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Revegetation Techniques and Fugitive Dust in the Western Mojave Desert

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REVEGETATION TECHNIQUES AND FUGITIVE DUST IN THE WESTERN MOJAVE DESERT

Final Report
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Abstract

In the Antelope Valley of the Mojave Desert, tillage and seeding of native shrubs reduced emissions of fugitive dust from disturbed lands by more than 95%, achieving ground cover comparable to surrounding old field successional areas. Wind fences, furrowing across the wind, and widely spaced roughness elements were also found to be effective for suppression of fugitive dust emissions. Revegetation by direct seeding was successful in one year with high rainfall but was not reproducible in other years using the same techniques, nor in small plot trials of many species with or without irrigation. Rangeland drilling or broadcast seeding on untilled surfaces were as effective in some years as tillage and seeding, and were less disruptive to natural shrub establishment processes. The use of transplants of nursery-grown native shrubs did not guarantee plant survival, and was more expensive than direct seeding. Plant survival exhibited large location effects, attributed to level of previous soil disturbance, which affected bulk density, nutrient status, and microorganism populations. Plastic cones placed over transplants increased plant survival. Land managers should consider minimally disruptive seeding protocols, but should not rely on successful shrub establishment in any given year. Mechanical mitigation strategies such as scattered roughness elements, wind fences, or furrowing, provide more rapid and reliable mitigation of fugitive dust emissions, but may be less sustainable than extensive shrub establishment.

Executive Summary

Large areas of the Antelope Valley of the western Mojave Desert have been successfully converted from native desert vegetation to irrigated farming. This removed the native plant species, altered soil profiles, surface structure, and fertility. Economic factors and depletion of ground water have reduced the profitability of many irrigated farming operations, and much farmland has been abandoned. Additional areas have been subject to intensive grazing by nomadic bands of sheep. During the drought of the late 1980's and early 1990's, seasonally high winds created dust storms which contributed to repeated violations of the federal and state ambient air quality standards for particulate matter in the downwind urban areas of Lancaster and Palmdale. Numerous incidences of reduced visibility and traffic accidents occurred, buildings and property were inundated with blowing sand, field and tree crops were damaged, and flight operations at Edwards Air Force Base were impacted. In February, 1992, with funding from the USDA Natural Resources Conservation Service (NRCS), an Emergency Watershed Protection (EWP) program was applied to about 1000 ha of the most seriously wind eroding areas. The goal was to provide both immediate and long term control of fugitive dust emissions, to abolish local dust storms, and to mitigate violations of PM_{10} standards. The multi-faceted protocol of the EWP program included simultaneous ripping and furrowing of the soil across the wind, drilling of rapidly establishing species, and broadcasting of slowly developing but sustainable native perennial shrubs. Wind fences were established near roadways and upwind of residential dwellings that had been subjected to severe fugitive dust problems.

We conducted detailed plant censuses over several years to evaluate the establishment and persistence of the revegetation in the EWP area. We also monitored fugitive dust in 1992, 1994, 1995, and 1996, by sampling coarse suspended particulate matter weekly during the windy season from treated and barren control areas.

Immediately following establishment of the EWP, abundant rainfall was received and widespread emergence of barley in the furrows and perennial seedlings was observed in many areas, which had a rapid suppressing effect on fugitive dust. Between 1992 and 1995, the California state standard for PM_{10} at the Lancaster monitoring site was exceeded only five days per year on average, compared with 25, 22, and 11 days in the preceding three years. Average perennial plant cover in the EWP area increased slightly from 1994 through 1996, followed by a significant decrease in 1997 attributed to two consecutive years of drought conditions. The change in percent cover over time varied between plant species, illustrated by a shift in the relative composition of the seeded shrubs between years and locations. Variability in shrub cover within the EWP area was associated with differences in soil classification, fertility and microbiology.

In 1994 we tested the seeding and furrowing protocol in a multiple location large plot study, along with several alternative surface stabilization strategies. Wind fences were established on large plots for evaluation of their effectiveness in controlling fugitive dust emissions. Multiple location small (garden) plot studies were also undertaken for evaluation of additional plant species and their potential for use in direct seeding efforts in this environment, in both irrigated and unirrigated field tests. In 1995, transplanting of individual shrubs was investigated as an alternative method of reestablishing native vegetation. Five native plant species (*Prosopis glandulosa* var *torreyana*, *Atriplex canescens*, *Atriplex polycarpa*, *Isomeris arborea*, and *Chrysothamnus nauseosus*) were chosen for evaluation. Seedlings were nursery-grown in high aspect containers in an artificial soil mix. *Prosopis* was intensely evaluated in a large plot study,

and all five species were compared in a replicated experiment established at six sites throughout the Western Mojave Desert, with sites selected to reflect the spatial variability in soil classification. Three mulch treatments and two types of herbivory protection were evaluated concurrently with the transplants. Plants were scored for vigor periodically over two years. Soil samples (0-10 cm depth) were obtained from each site and analyzed for nitrate and ammonium N levels, and for bacterial and fungal populations. These transplant evaluations were accompanied by evaluations of scattered artificial roughness elements and furrows for ability to control emissions of fugitive dust.

Attempts to replicate the EWP success over multiple years generally failed. Excellent response to some of the alternative treatments was obtained at one of the replicated large plot locations, where significant differences in plant density and species diversity were associated with the level of soil disturbance. Broadcasting of seed onto the barren soil surface yielded the highest plant density and richest species composition. Plant establishment was less in plots receiving rangeland drilling, and poorest in plots receiving highly disturbing furrowing protocols. Populations of invasive annuals increased with increasing soil disturbance. Rabbitbrush, an aggressive colonizer in this region, resisted establishment on disturbed plot areas, but established naturally in undisturbed plot areas from seed originating in an adjacent rabbitbrush stand. In the large plot study of honey mesquite, survival declined from near 85% in the first few months to near 40% 15 months after planting. Plants in narrow deep holes survived better than those in wide, hand-dug holes, and plants in plastic cones survived better than those in wire cages. In the multiple location experiment, *Atriplex canescens* ranked highest for survival and vigor among all species. Plastic cones significantly improved plant establishment compared to wire cages. Mulches had no significant effect. Significant site differences in plant vigor were attributed largely to edaphic factors associated with disturbance arising from contrasting agriculture practices over the last several decades, which affected microbial activity and nitrogen cycling. Dispersed artificial barriers were found to suppress saltation and reduce fugitive particulate emissions. Wind fences resulted in a substantial decrease in suspended particles downwind of the fences, and compared to similar eroding areas without wind fences. Furrows were effective in decreasing emissions of fugitive dust, and significantly increased the threshold friction velocity.

The most effective long term surface stabilization in the Antelope Valley, and similar arid regions, is achieved through revegetation with sustainable native shrub vegetation. To this end, direct seeding is more cost effective and nearly as reliable as transplantation of nursery grown materials. However, direct seeding remains uncertain for a given year and location and requires considerable time. Thus for emergency or urgent fugitive dust problems a mechanical solution should be applied instead of, or in addition to, revegetation. Prior to shrub establishment, furrowing across the wind and quick establishment of exotic annual species such as barley can provide initial control of emissions. In critical areas near roadways and residences, wind fences erected across the prevailing winds are highly effective in suppressing fugitive dust. Scattered roughness elements proved very effective in reducing emissions of fugitive dust, suggesting other available objects including discarded tires, large stones, etc., could prove just as effective. In both the direct seeding and transplanting protocols, *Atriplex canescens* proved to be the most generally adapted plant species tested. Rabbitbrush, *Chrysothamnus nauseosus*, was difficult to propagate and to seed using available seed dispensing devices and should be avoided. Honey mesquite, *Prosopis glandulosa* var *Torreyana*, did not perform well overall, but did respond favorably to abundant irrigation.

Introduction

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

Large areas of the Antelope Valley of the western Mojave Desert have been successfully converted from native desert shrub and bunchgrass vegetation to irrigated farming. This removed the native plant species, altered soil profiles, surface structure, and fertility. In recent years, economic factors and depletion of ground water have reduced the profitability of most irrigated farming operations, and much farmland has been abandoned. Additional areas have been subject to intensive grazing by nomadic bands of sheep. During the prolonged drought of the late 1980's and early 1990's, seasonally high winds created dust storms which contributed to repeated violations of the PM_{10} national ambient air quality standards in downwind urban areas (Table 1). Numerous incidences of reduced visibility and traffic accidents occurred, buildings and property were inundated with blowing sand, field and tree crops were destroyed, and flight operations at Edwards Air Force Base were impacted. In 1991, an aerial survey of the region by the Los Angeles County Fire Department estimated the area of erodable soils to be in excess of 4000 ha (Zeldin, 1994).

Reestablishment of stable, biologically diverse, native vegetation represents an aesthetically pleasing, and ecologically sustainable, long term strategy for surface stabilization and suppression of fugitive dust. Unfortunately, revegetation by natural recruitment tends to be slow and uncertain in arid and semiarid environments (Call and Roundy, 1991; Jackson et al., 1991). Initial germination of seed and seedling establishment occur only infrequently in these areas, associated with occasional episodes of abundant and/or well-timed rainfall. Following successful establishment the seedlings must develop adequately to tolerate unpredictable onset of cold and drought, and to overcome competition by rapidly developing annual species.

Table 1. Annual statistics for particulate levels monitored by the South Coast Air Quality Management District in Lancaster, CA.

Year	Exceedances of State Standard (Days)	[1]Maximum 24 hr ($\mu g\ m^{-3}$)	Annual arithmetic mean ($\mu g\ m^{-3}$)	[2]Annual geometric mean ($\mu g\ m^{-3}$)
1989	25	110	47.0	43.0
1990	22	342	52.9	43.8
1991	11	780	56.8	38.1
1992	5	68	32.4	29.5
1993	9	70	34.9	30.5
1994	3	97	31.4	27.7
1995	3	61	25.6	22.6
1996	2	67	29.2	25.6

[1] State standard of 50 $\mu g\ m^{-3}$ 24-hour average.

[2] State standard of 30 $\mu g\ m^{-3}$ geometric average.

Water availability is generally considered the single most limiting resource for plant growth (Boyer, 1985) particularly in arid or semiarid environments because rainfall is low, highly variable and inherently unpredictable. Differences in moisture requirements between species result in seedling recruitment of some species nearly every year, but of others only every decade or longer (Allen, 1991). As with natural recruitment, desert revegetation through direct seeding fails in most years (Bainbridge et al., 1993; Jackson et al., 1991; Cox et al., 1982; Bleak et al., 1965), although direct seeding coupled with fortuitously timed rainfall may result in highly successful plant establishment in these areas (e. g., Grantz et al., 1998a). Favorable conditions for natural plant establishment occur once every 7 - 15 years on the arid salt desert shrublands of the North

American Great Basin (Bleak et al., 1965)) and once in 4 years in semiarid regions in Australia (Silcock, 1986). Natural impediments and anthropogenic disturbance reduce the success of restoration plantings in the low deserts of California to about once in 10 years (Cox et al., 1982). While secondary succession may result in mature Mojave Desert creosote bush scrub within approximately 65 years (Carpenter et al., 1986), it may take up to 180 years for recovery of species diversity in severely disturbed sites (Webb et al., 1983).

Full recovery of vegetation to a pre-disturbance condition is further hindered by the permanent changes imposed by agriculture. The preexisting network of ephemeral streams has been converted into a system of roads, ditches, and leveled fields. Extensive tillage has mixed soil horizons, and additions of mineral fertilizers and organic pesticides, and soil compaction have drastically altered the physical and biotic characteristics of the edaphic environment, including substantially reducing populations of important symbionts such as vesicular-arbuscular mycorrhizal (VAM) fungi (Bainbridge, 1993; Bainbridge and Virginia, 1990) which form mutualistic associations with about 90% of species from arid and semiarid lands (Trappe, 1981). These symbiotic relationships increase the rooting volume via hyphal extension (Bainbridge et al., 1993), increasing access to nutrients, especially P, and water in exchange for carbohydrates (Harley and Smith, 1983; Allen and Boosalis, 1983). VAM fungi and phosphorus are both concentrated within the drip line of established shrubs (Allen and MacMahon, 1985). Spatial variability in shrub-dominated arid and semiarid sites is distinguished by resulting "islands of fertility," characterized by enhanced soil nutrients and organic matter under existing plant canopies, relative to areas between plants (Allen, 1991). This consolidation of resources by root scavenging and leaf litter deposition is a critical initiator of successional processes (Allen, 1991), improving soil tilth, moisture infiltration, and microbial activity (West, 1989).

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

Following transplanting, protection from herbivory, moisture stress, and wind damage must be provided. Herbivory, in particular, is a critical factor in plant establishment in arid and semiarid environments (Bainbridge and Virginia, 1990; Romney et al., 1987; McAuliffe, 1986), with grazing by blacktail jack rabbits (*Lepus californicus*) often a limiting factor in the Mojave Desert and Great Basin environments (Romney et al., 1987). A variety of plant protection techniques have been demonstrated, including the plastic, conical tree shelters and metal screens used in the present study, and rock mulches, plant collars, animal repellents, straw stubble, and mulches of standing senescent biomass. Applicability of each is determined by cost and individual site requirements (Bainbridge, 1995).

