	(0)*
	Z	+[d]	(2)[d]									+							
Streptanthella longirostris	Y	1	(+)	+	(+)	+	(+)	+	(1)	+	(+)	+	(+)	0*	(0)*	+*	(+)*	+	(+)
	Z	2[d]	(4)[d]	+	(+)	+	(+)	+	(2)	1	(1)	+	(+)			+	(+)	+	
Total Annual Forbs	X	13	(1)	2	(1)	2	(4)	3	(3)	2	(6)	1	(3)	1	(+)	+	(1)	2	(1)
	Y	6	(4)	4	(1)	2	(2)	1	(3)	+	(1)	+	(3)	+	(+)*	1	(2)*	+	(+)*
	Z	2[d]	(8)[d]	2	(1)	1	(1)	1	(9)	6	(12)	3	(6)	+	(1)	1	(2)	+	(+)
Total Cover (multi-canopy)	X	15	(1)	3	(3)	9	(6)	11	(7)	14	(17)	12	(13)	7	(11)	9	(21)	18	(15)
	Y	12	(10)	10	(3)	11	(8)*	19*	(12)	16	(8)	11	(9)	4*	(4)*	9*	(15)*	9*	(8)*
	Z	36[d]	(70)[d]	35	(47)	36	(56)	82	(57)	73	(54)	46	(47)	18	(14)	13	(62)	36	(37)

[a](s) indicates seeded species; (s?) were probably also introduced through the seed mix though not reported. [b]non-native species. [c]treatment abbreviations: RQ-Seeded = Rock Quarry Seeded; SP-Seeded = Sand Pit Seeded; SP-Control = Sand Pit Control. [d]values shown for 1992 SP-Control are from a single plot, unlike other years that are the average of two SP-Control plots.

Table 3—Mean density per 100 m^2 (extrapolated from density counts in 8 m^2 plots) of selected vascular plant species by treatment and data collection year at the Twist Hollow restoration site. An asterisk denotes values significantly higher or lower than the corresponding value of the previous data collection year according to a one-sided binomial sign test at alpha=0.05 (see text for details).

	Treatment[d]	1992	1993	1994	1995	1997	1998	2002	2005	2007
Shrubs										
Artemisia filifolia	SP-Seeded	0	0	0	5	0	3	2	6	2
	SP-Control	100[e]	137	494	106	119	81	44	19	31
Atriplex canescens (s)[a]	RQ-Seeded	0	38	50	19	13	19	13	6	0
	SP-Seeded	0	20*	0*	0	0	0	0	0	0
Chrysothamnus nauseosus (s?)	RQ-Seeded	0	0	6	6	6	6	6	0	0
Ephedra viridis	RQ-Seeded	0	0	0	0	0	0	6	6	19

Table 3 (Continued)—Mean density of selected vascular plant species by treatment and data collection year.