Establishing plants in arid areas is difficult without intensive irrigation. Methods of applying supplemental water include simple basin watering, deep pipes, buried clay pots, porous capsules, wicks, and drip systems (Bainbridge and Virginia, 1990). An alternative method increases retention of rainwater with microcatchments that reduce runoff and increase infiltration (Jackson et al., 1991; Virginia and Bainbridge, 1987; Shanan et al., 1970). In the case of formerly irrigated but abandoned agricultural lands, ground water depletion and consequent reliance on rainfall and run-off may further constrain recruitment, potentially excluding formerly dominant phreatophytes.

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

When direct seeding efforts and the use of transplants fail, discrete, dispersed natural or artificial barriers, such as sparse shrub vegetation, rocks, soil clods from tillage, can all effectively suppress dust emissions (Wolfe and Nickling, 1993; Buckley, 1987) according to their cross sectional dimensions, geometric arrangement and spacing, porosity and flexibility (Bilbro and Fryrear, 1995; Wolfe and Nickling, 1993). In areas where blowing dust requires immediate, effective, and certain intervention, these physical wind barriers offer an additional tool for controlling fugitive emissions. There have been few attempts to quantify the effectiveness of artificial barriers on fugitive dust emissions from abandoned desert agricultural lands.

In February, 1992, with funding from the USDA Soil (now Natural Resources) Conservation Service (NRCS), an Emergency Watershed Protection (EWP) program was applied to about 1000 ha of the most seriously wind eroding areas near and upwind of the unincorporated settlement of Antelope Acres in the Antelope Valley. The goal of the EWP program was to provide both immediate and long term control of fugitive dust emissions, to abolish local dust storms, and to mitigate violations of PM_{10} standards measured at the Lancaster, CA monitoring site by the South Coast Air Quality Management District. To this end a single, multi-faceted protocol was imposed on the entire 1000 ha area, consisting of a combination of treatments each of which was considered likely but not certain to succeed. This consisted of simultaneous tillage, drilling of rapidly establishing species, and broadcasting of slowly developing but sustainable native perennial shrubs. Wind fences were established near roadways and upwind of residential dwellings that had been subjected to severe fugitive dust problems.

In 1994 this protocol was repeated in a multiple location large plot study, along with several alternative surface stabilization protocols. Multiple location small (garden) plot studies were undertaken for evaluation of additional plant species and their potential for use in direct seeding efforts in this environment, in both irrigated and unirrigated field tests. Wind fences were established concurrently on large plots for evaluation of their effectiveness in controlling fugitive dust emissions.

In Fall 1995, several nursery-grown plant species were transplanted throughout the western Antelope Valley, in a factorial treatment arrangement with different mulches, planting hole excavation methods, and types of herbivory protection.

This report integrates the research and demonstration projects conducted by the University of California from January 1992 through the conclusion of the work under the current ARB Contract No. 94-337. We evaluate the establishment and survival of the direct-seeded plant species during and following the EWP program in 1992, and during subsequent unsuccessful attempts to reproduce these successful results. We also document the effective control of fugitive dust achieved through this EWP protocol from 1992 through 1996, and present evaluations of alternative direct seeding strategies and direct comparisons of potentially useful plant species. Also presented are evaluations of several native shrub species transplanted to various sites in the Antelope Valley of the western Mojave Desert, several different planting techniques, including contrasting methods of hole excavation, mulches, herbivory protection, and the role of site disturbance in predicting transplant survival. The effectiveness of artificial wind barriers for controlling fugitive dust is estimated. These include wind fences in differing configurations, discrete widely distributed roughness elements (plastic cones and wire cages intended for herbivory protection), and furrows.

Materials and Methods

Direct Seeding

The direct seeding portion of this work incorporates results of three distinct experiments. First, the emergency Watershed Protection Program (EWP) was used to revegetate about 1000 ha of seriously eroding land, using a single, multi-faceted protocol of tillage and revegetation. Second, the EWP protocol was repeated in successive years in Large Plots (LP), along with a range of less complex and less costly protocols. Third, a wide range of plant species, including those used in the EWP, was evaluated in small common Garden Plots (GP). We evaluate revegetation success in each experiment and dust suppression by the vegetative cover established in the EWP program over several subsequent years.

Emergency Watershed Protection Program

The area of ongoing fugitive dust emissions treated with the EWP protocol was located between 34° 44' 40" and 34° 48' 54" N latitude, and between 118° 17' 50" and 118° 20' 43" W longitude, with a mean elevation of approximately 760 m. Soils were of the Rosamond and Hesperia series, with surface textures ranging from fine sandy loams, loamy fine sands, loams, to silty clay loams (USDA, 1970) with some clay enrichment below the surface 10 cm. In some areas there was an overburden of blown sand.

Preparation of the site in February 1992 included initial burning of annual vegetation, primarily Russian thistle, without dusturbing any remnant perennial vegetation. Exposed mounds of wind-deposited soil and sand were leveled using road graders. This was followed by farm cultivation equipment for ripping of the soil perpendicular to the prevailing winds on 0.46 to 0.51 m centers to a minimum depth of 0.30 m, and furrowing on 0.91 to 1.02 m centers to a minimum depth of 0.20 m, with simultaneous drilling of a seed mixture into the furrow bottoms.

The seeding strategy (Table 2) included a horticultural component (drilling barley, *Hordeum vulgare* cv 'Seco' or 'Solum' into the furrows) to achieve rapid vegetative cover to increase surface roughness and decrease surface wind velocity and sufficient root proliferation to bind the soil. Indian ricegrass (*Achnatherum hymenoides*), a perennial bunchgrass widespread throughout rangelands of the western United States, and well adapted to sandy soils in temperate deserts (Young et al., 1994), was also drilled along with the barley in the furrow bottoms.

Table 2. Plant species, planting methods, and seeding rates used in the Emergency Watershed Protection program (EWP).

Scientific name	Common name	Seeding method	Seeding rate[3] (kg ha^{-1})
Atriplex canescens	Four-wing Saltbush	Aerial[1]	0.73
Atriplex polycarpa	Allscale Saltbush	Aerial	0.73
Eriogonum fasciculatum	California Buckwheat	Aerial	0.55
Eschscholzia californica	California Poppy	Aerial	0.1
Achnatherum hymenoides cv. 'Paloma'	Indian Ricegrass	Ground[2]	1.1
Hordeum vulgare cv. 'Seco' or 'Solum'	Barley	Ground	0.3

[1]Broadcast by helicopter.

[2]Drilled in furrow bottoms.

[3]Minimum target rates. Actual seeding rates were about 66% higher to allow for spreader calibration and wind drift.

Following ground operations an additional seed mixture of native shrubs and a wildflower were broadcast over the entire area from the air by helicopter. Aerial seeding of these mid- to late-seral desert shrubs, well adapted to this region, constituted the final step in the procedure, as no further treatments (irrigation, herbicide, tillage) were applied. The wildflower, California poppy (*Eschscholzia californica* Cham.) provided color for aesthetic purposes, as well as a marker for successfully seeded areas.

Vegetative cover in the EWP area was assessed in June 1994 by conducting 38 randomly located 50 m line intercept (Krebs, 1989) transects throughout the 1000 ha EWP Site. Individual plants that intercepted the line were recorded and the fraction of line intersected by each species was converted to percent of ground area covered. Barren areas were similarly classified as percent ground area and additionally characterized by length for estimation of fetch and potential to emit fugitive dust.

Vegetative cover was assessed in 1995, 1996, and 1997 using a more complex protocol of stratified random sampling, in which the EWP area was first classified by soil surface texture (USDA, 1970) and transect locations were then randomly located within each class. Transect lengths were increased to 100 m, and a point intercept technique (1 m intervals; Krebs, 1989) adopted. Twenty-six transects were marked permanently with metal stakes to permit a Repeated Measures Analysis of Variance (SAS, General Linear Models, 1988). This analysis provides information about changes in percent of ground covered by vegetation over time. It also provides a test of significance for the effects of species, soil type, and their interaction while ignoring the time effect, based on combined data from the three year period.

Control areas for comparative measurements of dust emissions

In 1992 a control site was established near the western end of the Antelope Valley (Site A). This control site was outside the EWP area, but with a similar soil (Ramona loam) and wind erosion history. The soil surface in this location was devoid of vegetation, similar to that of the EWP area prior to reseeding.

In 1994 - 1996 a control site closer to the EWP area was established. A large (183 m x 91.5 m) plot near the EWP area (Site K) was maintained in a barren state throughout the experiment by either burning annual vegetation as it emerged with a tractor-drawn propane weed burner, or by abrading the surface lightly with a tractor-drawn disk harrow that was adjusted to just contact the previously leveled soil surface.

Alternative stabilization protocols

Eight surface stabilization treatments were installed in February 1994 at three sites (Sites B, G, and K) constituting a Randomized Complete Block (RCB) design (Grantz et al., 1996). Plot size was 91 m by 183 m. Treatments were chosen to represent a range of candidate approaches to stabilizing these abandoned farmlands (Table 3), including evaluation of the individual components of the combination EWP protocol. These included non-disturbing (burning existing vegetation, broadcasting seed), minimally-disturbing (burning, rangeland drilling seed), and highly-disturbing (ripping, furrowing, drilling seed) treatments. Four of these eight treatments (treatments 3, 4, 5, and 6) utilized the same seed mixture (similar to that used in the EWP), with pure live seed applied at 0.40 (*A. canescens*), 0.26 (*A. polycarpa*), 0.27 (*E. fasciculatum*), and 0.20 kg ha^{-1} (*C. nauseosus*), to test the effect of the method of sowing and the level of soil disturbance. One treatment involved applying the EWP protocol in widely spaced (50 m) strips that were the width of the cultivator tool bar (5.5 m). An additional treatment involved rangeland drilling the standard seed mix in a series of perpendicular strips separated by 11 m and intersecting in areas receiving twice the standard seeding rate, leaving an internal control receiving no seed.

Table 3. Candidate fugitive dust stabilization treatments tested in Large Plots.

Treatment	Description
1	Control. Burned followed by light disking as needed (Sites B and K only).
2	Ripped (0.3 m deep, 0.46 m wide) and furrowed (0.2 m deep, 0.9 m wide) in North-South direction.[1]
3	Ripped, furrowed, and drilled with the seed mix.[1,2]
4	Ripped, furrowed, and drilled seed in strips, one pass across the wind at 50, 100 and 150 meters from the upwind edge of plot.[3]
5	Broadcasted the seed mix without tillage.[2]
6	Rangeland drilled the seed mix.[2]
7	Rangeland drilled *Bromus rubens*.
8	Rangeland drilled the seed mix in a pattern of intersecting strips; seed 1 pass, skip 2 in both directions.

[1]EWP specifications required ripping to a minimum of 0.3 m deep and between 0.46-0.51 m wide (shank separation), and furrowing 0.91-1.02 m wide (furrow centers).

[2]Seed mix differed from that used in the EWP.

[3]Strip width was 5.5 m.

Two of these sites (B and K) exhibited no germination on any treatment and are not evaluated here. Site G began to exhibit germination in the second year following seeding and provided useful information on the candidate protocols (below). Plant densities were evaluated on several dates by the point-quarter technique, with n = 10 for each plot (Krebs, 1989).

To evaluate a broader range of vegetation than could be accommodated in Large Plots, nine plant species were seeded in a 3 X 3 Balanced Lattice Design (9 treatments in incomplete blocks of 3 experimental units, with 4 replications yielding 36 plots per location; Cochran and Cox, 1957). Experimental units (plots) were 2 m x 6 m. Seed was hand broadcast over lightly tilled soil at a rate of about 75 pure live seeds per square meter, and covered by hand raking. Replicate lattice designs were installed at 4 locations, 2 with loamy and 2 with sandy soils in March 1994, and two additional lattices (one irrigated with 0.8 cm weekly for 3 weeks) at each location in November 1994.

The species used were those in the EWP program (*A. canescens, A. polycarpa, Achnatherum hymenoides,* and *E. fasciculatum*) plus *C. nauseosus* and *Bromus rubens* L., both early successional species on disturbed lands in this region, *Achnatherum speciosum* (Trin. & Rupr.) Barkworth, a bunch grass native at slightly higher elevations in the area, *Larrea tridentata* (DC.) Cov., a large perennial shrub native to the area, and asexually propagated *Vetiveria zizanioides,* a subtropical grass used to control soil erosion by water (National Research Council, 1993). *Vetiveria,* alone, was transplanted into three rows at each site, with five slips (vegetative propagules) per row. This species did not survive in this environment and was removed from further evaluation. No germination was observed in any small Garden Plot, with or without irrigation.

Fugitive dust monitoring protocol

Fugitive dust was monitored in 1992, 1994, 1995, and 1996, by sampling suspended particulate matter weekly during the windy season, April through June (through October in 1995). Samples were obtained using passive, near-isokinetic collectors (Big Springs Number Eight (BSNE)) with high efficiency for particles above about 45 μm aerodynamic diameter (Stout and Fryrear, 1989). The samplers are not efficient for finer particles, including the criteria pollutant PM_{10} (≤10 μm) but provide an excellent measure of saltation and horizontal transport of soil-derived sediment (Shao et al., 1993b; Nickling and Neuman, 1997), processes intimately linked with emissions of suspended fugitive dust and PM_{10} air pollution (Gillete et al., 1995; Shao et al., 1993a). Relatively good linear relationships have been shown between mass of material collected in BSNE samplers and mass of PM_{10} collected in high volume PM_{10} samplers (Stetler et al., 1994). The BSNE samplers passively orient to face the wind, allow entry of particle-laden air, and are wedge-shaped to slow air movement within the sampler to allow dust to settle out through gravitational sedimentation. Air and many fine particles exit the top of the sampler through fine mesh screen. At the end of each collection period dust was removed from the BSNE samplers under wind sheltered conditions with a soft brush, directly into tared, zip-lock bags for gravimetric determination in the laboratory.

In 1992, the BSNE samplers were deployed at 0.2, 1.0, and 2.0 m above mean soil surface, mounted on two, 3 m lengths of 1.27 cm diameter pipe. These were driven into the soil at the leeward edge of the EWP and control areas. The EWP area extended to the west, upwind, for approximately 3.2 km from the samplers. The control area (Site A) extended 1.2 km upwind from the samplers. In 1994 - 1996 BSNE samplers were deployed only at 1.0 m height at the downwind edge of the EWP and control sites. Three replicate samplers were mounted on separate lengths of pipe. The barren area extended 183 m upwind from the samplers at the control area (Site K).

Transplants

Plant material

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

Two saltbushes, fourwing saltbush (*Atriplex canescens*) and allscale saltbush (*A. polycarpa*), are well adapted to the study area and occur commonly throughout the western Mojave Desert. Bladderpod (*Isomeris arborea*) is a highly branched shrub formerly common in the study area, and has shown some promise for use in stabilizing disturbed arid areas (Hickman, 1993). Rabbitbrush (*Chrysothamnus nauseosus*) is widely adapted to diverse habitats from British Columbia to Baja California (Hickman, 1993) with numerous biotypes/subspecies. It is an early successional species in the Western Mojave Desert, exhibiting vigorous colonization of abandoned, denuded or burned areas which have not been subjected to extensive physical soil disturbance (e.g., by tillage; Grantz et al., 1998a). Following soil disturbance it is usually displaced by invasive annuals including Russian thistle (*Salsola pestifer* Nelson).

Seedlings of all species were grown by the California Department of Forestry in Davis, CA in high aspect 5 x 5 x 35.5 cm containers (plant bands; Bainbridge et al., 1993), in an artificial soil mix comprised of (by volume) 40% sand, 45% perlite, 5% vermiculite, 5% fir bark, and 5% coarse peat (L. Lippett, personal comm.). Fertilizer (38-45-0; N-P-K; 590 g m^{-3}) and gypsum (2950 g m^{-3}) were added prior to planting.

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

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

Transplant Experiment I

This experiment was conducted on a site (Table 4; Site K) subjected to intensive farming over the last several decades but abandoned in 1989. Between 1954 and 1989 this land was cropped to alfalfa (*Medicago sativa*, 7-8 years per cycle) in rotation with small grain grown for a single year between alfalfa plantings (P. Kindig, personal comm.). Alfalfa was harvested 5 times annually with 3 flood irrigations between harvests. Commercial phosphate fertilizer was added annually for alfalfa, and nitrogen fertilizer was added for small grains.

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

Two planting methods were applied to transplanting locations pre-marked with wire flags. Several crews of range-fire fighters with revegetation experience moved across the field, equipped with a power-auger (excavating a 10 cm diameter x 36 cm deep hole; 370 plants) or a pickax (excavating a 40 x 40 x 40 cm deep hole; 410 plants). The resulting distribution of planting methods to experimental units was randomly determined by which crew arrived first at each flag. Two L of water were added to each hole and allowed to drain before transplanting. Plants were placed in the hole and the plant band removed. The hole was back-filled and the soil lightly compacted. An additional 1 L of water was added after planting and another 2 L on 8 subsequent occasions during the first dry season.

Two types of transplant protection were also randomly assigned. Four-hundred seventy-five plants were covered with plastic tree shelters (cones; base diameter 20 cm, top diameter 10 cm, height 61 cm; Tree-Pee, Baileys Inc., Laytonville, CA) and 305 plants were covered with cylindrical stucco wire cages (diameter 30 cm, height 91 cm) held in place with a metal rod threaded through the wire mesh and driven into the soil. The height of the *P. glandulosa*

Table 4. Site, elevation, soil classification, and surface characteristics for six common garden plots (Transplant Experiment II).

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

transplants was 15-25 cm. Protective covers were removed in October 1996 when plants began to emerge from the shelters.

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

Plants were scored for vigor (a continuum from 0 = dead to 8 = most vigorous) using defined criteria (Table 5), on six dates between planting and January 1997.

Table 5. Vigor rating scale used to assess transplanted seedlings.

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

Contingency analyses were performed on the survival data (score of 0 versus sum of all other scores) on selected dates to determine the effect of the four planting methods on plant survival. A 2-way ANOVA (hole type x protection type) was performed on the vigor data, (General Linear Model; PROC GLM, SAS, 1988) on selected dates to determine the effect of the four planting methods on plant vigor. Mean separation of vigor scores was by Duncan's Multiple Range Test.

Transplant Experiment II

A multi-species comparison was established at six sites (Table 4) throughout the Western Mojave Desert. Sites were selected in October 1995 to incorporate the spatial variability observed in soil classification (US Department of Agriculture, 1970) and in the success of the previous revegetation by direct seeding in the EWP (Grantz et al., 1998a).

The difficulties with nursery propagation noted above led to elimination of *C. nauseosus* from the experiment and to a range of planting dates for the remaining species (Table 6). All transplants were placed in power-augered holes and irrigated as above. There were no additional irrigations.

Table 6. Planting dates for four species at six sites (Transplant Experiment II).

Site	Planting date by species			
	Prosopis glandulosa	*Atriplex canescens*	*Atriplex polycarpa*	*Isomeris arborea*[2]
B	10/25/95	1/11/96	1/24/96	5/2/96
K	10/25/95	1/11/96	1/24/96	5/2/96
W[1]	1/31/96	1/11/96	1/24/96	5/2/96
C100S	10/26/95	1/12/96	1/25/96	5/2/96
C100N	10/26/95	1/12/96	1/25/96	5/2/96
B120W	10/26/95	1/12/96	1/25/96	5/2/96

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

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

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

Plants were scored for vigor periodically after planting, utilizing the 0 - 8 rating scale (Table 5). Three of the transplanted species (*A. canescens, A. polycarpa, and P. glandulosa*) were evaluated five times between April 1996 and April 1997. *I. Arborea* was evaluated four times. Differing planting dates prevented the planned complete factorial analysis. Therefore a within-species ANOVA of plant vigor was undertaken, using a General Linear Model (PROC GLM; SAS, 1988) of site, protection, mulch and interactions. Mean separation for significant site effects within each species was by Duncan's Multiple Range test. The simple effects of protection or mulch type within a site were evaluated only if main effects or interactions across all sites were significant.

Three randomly located soil samples (0-10 cm depth) were obtained from each of the six sites in April 1996 and analyzed for nitrate and ammonium N levels (Keeney, 1982), and for bacterial and fungal populations (Anderson and Slinger, 1995; Trent, 1993; Conners and Zink, 1994). Soil data were analyzed by one-way ANOVA, and significant differences between site means were determined by Fisher's protected LSD.

Artificial wind barriers

General

Three sites were selected for intensive measurements. Site K (Table 4) was located in mid-Antelope Valley. Site F (118° 17' W, 34° 45' N) was a 25 ha area with a soil type of Cajon loamy sand with a loamy substratum (sandy, mixed, thermic, Typic Torripsamment) overburdened with a 450 m fetch of unstabilized mixed fine and coarse blown sand. Sites A, X and W were nearly contiguous and located near the western end of the Antelope Valley (118° 35' W, 34° 48' N). Sites A, X, and W contained Hanford loamy sands (coarse-loamy, mixed, nonacid, thermic Typic Xerothents). These sites were abandoned agricultural land, barren since at least 1991, that were overburdened with blown sand.

Suspended particulate matter was sampled with BSNE samplers. The samplers were mounted on 3 m lengths of 1.27 cm diameter pipe which were driven into the soil. After each sample period, collected particles were removed from the BSNE samplers under wind shelter with a soft bristle brush, into tared zip-lock bags for gravimetric determination in the laboratory. Collected mass was expressed as total loading, as all BSNE samplers in each comparison exposed the same inlet areas (1.0 x 10^{-3} m^2) over identical sampling intervals (approximately 1 wk) and wind erosion conditions. Most sampling periods were characterized by the absence of discrete wind events but in a few cases deposition was dominated by a single large event.

Dispersed barriers

In September of 1995 at Site K, a barren parcel (91 m by 183 m) aligned east-west with the prevailing wind, was treated with dispersed plastic cones (base diameter 20 cm, top diameter 10 cm, height 61 cm) and cylindrical wire cages (stucco wire, 17 gauge; diameter 30 cm, height 91 cm). These were placed over the young mesquite transplants (that were being evaluated as part of the transplant portion of this project) to protect against herbivory (Grantz et al., 1998b) in a rectangular grid spaced 9.1 m by 2.3 m. An adjacent plot of the same dimensions was maintained in a barren condition and used as the control. The effectiveness of these small, dispersed physical barriers in suppressing fugitive dust emissions was evaluated in Spring of 1996. At the time of this study the transplants had not emerged from the herbivory shelters.

BSNE samplers were installed at the downwind edge of each plot at Site K at logarithmically based heights of 0.2, 0.37, 0.67, 1.16, and 2.0 m, with three replicate samplers at each height. Samples were collected between 3 April and 16 June. Saltation was measured at the downwind edge of the barrier plot using a piezo-electric quartz sensor (Gillette and Stockton, 1986; Fryrear et al., 1991), sensitive to particle impact. The number of impacts per hour was averaged within specified ranges of wind velocity (0.5 m s^{-1}) and expressed as a function of velocity. This allowed direct determination of threshold velocities for wind erosion.

An alternative method of estimating threshold velocity for wind erosion, requiring no specialized instrumentation, was evaluated at several locations. Twenty minute averaged wind velocities were summed above seven potential threshold velocities (0, 2.5, 5.0, 5.5, 6.0, 6.5, and 7.0 m s^{-1}). This removed lower, non-erosive, wind speeds from the analysis and weighted remaining wind velocities according to duration (i.e., wind run above the threshold). Each potential threshold velocity was evaluated by regressing the mass of coarse particles on the velocity summation, expressed as a coefficient of determination (r^2; PROC REG, SAS, 1988). Wind speed and direction were measured at 2.0 m (Sites F and A), or calculated (Site K) at 2.0 m from measurements at 10.0 m and 1.0 m (Roberts Environmental Services, Inc., unpublished data) assuming a logarithmic wind speed profile with roughness length, z_0 = 1.0 cm (Grantz et al., 1995).

Continuous barriers

The wind fence utilized in these studies (1.22 m in height; 55% porosity) was constructed of ultraviolet (UV) -stabilized high density polyethylene, attached by UV-stabilized plastic ties to 1.33 gauge T-type steel posts placed on 1.83 m centers. In March of 1992, three parallel wind fences (10 m between fences) were established, perpendicular to prevailing winds, across the leeward side of the 25 ha area at Site F. Installation of the fences was undertaken by USDA-NRCS in cooperation with the County of Los Angeles Fire Department (Grantz, 1998c; Sims, 1993; Spitzer, 1993). Over the following months, two more sets of paired (10 m apart) wind fences were installed, one pair near the middle and one pair near the upwind edge of the area of blown overburden sand.

During Spring, 1992, we evaluated the effectiveness of the first installation of three parallel wind fences at Site F. An array of BSNE samplers was deployed in a transect from upwind of the blowing area (a region stabilized by natural vegetation), through the unconsolidated sandy area containing the wind fences, continuing to the leeward edge (Fig. 1A, locations A through F). Two replicate sampler assemblies were installed at each position. Three BSNE samplers were mounted on each pole at heights of 0.2, 1.0, and 2.0 m above mean soil surface. Collections were made weekly between 2 April and 25 June 1992.

Mass of collected soil particles at each height from the two replicate sampler arrays at each site were averaged and normalized to the mass collected at 335 m into the fetch (upwind of the first fence at Site F, location B in Fig. 1A). The vertical and longitudinal distributions were then compared and evaluated. The control site (Site A) had similar soil surface characteristics, erosion history, and field length, but no wind fences.

Following their installation, all three sets of wind fences at Site F were evaluated in Spring 1995 with a longitudinal sampling array through the series of fences. BSNE samplers were deployed at 1 m above mean grade, with a single sampler located 10 m upwind and 10 m downwind of each of the three sets of parallel fences (Fig. 1A, locations a through f).

In 1994, wind fences were evaluated at Sites X and W. At each site, two plots, 91 m wide by 183 m long, were established. On one plot at each site 3 single wind fences were installed perpendicular to prevailing winds, and spaced equidistant along the length of the plot (Fig. 1B). BSNE samplers were deployed in an array (Fig. 1B) at 1.0 m height from 13 April until 30 May. On 30 May, sample height was reduced to 0.2 m and data collected until June.

Furrows

In 1994, furrows were established across the wind on a 100 m by 200 m plot at Site K (Table 4) with an adjacent control plot. Tillage specifications were those used in the large plot evaluation of alternative stabilization treatments (Table 3, Treatment 2). In 1995, replicate BSNE samplers were installed at 1.0 m height (n = 3 per height) with weekly samples for six weeks. Samplers were then relocated at logarithmically determined heights of 0.20, 0.37, 0.67, 1.0, 1.16, and 2.0 m above the soil surface (n = 3 per height) at the downwind edge of each plot, with weekly samples for 11 weeks.