	Treatment[d]	1992	1993	1994	1995	1997	1998	2002	2005	2007
Gutierrezia sarothrae	RQ-Seeded	0	0	13	0	0	0	19	181	56
	SP-Seeded	47	89	77	172	203	141	144	880*	294
Opuntia polyacantha	RQ-Seeded	0	0	0	0	0	6	0	0	0
	SP-Seeded	0	0	0	0	0	2	2	0	0
		Perennial Grasses								
Aristida purpurea	SP-Seeded	0	0	0	0	0	0	2	2	3
Hilaria jamesii (s)	RQ-Seeded	0	0	13	19	0	6	13	0	0
Sporobolus cryptandrus (s)	RQ-Seeded	0	0	19	0	0	0	0	0	0
	SP-Seeded	3	2	52	8	5	6	0	0	23
	SP-Control	26[e]	25	44	31	13	1169	38	81	56
Stipa hymenoides (s)	RQ-Seeded	0	56	50	75	106	94	44	50	19
	SP-Seeded	59	78	156	113	222*	116	134	84	19
	SP-Control	62[e]	94	156	119	100	19	13	6	0
		Perennial Forbs								
Abronia fragrans	SP-Seeded	0	0	2	0	3	0	0	3	5
	SP-Control	0[e]	306	319	150	69	113	31	44	6
Allium nevadense	SP-Seeded	0	2	0	0	5	6	0	0	0
	SP-Control	0[e]	0	0	0	363	300	0	6	0
Baileya multiradiata	SP-Seeded	0	0	0	0	0	0	6	13	8
	SP-Control	0[e]	0	0	0	0	0	0	13	6
Chrysopsis villosa	RQ-Seeded	0	13	13	56	244	513	38	563	275
	SP-Seeded	5	16	16	248	50	95	67	1081*	108
	SP-Control	0[e]	113	31	44	63	6	0	0	0
Croton californicus	RQ-Seeded	0	0	6	6	6	6	13	6	0
	SP-Seeded	2	3	3	6	19	28	13	73	23
	SP-Control	0[e]	38	25	44	6	25	0	31	6
Eriogonum inflatum	SP-Seeded	0	0	0	0	0	0	0	3	6
Lotus plebeius	RQ-Seeded	0	0	0	0	0	0	0	6	0
	SP-Seeded	41	173	105	794*	153	613	2*	180*	3*
	SP-Control	26[e]	6	0	6	31	44	0	6	0
Penstemon eatonii	SP-Seeded	0	0	0	2	0	0	0	3	0
Penstemon palmeri (s)	RQ-Seeded	0	0	13	6	275	194	6	69	0
	SP-Seeded	0	0	3	6	2	2	2	13	2
Sphaeralcea ambigua	RQ-Seeded	0	0	0	0	0	6	6	0	0
	SP-Seeded	0	0	17*	3	3	0	2	13	2
Sphaeralcea grossulariifolia (s)	SP-Seeded	0	0	0	2	0	6	2	0	0
Stephanomeria pauciflora	RQ-Seeded	0	0	0	13	94	44	0	0	0
	SP-Seeded	0	0	2	5	22	9	25*	78	27
		Annual Grasses								
Bromus diandrus[b]	RQ-Seeded	0	0	0	0	0	0	0	44	0
	SP-Seeded	0	0	0	2	0	0	0	6	0
	SP-Control	0[e]	0	0	0	0	0	0	31	0
Bromus rubens[b]	RQ-Seeded	0	0	0	0	519	0	25	300	0
	SP-Seeded	0	95	16	2	41*	22	0	750*	0*
	SP-Control	0[e]	0	0	0	19	0	0	0	0
Bromus tectorum[b]	RQ-Seeded	256	413	1481	3519	3869	4169	6	38438	22219
	SP-Seeded	1159	839*	2108*	8720*	2641*	8105*	513*	8022*	4098*
	SP-Control	66375[e]	39663	182719	33125	29406	30125	3850	77563	32938
Festuca octoflora	RQ-Seeded	0	0	0	0	0	0	0	38	0
	SP-Seeded	0	11	2	22	77	161*	17*	3919*	0*
	SP-Control		613	781	813	469	375	0	2000	69
Schismus barbatus[b]	SP-Seeded	0	13	19	103*	147	150	2*	5167*	2983
	SP-Control	0[e]	0	0	0	19	6	0	44	100

Table 3 (Continued)—Mean density of selected vascular plant species by treatment and data collection year.