Weather data

A weather station was established at Site F and operated continuously throughout the period of evaluation of wind fences in 1992. Wind speed and direction were measured at 2.0 m with a cup anemometer and wind vane (R. M. Young Wind Sentry Set; Campbell Scientific, Logan, UT) sampled at 1 Hz with a data logger (Model 21X; Campbell Scientific, Logan, UT). Temperature and relative humidity were measured with a temperature and humidity probe (Model 207; Campbell Scientific, Logan, UT). Solar radiation was measured with a pyranometer sensor (Model LI-200SB; LiCor, Lincoln, NE), and rainfall was measured with a tipping bucket rain gauge (Model TR-525; Texas Electronics, Dallas, TX). Observations were made at 1 second intervals, averaged every 20 minutes, and stored in solid state storage modules (SM 192; Campbell Scientific, Logan, UT).

In conjunction with the large plot direct seeding, and the later transplant work and the evaluation of the wind fences at Sites X and W, a micrometeorological station was operated at a secure site (118° 35' 15" W, 34° 51' 00" N) from 6 April 1994 through 17 January 1997. Instrumentation and sampling protocol were identical to those used at Site F in 1992.

Diskettes containing files of this weather data are provided in spreadsheet format (Excel 7.0) on PC compatible 3.5" disks, and a listing of the files and their content is given in the Appendix.

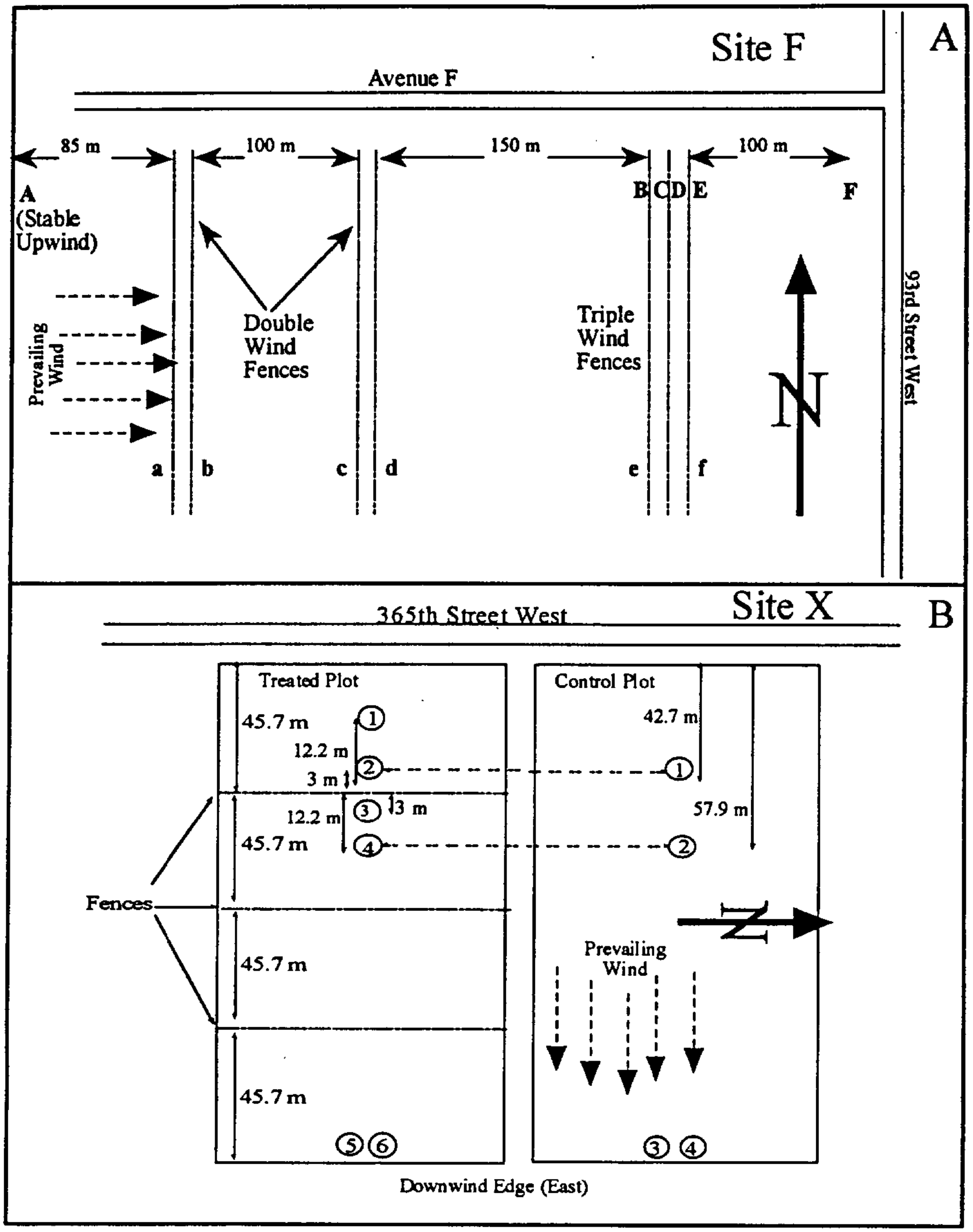

Figure 1. Diagram of sandy experimental sites in (A) mid-Antelope Valley (Site F) and (B) in upwind, western Antelope Valley (Site X shown, duplicate Site W not shown). Locations of wind fences on barrier plots and samplers on both barrier and control plots are shown.

Results and Discussion

Direct seeding

Revegetation in the EWP

Immediately following establishment of the EWP in February 1992, abundant rainfall (200% of normal) was received (Fig. 2) and a dense ground cover of barley in the furrows and perennial seedlings was observed in many areas (not shown). These had a rapid suppressing effect on fugitive dust. Between 1992 and 1995 exceedances of the California state standard for PM_{10} (50 $\mu g\ m^{-3}$, 24 hour average) at the Lancaster monitoring site were reduced to only five exceedance days per year on average, compared with 25, 22, and 11 days in the preceding three years emissions (Table 1). Natural establishment of native and introduced annual species in areas of the EWP where shrub establishment was poor also contributed to the vegetative cover.

Detailed plant censuses were conducted beginning in Spring of 1994 to evaluate the persistence of the revegetation in the EWP area. Average perennial plant cover increased slightly from 1994 through 1996, followed by a sharp decrease in 1997 attributed to two consecutive years of drought conditions (Fig. 2 and inset). The differences in percent cover of seeded perennial species observed between the years 1995 and 1997 were highly significant ($P < 0.01$; RMANOVA; SAS, General Linear Models, 1988). In 1994, though 69% of the surveyed area was classified as barren (i.e., only 31% vegetated, Fig. 3), the cover that existed compared favorably with perennial cover generally observed in surrounding old field successional areas of Mojave desert scrub (i.e. 20 - 30% cover, Carpenter et al., 1986). Transects conducted in an undisturbed area near the EWP revealed that perennial cover, provided here mostly by *A. canescens* and *Ephedra nevadensis* S. Watson averaged 46 ± 3.8%. The barren areas observed in 1994 were mostly (>66%) less then 2.0 m in length, with only 6% greater than 8.0 m. Despite the large total area of barren soil, the spatial arrangement of vegetative elements reduced wind velocity at the soil surface, providing insufficient fetch to entrain soil particles.

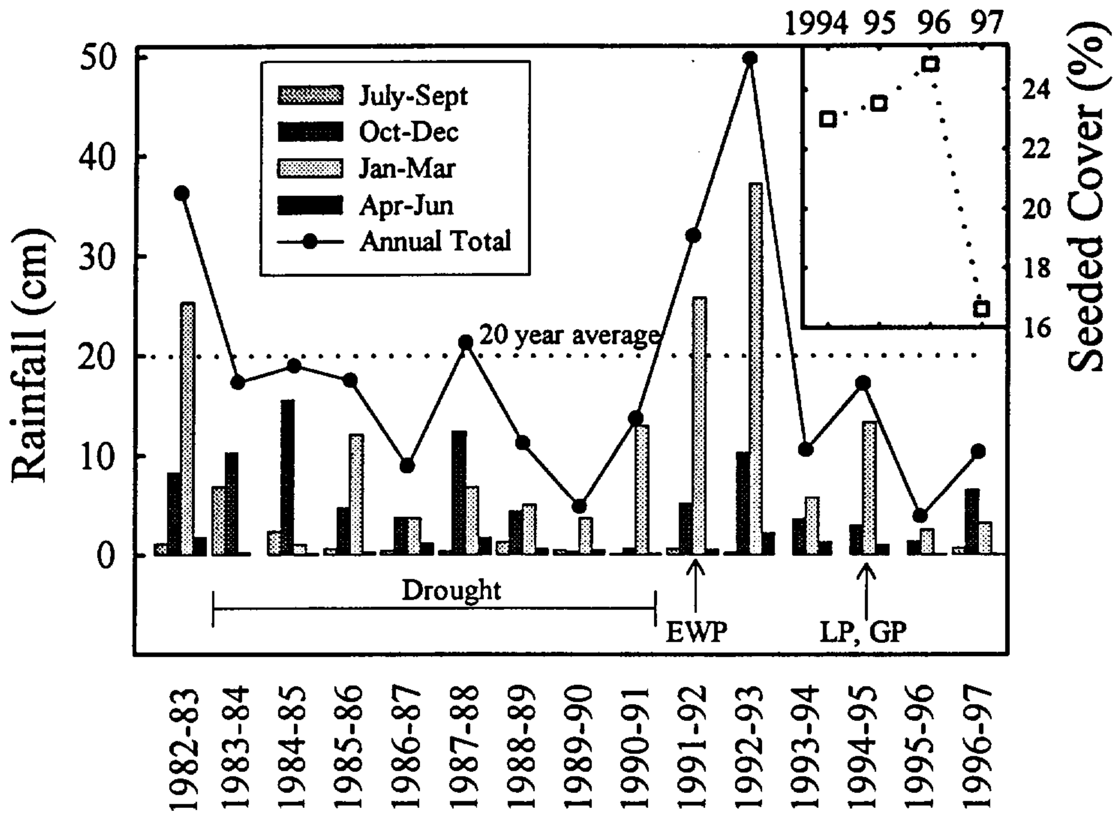

Figure 2. Quarterly (bars, means ± S.D.) and annual total (solid circles) rainfall at Lancaster, CA from July 1982 through June 1997. The prolonged drought, and time of installation of the Emergency Watershed Protection program (EWP), and of the Large Plots (LP) and common Garden Plots (GP) are shown. The total percent of ground area covered by the directly seeded shrub species declined following a period of low rainfall (inset).

The plant cover observed in the EWP area in 1994 consisted of the seeded woody shrubs *Atriplex canescens* (7%), *A. polycarpa* (7%), and the smaller but more numerous *Eriogonum fasciculatum* (7%), with about 2% cover attributed to the seeded perennial bunchgrass, *Achnatherum hymenoides*, and 8% annual species, including the invasive Russian thistle (*Salsola pestifer*, 6%). The seeded California poppy (*Eschscholzia californica*), though observed in 1992, was uncommon in the EWP area by 1994, with no intercepts on any transect.

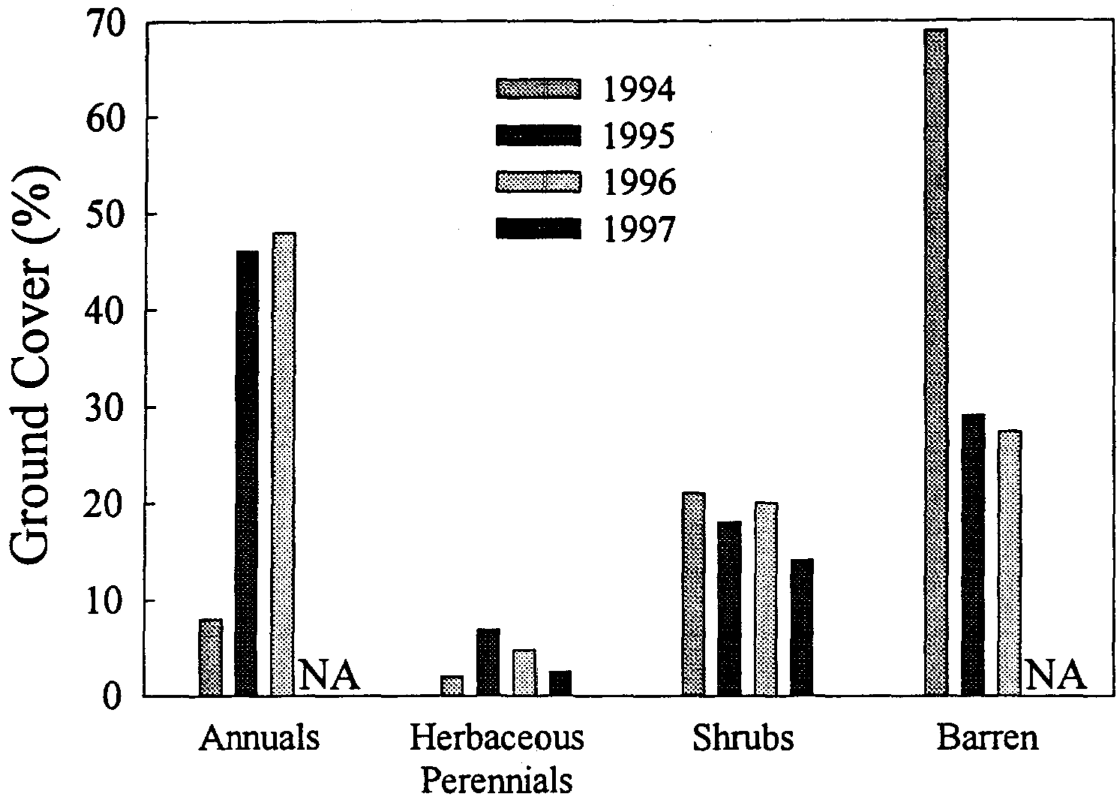

Figure 3. Percent of the ground surface covered by plant type or barren soil averaged over four years and all areas of the Emergency Watershed Protection program. (NA, data not available).

Abundant rainfall, averaging 3.2 cm per month between October 1994 and March 1995 (Fig. 1), resulted in extensive vegetative cover of many winter annual plant species, including annual grasses such as *Bromus* and *Schismus* species. This was accompanied by a proportional decrease in barren area, while shrub covered area decreased slightly (Fig. 3). The most abundant annuals were Tumble mustard (*Sisymbrium altissimum* L., 27%), filaree (*Erodium cicutarium* (L.) L'Hér., 4%), *Bromus* spp. (8%), Russian thistle (4%), and Western Tansy mustard (*Descurania pinnata* (Walter) Britton, 1.5%). Fifteen other annual species were documented at low frequency.

The percent of the ground surface covered by annuals in 1996 (Fig. 3) is of particular note. In contrast to the rainfall in 1994-95 (86% of normal), in 1995-96 rainfall was meager (19% of normal) and poorly timed, falling early in the season (Fig. 2). The resulting initial germination of annuals was followed by only limited growth and survival. By June 1996, there were only rare transect intercepts with living annuals. Rosette diameter of the ubiquitous filaree (*Erodium cicutarium*) was only 5 to 6 cm in 1996, compared with 50 to 60 cm in 1995. Senescent annuals that became established in 1995 and preceding periods of high rainfall, remained in place in the dry year, 1996 where they continued to reduce wind speed at the surface and to suppress fugitive dust, especially in areas where shrub establishment was poor. During periods of drought, non-living but still standing biomass contributes substantially to stabilizing the surface against wind erosion (Wolfe and Nickling, 1993).

A significant ($P < 0.02$) time x plant species interaction indicated that the change in percent cover over time varied between plant species. This is illustrated by the shift in the relative composition of the seeded shrubs between years and transect locations (Fig. 4).

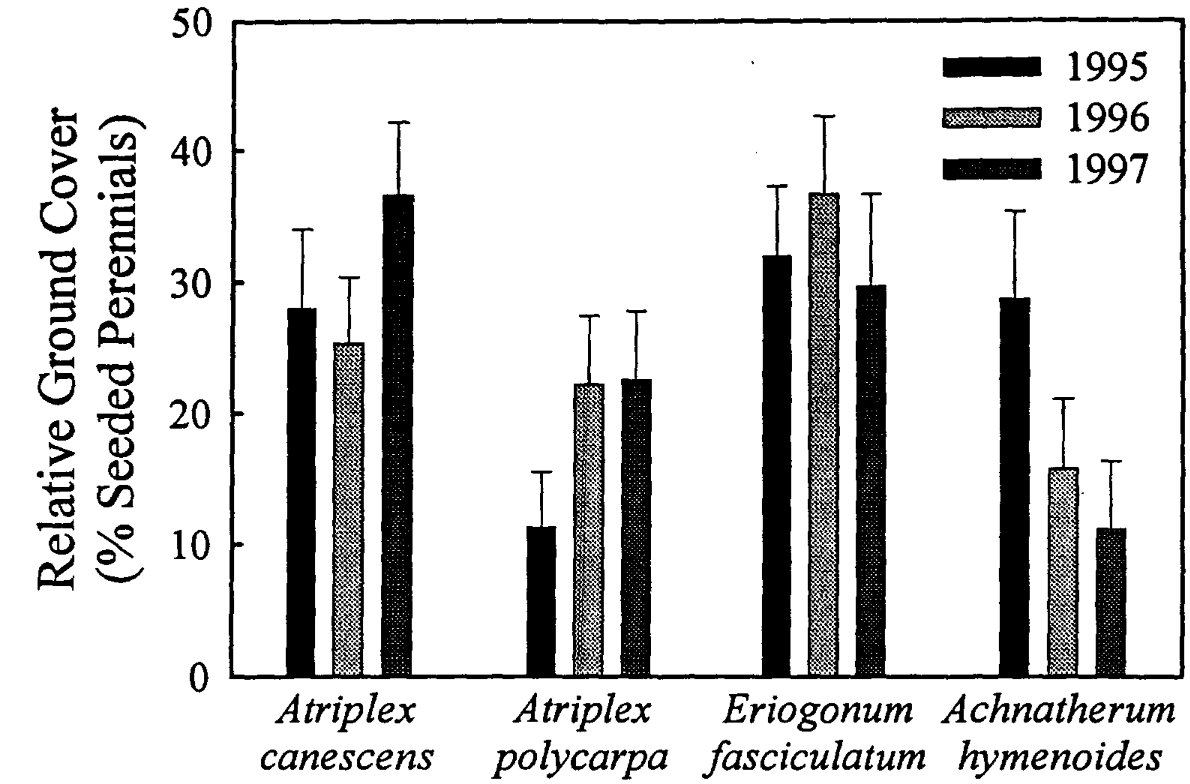

Figure 4. Ground cover by seeded perennial species relative to the total area covered by all seeded perennial species, averaged over all areas of the Emergency Watershed Protection program.

On average, adequate establishment of the 4 seeded perennial species occurred across the EWP area, though *Achnatherum* declined in most locations over time and remained only locally dominant. The two saltbush species maintained about 20 to 30% of the seeded ground cover, though *A. polycarpa* was much slower to establish than *A. canescens*. The smaller statured California buckwheat (*E. fasciculatum*) was widespread throughout the EWP area, representing a stable third of the area covered by the seeded perennials. The significant time by species interaction likely reflects developing competitive interactions under the pressure of limited hydrologic and nutritional resources. For example, between 1995 and 1996 a transect with a particularly dense (56%) shrub cover in 1995, decreased significantly to a more representative 30% cover in 1996. The dry 1995-96 winter contributed to the death of many small (height < 0.5 m) individuals of *Atriplex canescens* as initially larger shrubs out-competed the smaller individuals. Between 1994 and 1996 the relative composition of the *Atriplex* species generally increased while that of *Eriogonum* and *Achnatherum* declined (Fig. 4).

Variability in shrub cover between individual transects within the EWP area was associated with differences in soil classification (Figs. 5; 6A) and with differences in soil fertility and microbiology (Figs. 6B, D). By combining the data from 1995 - 1997, the RMANOVA provides a test of the hypothesis that the different species, soil types, and their interaction have no effects on percent of ground covered, while ignoring the within-transect effect of time. Significant effects existed for soil type ($P < 0.03$) and for the soil type x plant species interaction ($P < 0.01$). *Eriogonum* performed significantly better on the Rosamond fine sandy loam and *Achnatherum* significantly better on the Rosamond loamy fine sand than on other soil types. Time averaging reduced between-species differences to a non-significant level. When the time factor was specifically included, the significant three-way interaction of time x species x soil type demonstrated that the changes in vegetative ground cover with time differed between species in different soil types (Fig. 5).

These differences in plant establishment suggest methods for determining optimal plant species to seed in specific areas. The three shrub species were generally less frequent in sandy areas than elsewhere, while *Achnatherum* was restricted to these sandy areas, where it outperformed all other seeded species (Fig. 5D). No transect intercepts were encountered with *A. polycarpa* on sand, though *A. canescens* was able to exploit these microenvironments in some cases, further reflecting its widespread adaptation to this harsh desert environment. Annual species were less frequent in the sand compared with other soil types (30% vs. 56%), perhaps because of the lower water holding capacity in the surface layer. In the predominant soil type (fine sandy loams) perennial shrubs maintained sufficient coverage, with both *Atriplex* species performing best on the Hesperia series (Fig. 5A, B) and *E. fasciculatum* competing best on the Rosamond series soils (Fig. 5C).

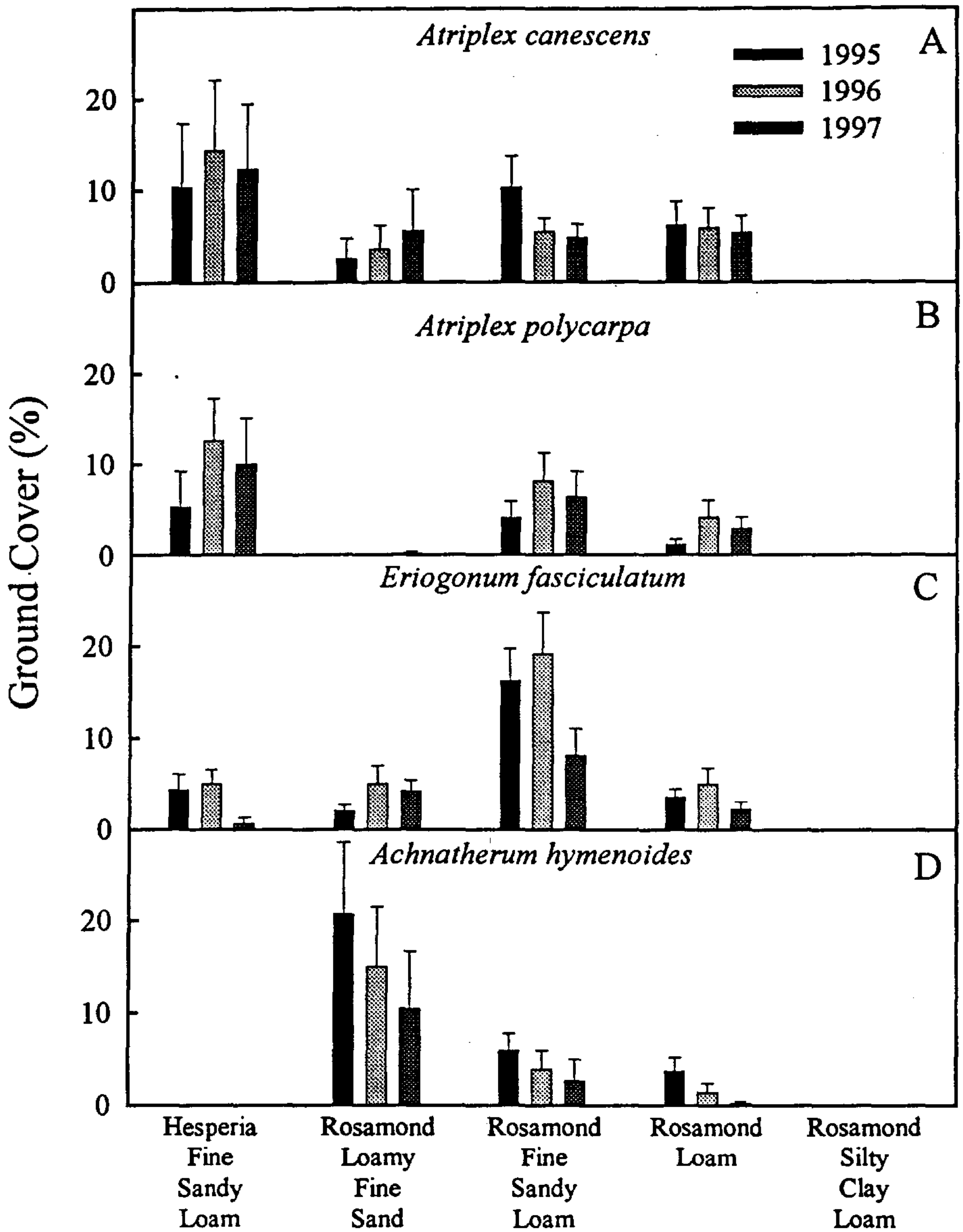

Figure 5. Percent of the ground surface covered by individual seeded species by soil type within the EWP area (bars not visible are near zero).