	Treatment[d]	1992	1993	1994	1995	1997	1998	2002	2005	2007
		-----Annual Forbs-----								
Ambrosia acanthicarpa	RQ-Seeded	6	0	3219	2013	1669	475	0	119	0
	SP-Seeded	73	1316*	2914	2161	1781*	1978	134*	161	0*
	SP-Control	12[e]	6	6	0	0	0	31	38	0
Astragalus nuttalianus	RQ-Seeded	0	0	6	0	6	31	0	31	0
	SP-Seeded	0	0	0	0	2	9	0	17*	5
Cryptantha micrantha	SP-Seeded	0	3	0	277*	173	4597	902	1116	234*
	SP-Control	0[e]	119	6	7031	12463	11281	3006	1294	250
Cryptantha pterocarya	RQ-Seeded	0	0	0	0	0	0	0	13	0
	SP-Seeded	0	0	2	11	14	22	0	11	0
	SP-Control	0[e]	31	25	106	431	163	0	31	0
Descurainia spp.[c]	RQ-Seeded	0	0	0	13	25	13	0	6	0
	SP-Seeded	0	2	0	33*	8	0	0	6	0
Dicoria canescens	SP-Seeded	117	263*	103*	120	50	42	2	13	0
	SP-Control	0[e]	100	19	0	31	0	0	0	0
Eriastrum spp.	SP-Seeded	0	0	0	14	19	66	0	0	331*
	SP-Control	62[e]	44	213	331	1275	244	0	0	31
Eriogonum spp.	SP-Seeded	0	0	0	0	0	6	5	113	0
Eriophyllum wallacei	SP-Seeded	0	0	0	0	0	2	0	16	0
	SP-Control	0[e]	1300	644	3594	8563	8981	481	5838	81
Erodium cicutarium[b]	RQ-Seeded	6	13	231	844	2519	2669	0	1625	625
	SP-Seeded	2	17	30	33	67	555*	9*	2302*	519
	SP-Control	237[e]	88	38	169	506	775	0	1188	50
Gilia spp.	RQ-Seeded	0	0	163	19	88	419	0	456	6
	SP-Seeded	0	0	0	5	2	2	0	64	0
	SP-Control	0[e]	0	0	0	6	6	0	6	0
Linanthus bigelovii	SP-Seeded	0	0	0	3	5	9	3	0	0
	SP-Control	0[e]	0	6	31	6	6	0	0	0
Linanthus demissus	SP-Seeded	0	0	0	0	0	0	0	2386*	0*
	SP-Control	0[e]	0	0	0	0	6	0	4500	0
Lupinus concinnus	SP-Seeded	2	2	0	0	5	2	0	89*	8
	SP-Control	0[e]	0	0	0	6	0	0	0	0
Medicago sativa[b] (s?)	RQ-Seeded	0	0	0	6	13	0	0	0	0
	SP-Seeded	0[e]	14	0	0	0	2	0	2	0
Melilotus officinalis[b] (s?)	SP-Seeded	0	0	8	1780	0	77	0	9	0
	RQ-Seeded	0	0	6	0	0	0	0	0	0
Mentzelia albicaulis	RQ-Seeded	0	0	344	513	238	213	6	13	0
	SP-Seeded	0	0	0	0	0	0	0	0	2
Pectocarya setosa	SP-Seeded	0	0	0	0	0	0	0	50	0
Plantago patagonica	SP-Seeded	0	0	0	0	0	0	0	17	16
	SP-Control	0[e]	31	0	69	56	81	0	756	50
Salsola tragus[b]	RQ-Seeded	69	1731	988	175	638	188	0	0	0
	SP-Seeded	27	505*	386	111	27	16	2	0	2
	SP-Control	0[e]	0	0	0	6	0	0	0	0
Sisymbrium spp.[b]	RQ-Seeded	0	6	13	0	0	0	0	81	0
	SP-Seeded	0	41	22	41	17	2	0	63*	0*
	SP-Control	100[e]	0	0	0	0	0	0	0	0
Streptanthella longirostris	SP-Seeded	11	33	19	170	138	33	0*	61*	6*
	SP-Control	262[e]	44	38	113	263	25	0	6	0

[a](s) indicates seeded species; (s?) were probably also introduced through the seed mix though not reported. [b]non-native species. [c]native and/or non-native species. [d]treatment abbreviations: RQ-Seeded = Rock Quarry Seeded; SP-Seeded = Sand Pit Seeded; SP-Control = Sand Pit Control. [e]values shown for 1992 SP-Control are from a single plot, unlike other years that are the average of two SP-Control plots.

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