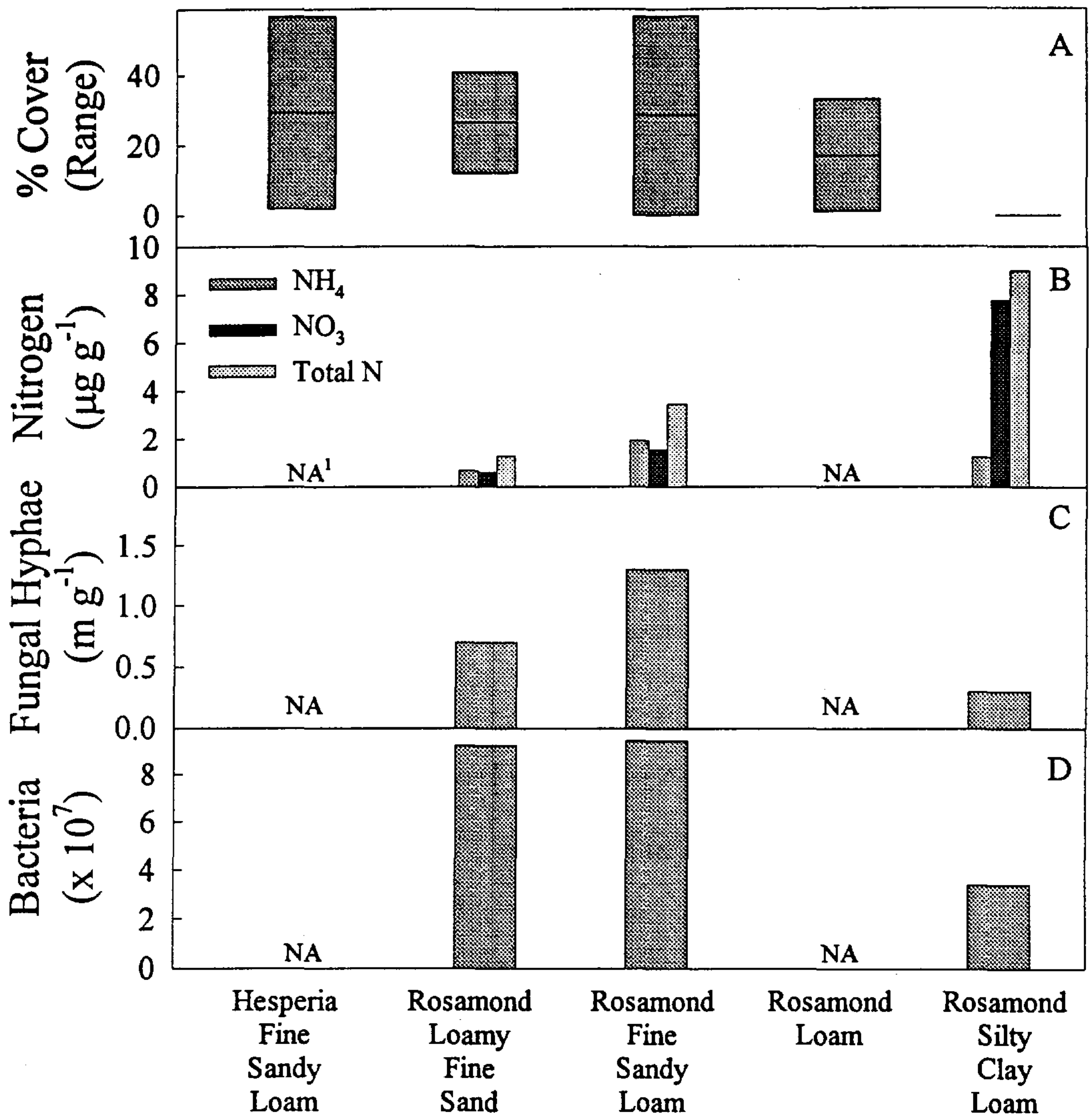

Figure 6. (A) Variability in total plant cover (horizontal lines, mean; bars, range) between transects within each soil type in the EWP; (B): soil and abundance of ammonium, nitrate, and total nitrogen; (C) soil fungal biomass; and (D) soil bacterial populations. (NA, data not available).

Within the EWP area sites with these two predominant soils contained the lowest concentrations of residual nitrogen (Fig. 6B) from previous agricultural amendments and the highest concentrations of fungal hyphae (0.70 and 1.30 m g^{-1}, respectively; Fig. 6C) and of bacteria (9.2 and 9.4 x 10^7 g^{-1}, respectively; Fig. 6D). Mycorrhizal fungi form symbiotic relationships with many plant species (Allen, 1988; Trappe, 1981), including the late seral shrub species native in these arid regions. The fungi facilitate acquisition of nutrients and water in exchange for carbohydrates from the host plant (Harley and Smith, 1983). Bacteria are also important ecosystem components with roles in nutrient acquisition and cycling (West, 1991). In the heavier soil, Rosamond silty clay loam, none of the seeded species became established (Fig. 5), and the soil had much lower concentrations of fungal hyphae (0.3 m g^{-1}) and bacteria (3.4 x 10^7 g^{-1}). It may be important in future work to separate the effect of these soil parameters from the soil characteristics themselves. However, soils in all areas had been previously cultivated with the resulting potential for residual nutritional and microbiological alterations, yet these characteristics were strongly stratified by soil classification (Fig. 6). Many colonizing annuals do not form mycorrhizal associations (Allen, 1988), and are thus particularly adapted to the disturbed areas with low levels of fungal inoculum. The Rosamond silty clay loam became particularly densely covered with the invasive annual *Sisymbrium altissimum*.

Evaluation of alternative stabilization strategies

The direct seeding protocol used in the EWP was repeated in Large Plots and approximated in small common Garden Plots, with a variety of sowing techniques, and with or without irrigation. These attempts to replicate the earlier success over multiple years generally failed. At two of the three Large Plot locations (Sites B and K), and at all Garden Plot locations (both with and without supplemental irrigation) no emergence of any seeded species was observed, indicating that the EWP direct seeding strategy may be successful in some years but is not reliably reproducible in any given year or place.

At one of the 3 Large Plot sites (Site G) however, excellent response to some treatments was obtained. At this location greater plant density and species diversity were obtained in some treatments than in successfully revegetated areas of the EWP.

Effects of soil disturbance

All plots were initially burned to remove annual vegetation, without disturbing the soil surface. The least intrusive protocol tested was to follow this burning with broadcasting of seed onto the barren soil surface (Fig. 7; Broadcast Seed Mix). Despite concerns that the seed would be removed from the plot by wind, this treatment yielded the highest plant density, and richest species composition (Fig. 7; Panels A-D), of any protocol tested. In February 1996, *E. fasciculatum* (California buckwheat) exceeded 6000 plants ha^{-1} on this plot, approximately 6 cm tall, though later the density decreased substantially (Fig. 7C) with below average rainfall (Fig. 2). Establishment of the annual species Tumble mustard (*Sisymbrium altissimum*) and highly invasive Russian thistle was observed to be less severe in this treatment than in either the seeded or unseeded treatment incorporating ripping and furrowing, demonstrating the preference of these invasive annual species for disturbed soil surfaces.

A greater level of soil disturbance than by broadcasting seed was caused by rangeland drilling the seed mix following removal by burning of the annual vegetation. This protocol resulted in lower densities of *E. fasciculatum*, *A. polycarpa*, and *C. nauseosus*, but higher densities of *A. canescens* than in the broadcast treatment (Fig. 7). Populations of invasive annuals on this plot were greater than in the broadcast plot, but lower than in either plot that was ripped and furrowed. The success of *A. canescens* in this relatively non-disruptive treatment is noteworthy.

The greatest level of disturbance was imposed on plots receiving the ripping and furrowing treatments followed by seeding, similar to that imposed in the EWP protocol. Although a few seeded shrubs became established in this highly disturbed soil, species diversity and plant density remained low (Fig. 7), and high densities of invasive annuals were observed. The least successful treatment, as expected, was the ripped and furrowed plot to which no seed was applied. Virtually no shrubs became established and invasion by tumble mustard, Russian thistle, and grasses, primarily *Bromus rubens* (red brome), *B. tectorum* L. (cheatgrass) and *Schismus* spp., resulted in a dense population of annual species.

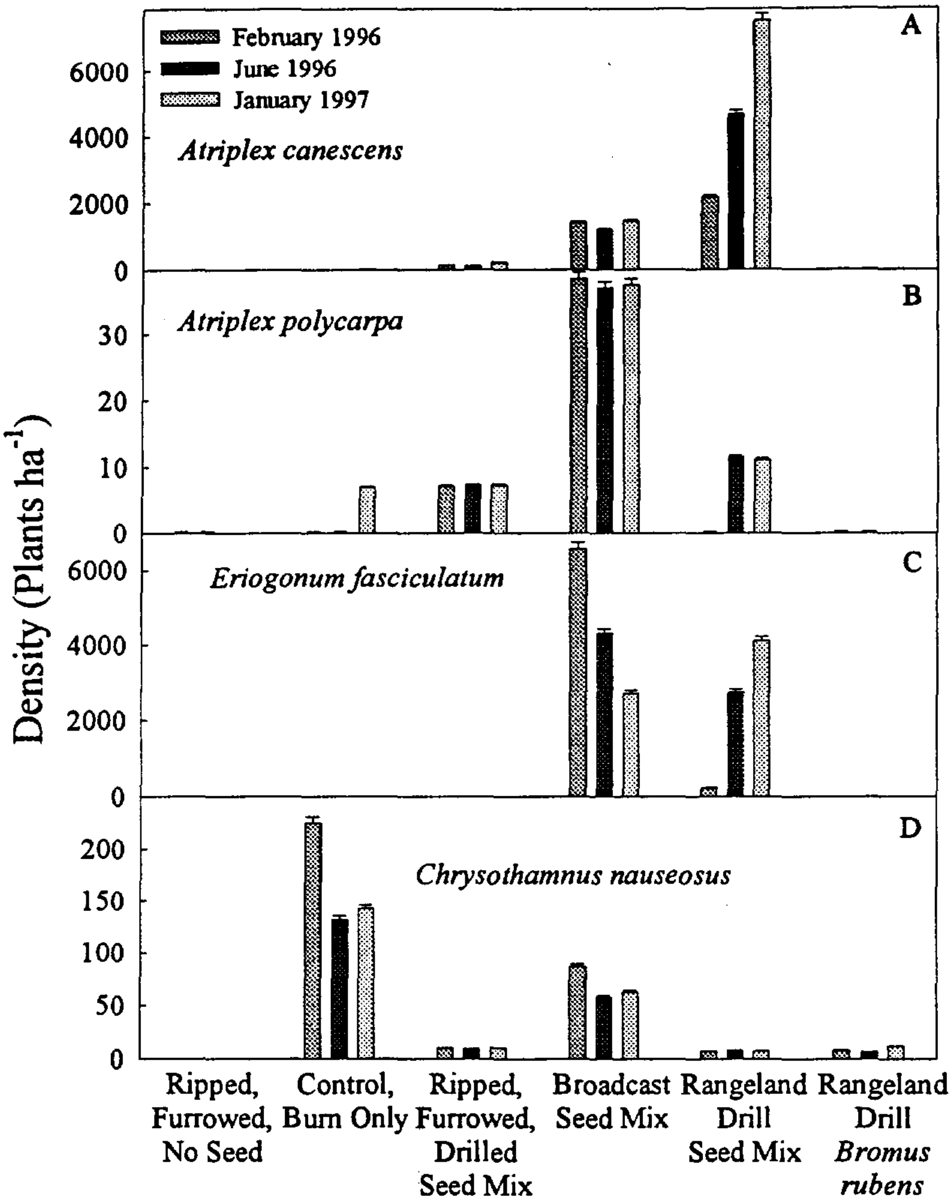

Figure 7. Plant density of individual seeded perennial species (A-D) at Site G resulting from the six contrasting fugitive dust stabilization protocols, on three sample dates. (Bars not visible are near zero).

Rangeland drilling the seed mix in intersecting strips resulted in areas with no seed, and areas with one-fold and two-fold the normal seeding rate, with corresponding resultant plant densities. Areas receiving no seed (and no disturbance; Fig. 8A) had high populations of annual grasses, but the normally invasive Russian thistle and Tumble mustard were less frequent here than on the plots subject to soil disturbance by tillage. In areas receiving the EWP seeding rate (Fig. 8B) excellent establishment of *A. canescens* was obtained, along with moderate establishment of the other shrubs, with only moderate invasion by annual seedlings. Areas receiving the two-fold rate (Fig. 8C) attained seeded shrub densities (primarily *A. canescens*) that were very high, along with nearly complete suppression of annual species. While all four shrub species utilized in the seed mix except *C. nauseosus* performed well when either broadcast or applied with a rangeland drill, performance of all was degraded by the ripping and furrowing of the EWP protocol.

Rabbitbrush

The early seral species *Chrysothamnus nauseosus* is an aggressive colonizer in the western Mojave Desert (Kay 1979), establishing well on barren land, but resisting establishment on disturbed surfaces. Removal of competition from annual or other shrub species by natural or prescribed burning (Grantz et al., 1996) enhances establishment (Fig. 8A).

The most successful establishment of this shrub at Site G occurred on the control plot and in the non-seeded areas of the plot with intersecting strips, areas from which annual vegetation was removed by burning, but to which no seed of rabbitbrush nor of other shrubs was applied (Fig. 7). The natural establishment of this species in these areas was attributed to seed that was blown in from an adjacent undisturbed area with a natural rabbitbrush density of 3083 ± 79 plants ha^{-1}. The serotinous character of this shrub, with mature seed being released over a prolonged period, contrasts with the pulse of seed release characteristic of a direct seeding protocol.

The plot that was burned and broadcast seeded with rabbitbrush and other perennial species developed substantial, but lower, rabbitbrush density (Fig. 7D) than the unseeded areas. These rabbitbrush plants that became established may have derived from the natural seed bank or from the sown seed. In contrast, rabbitbrush establishment on plots where the soil surface was disturbed by ripping and furrowing, or with the rangeland drill, was considerably less successful (Fig. 7D), even though they were also downwind of the natural seed source.

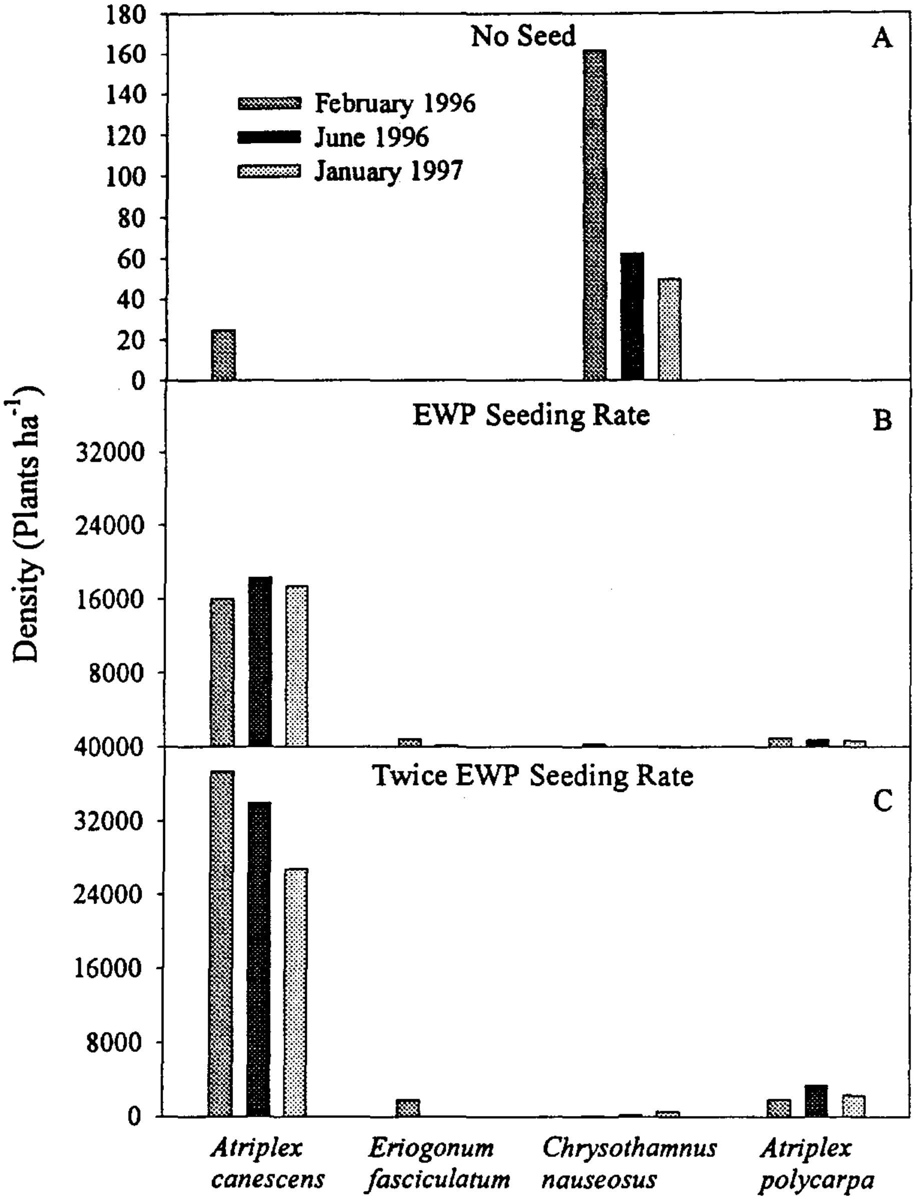

Figure 8. Effect of seeding rate (A-C) on plant density of the four individual seeded perennial species at Site G. The plot was burned and received no seed (A) except in strips which received the EWP seeding rate (B) or twice this rate (C) where perpendicular seeded strips intersected. (Bars not visible are near zero).

In the plot that received three parallel strips of EWP protocol, separated by 50 m of burned but otherwise undisturbed surface, rabbitbrush density between the strips increased exponentially with decreasing distance from the native seed source (Fig. 9). In contrast, no rabbitbrush plants were observed in any of the furrowed and seeded strips between these areas, even closest to the upwind seed source. Similarly, transects evaluated over three years in the ripped and furrowed EWP area did not encounter a single individual of *C. nauseosus*, though the species is ubiquitous in surrounding areas. During revegetation along the Los Angeles aqueduct (Kay, 1979; Kay; 1988) rabbitbrush established naturally along adjacent roadways but not in treated areas where the soil had been ripped. Rabbitbrush establishment adjacent to roadways is still observed throughout the Antelope Valley, restricted to the areas along the road cuts and on abandoned farmland that has been undisturbed for several years.

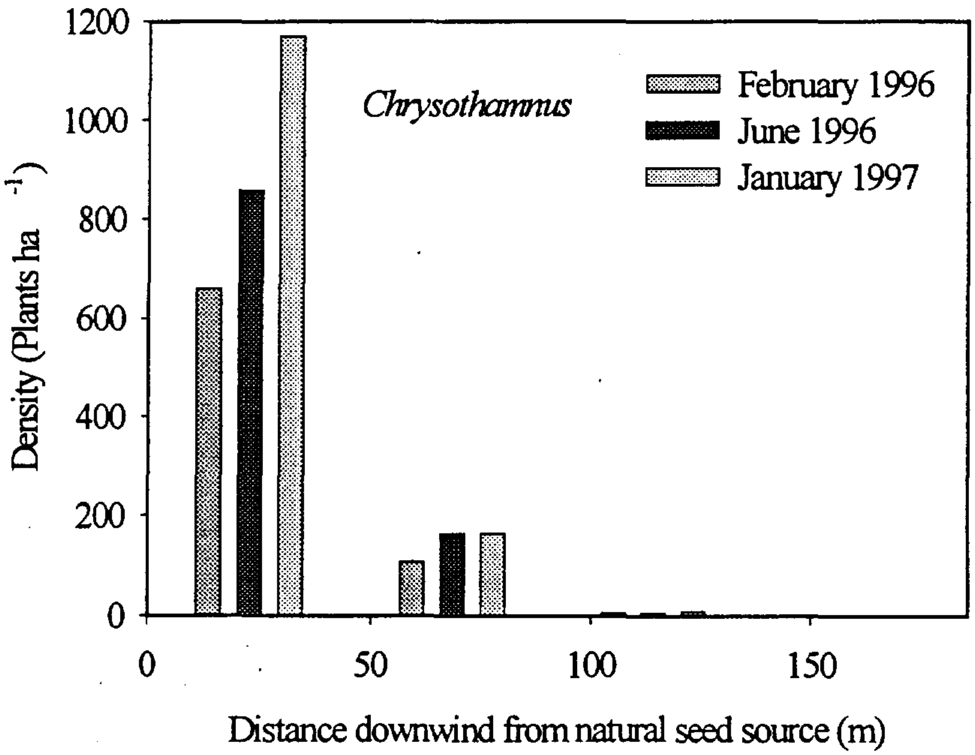

Figure 9. Plant density of *Chrysothamnus nauseosus* at Site G in the burned but unseeded areas between three parallel strips receiving the EWP protocol, as a function of distance from a natural upwind seed source. (Bars not visible are near zero).

For several reasons, rabbitbrush should not be included in seed mixes for these areas. Under controlled nursery conditions, repeated seedings of this species demonstrated the difficulty of attaining reliable germination (L. Lippett, personal communication). In addition the copious pappus of the mature seed makes it difficult to handle in seeding equipment, especially in mixtures with small dense seed such as that of *A. polycarpa*. In any case, barren areas proximal to native rabbitbrush stands may require no intervention, except removal of competing annual vegetation by burning to foster abundant establishment by rabbitbrush. The wide distribution of rabbitbrush across the Antelope Valley suggests that this technique may be widely applicable. In areas without a nearby seed source, repeated broadcasting of locally gathered seed may offer the greatest probability of establishment. Surface tillage should be avoided.

Control of fugitive dust by the EWP

Stable areas of undisturbed desert scrub vegetation are not sources of fugitive dust unless the vegetation is disturbed or removed. Reestablishment of this vegetation following disturbance leads to restabilization of the soil surface and reliable suppression of fugitive dust emissions. In the first months after implementation of the EWP protocol in early 1992, vegetation remained low-statured and shrub seedlings were not uniformly distributed over the EWP area. Rapid germination of the seeded barley occurred in many areas, followed by some germination of California poppies. While sparse vegetation may extract considerable momentum from the wind (Wolfe and Nickling, 1993), thereby reducing wind erosion, the almost complete suppression of dust emissions during this period (Table 7) is attributed principally to tillage across the wind, before significant shrub establishment.

The ripping component of the EWP protocol brought non-erodable soil aggregates to the surface, thereby increasing surface roughness and providing wind-sheltered areas in which moving particles were trapped (Bilbo and Fryrear, 1995). Furrowing the soil provided an additional level of surface roughness, with the furrow bottoms acting as a catchment for saltating and creeping particles derived from the furrow tops. These physical alterations immediately presented a more complex, rougher surface, with more large aggregates in exposed positions, and more abundant sheltered positions, thus requiring higher sheer forces to initiate particle movement (Farber et al., 1996). Tillage is a traditional and highly effective protocol for short term stabilization of disturbed areas subject to emissions of fugitive dust. It does, however, disturb the surface and may inhibit longer term stabilization by revegetation.

Table 7. Mass of fugitive dust collected at 1.0 m height downwind of the Emergency Watershed Protection Site over several years, and percent control relative to the mass collected at 1.0 m downwind of barren areas. Collection periods shown are those with wind gusts above 15 m s-1.

				Dust Collected (g)		
Collection Period Year (DOY)	Mean Wind Velocity ($m\ s^{-1}$)	Maximum Wind Gust ($m\ s^{-1}$)	Sampler Height (m)	Control	EWP	Percent Control at EWP
1992 (105 - 112)	4.0	20.5	1.0	75.1[1]	0.38	99.5%
1994 (136-155)	4.2	19.7	1.0	0.05[2]	0.003	94.1%
1995 (155-162)	4.15	19.6	1.0	0.54[2]	0.01	82.0%
1996 (97-104)	5.23	24.4	1.0	0.81[2]	0.026	96.8%

[1]1992 control was a naturally occurring barren area upwind of the EWP site.

[2]1994-1996 control was a plot at Site K kept barren by removing annual vegetation as necessary by burning or light disking.

During 1994-1996 several factors (Grantz et al., 1996) combined to result in low levels of fugitive dust emissions from the EWP area (Table 7). Establishment and growth of seeded perennial species became widespread, though spatially variable, throughout the EWP area, during a period of above average rains following EWP installation (Fig. 2). Prolific growth of native and exotic winter annuals was also stimulated so that even in areas of poor shrub establishment, and in areas outside the EWP treatment area, adequate ground cover was achieved. Also during this period, episodes of high wind were infrequent.

During the few high wind events during this period the protocol imposed at the EWP Site provided adequate surface stabilization to control fugitive dust emissions by over 80% (Table 7).

During periods of lower wind speed (not shown) smaller dust samples were more variable but suggested similar levels of control.

Transplants

Rainfall was below normal in 1995-96 (19% of the 20 year average; Grantz et al., 1998b), and in 1996-97, (34% of the 20-year average by late April) (Fig. 10A). The drought conditions over these two years exerted a substantial impact on the outcome of these experiments.

Experiment I.—Large plot evaluation of P. glandulosa

Although hot dry conditions prevailed during and following transplanting of the *P. glandulosa* plants at Site K, greater than 85% survival was obtained during the first two months. Although rainfall is unlikely during the warm season (May through September, Fig. 10B), seedlings were transplanted, with supplemental water, at this time to foster some root proliferation before the onset of cold weather and winter dormancy. By March, after five additional irrigations and at the beginning of the dry season, survival had decreased to less than 80%, a decline which continued through the summer of 1996. By early January of 1997 survival had fallen to near 40% (Fig. 11A).

A contingency analysis of the survival data from four evaluation dates (Fig. 11A) indicated a significant effect of planting method on survival (χ^2 = 43.5, 68.7, 136.3, 129.8 for successive dates, all $p < 0.005$). In January 1997 62% of plants in narrow deep holes with plastic cone protection survived, compared with only 10% in broad holes with wire cages (Fig. 11A). Significant differences were also observed in plant vigor between these treatments within each date (Fig. 11B,C). Plants protected with plastic cones exhibited significantly greater vigor than those with wire cages (Fig. 11B; average vigor 1.28 vs. 0.60 in January 1997). We speculate that the plastic cones increased the relative humidity, decreased incident solar radiation and leaf temperature, and decreased wind velocity, relative to plants in the more open wire cages. These beneficial changes in plant microenvironment were apparent to the eye and hand, but were not explicitly measured. In January 1997 plants in augered holes were significantly more vigorous than those in holes dug with a pickaxe (Fig. 11C; 1.58 vs 0.47, $P < 0.001$). This may reflect

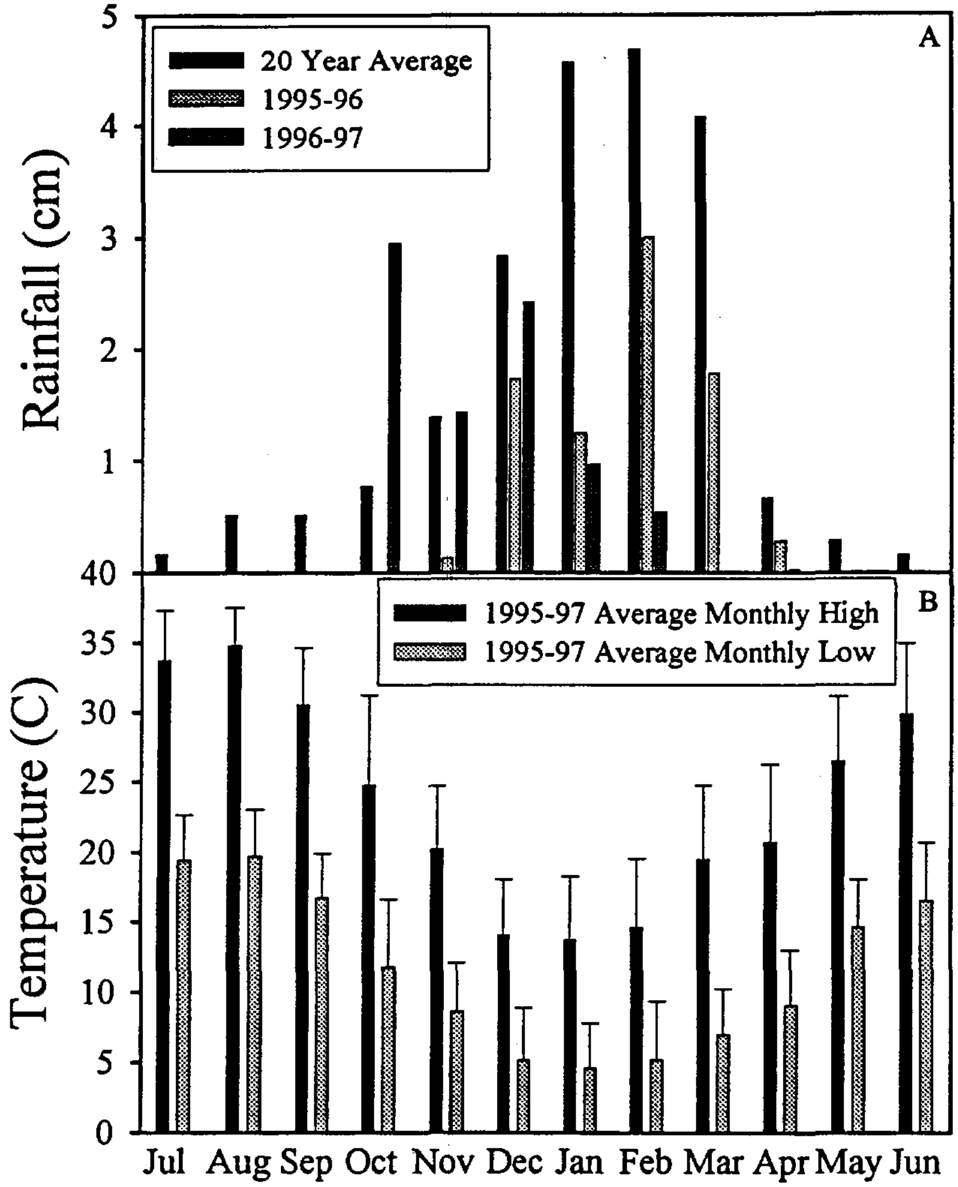

Figure 10. Twenty-year average rainfall as measured at the Fox Field National Weather Service Station at Fox Field, Antelope Valley, and for the two years of transplant evaluations as measured by an on-site meteorological station (Panel A), and average monthly high and low temperatures from the same on-site station (Panel B). Error bars represent one standard deviation.

concentration of water in the narrow augered hole and minimal disturbance of the root systems during planting, compared to the large hand dug holes. The combination of augered holes with plastic cones yielded significantly more vigorous plants on every evaluation date than any of the other three treatment combinations, and this protocol is to be recommended for transplanting native shrubs in this arid environment.

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

Herbivory protection was removed from all plants in October 1996 when many individuals had emerged from their shelters. Above average rainfall initiated establishment of annual species such as filaree (*Erodium cicutarium* (L.) L'Hér) that could provide alternative forage for herbivores. Nonetheless, new leaves and shoots of *P. glandulosa* were intensely grazed by indigenous herbivores with a subsequent decline in vigor in January 1997 (Fig. 11).

Experiment II.—Test of species x site

The site main effect was significant for all species (Fig. 12), while the protection main effect was significant for *A. polycarpa,* attributed to the significant simple effect of cones observed at Site C100N (Fig. 12B). The site x protection interaction was significant for *P. glandulosa*, attributed to the significant simple effect of the cones at Site B (Fig. 12C). *A. canescens* was very successful in these tests, performing well at 4 of the 6 sites (Fig. 12A). *A. polycarpa,* although naturally occurring throughout the western Mojave, survived at only one site. *I. arborea* survived at only two sites. At sites B and K this species was eliminated within 48 hours of transplanting by grasshoppers (order Orthoptera, family Acrididae). At Sites B120W and C100S, though grasshopper herbivory was not a factor, all individuals of this species died from desiccation. *P. glandulosa* performed poorly at all sites.

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

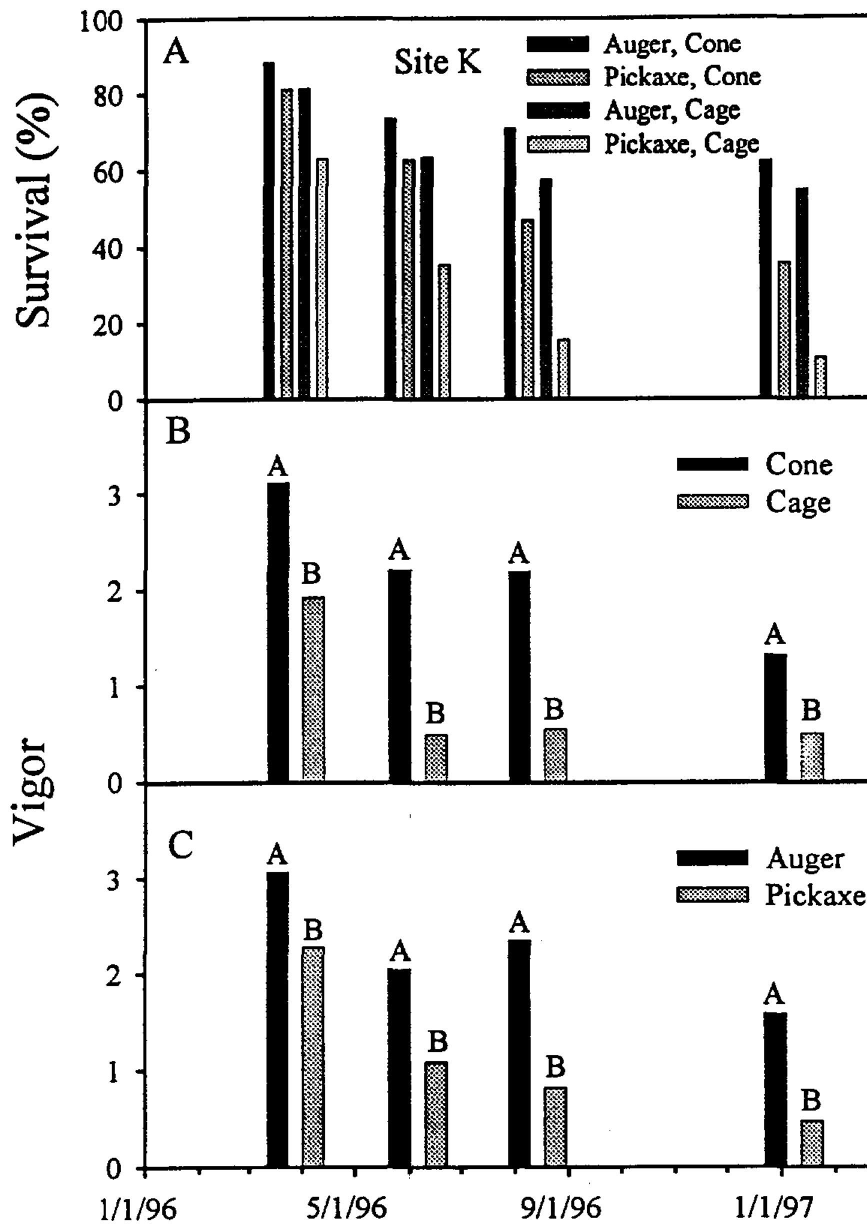

Figure 11. Time course of survival (A) and vigor of *Prosopis* plants with differing types of herbivory protection (B) and planting hole excavation methods (C) at Site K in the western Mojave Desert. Means associated with different letters within evaluation dates are different at p = 0.05.

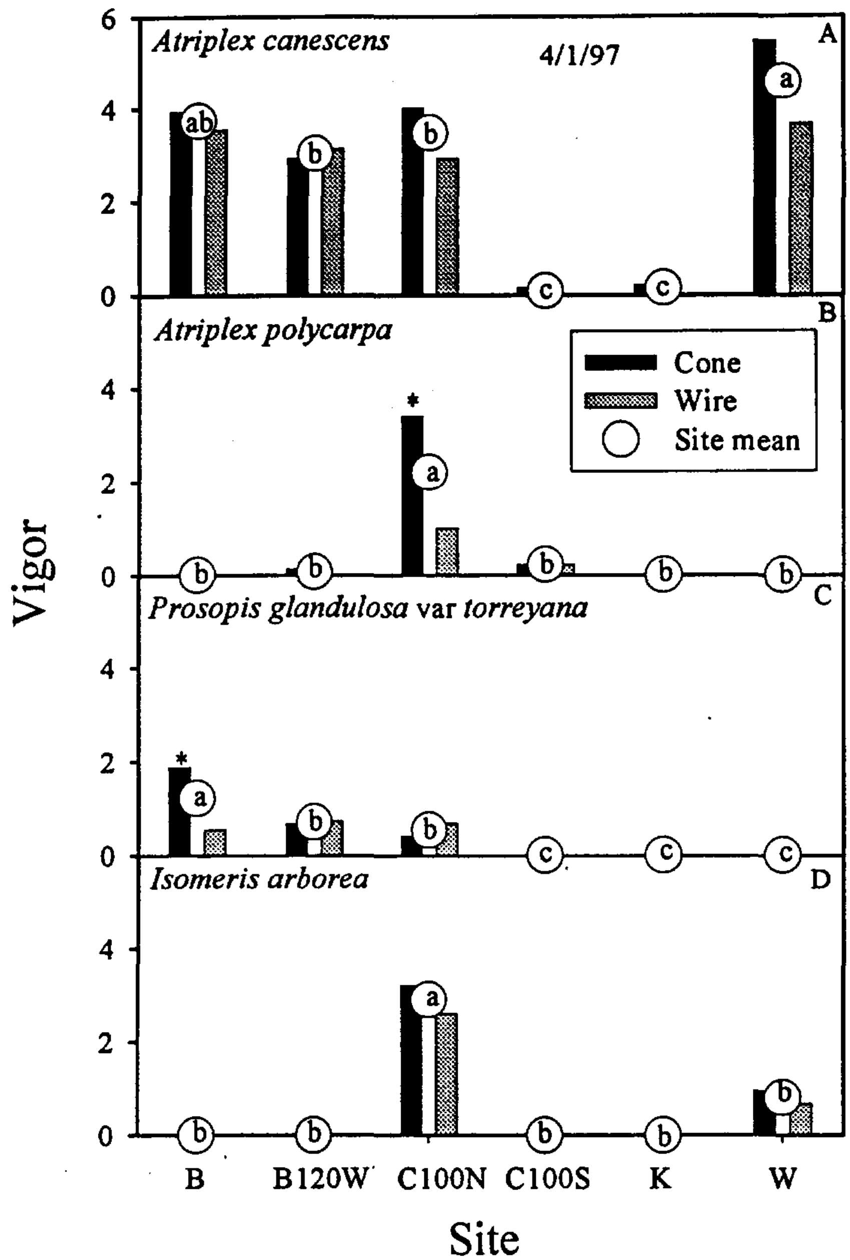

Figure 12. Mean vigor of individual shrub species treated with plastic cones or wire cages for herbivory protection (bars) and species site means (circles) on the April 1997 evaluation date. Site means associated with different letters are different at p = 0.05. Herbivory protection means within species and sites identified with asterisks are different at p = 0.05.

The negligible difference in vigor that was observed between plants grown under plastic cones or wire cages in April 1997 (Fig. 12) contrasts with the greater vigor of plants in cones that existed at all sites except W on previous evaluation dates, when the devices were still in place (Fig. 13 A, B, C). A factorial analysis of these data (Fig. 13) revealed large and highly significant ($p < 0.001$) date, site, and protection main effects, as well as highly significant interactions. Average plant vigor decreased from 3.8 to 1.6 between April (Fig. 13A) and August (Fig. 13C) of 1996, followed by a further decrease to 0.86 in January of 1997 (Fig. 13D) following removal of the protective devices in October 1996. Increased herbivory following removal of both forms of herbivory protection in October 1996 resulted in greater grazing on the succulent cone-protected plants, and therefore fewer significant differences between the methods observed in January 1997 (Fig. 13D).

The six sites represented a range of soil types (Table 4) and land use history. Sites B120 W and C100S had land use histories similar to Site K, with alfalfa in rotation with small grains and sugar beets (J. Santos, personal comm.). Site B was used for strip cropping of dryland barley between 1948 and 1989 (B. Barnes, personal comm.). Soil amendments, other than grain stubble, were not added at this site. Site C100N had not been subjected to agriculture in recent decades as mature saltbush scrub existed here prior to a natural wildfire in the winter of 1995-96. The significant site differences in plant vigor (Fig. 12) are attributed largely to edaphic factors associated with disturbance arising from contrasting agriculture practices over the last several decades. The proximity of the sites suggests similar aerial environmental conditions.

The contrast in plant survival and vigor between sites C100N and C100S (Figs. 12, 13) is notable since these two sites are adjacent, separated only by a narrow roadway that divides fields with different apparent use histories. These two sites were chosen to explore the visible contrast in revegetation success following the earlier direct seeding efforts in 1992 (Grantz et al., 1998a). Site C100N had not been disturbed for decades and was covered with mature saltbush scrub. It was contiguous with an area in which all previously seeded species established well.

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

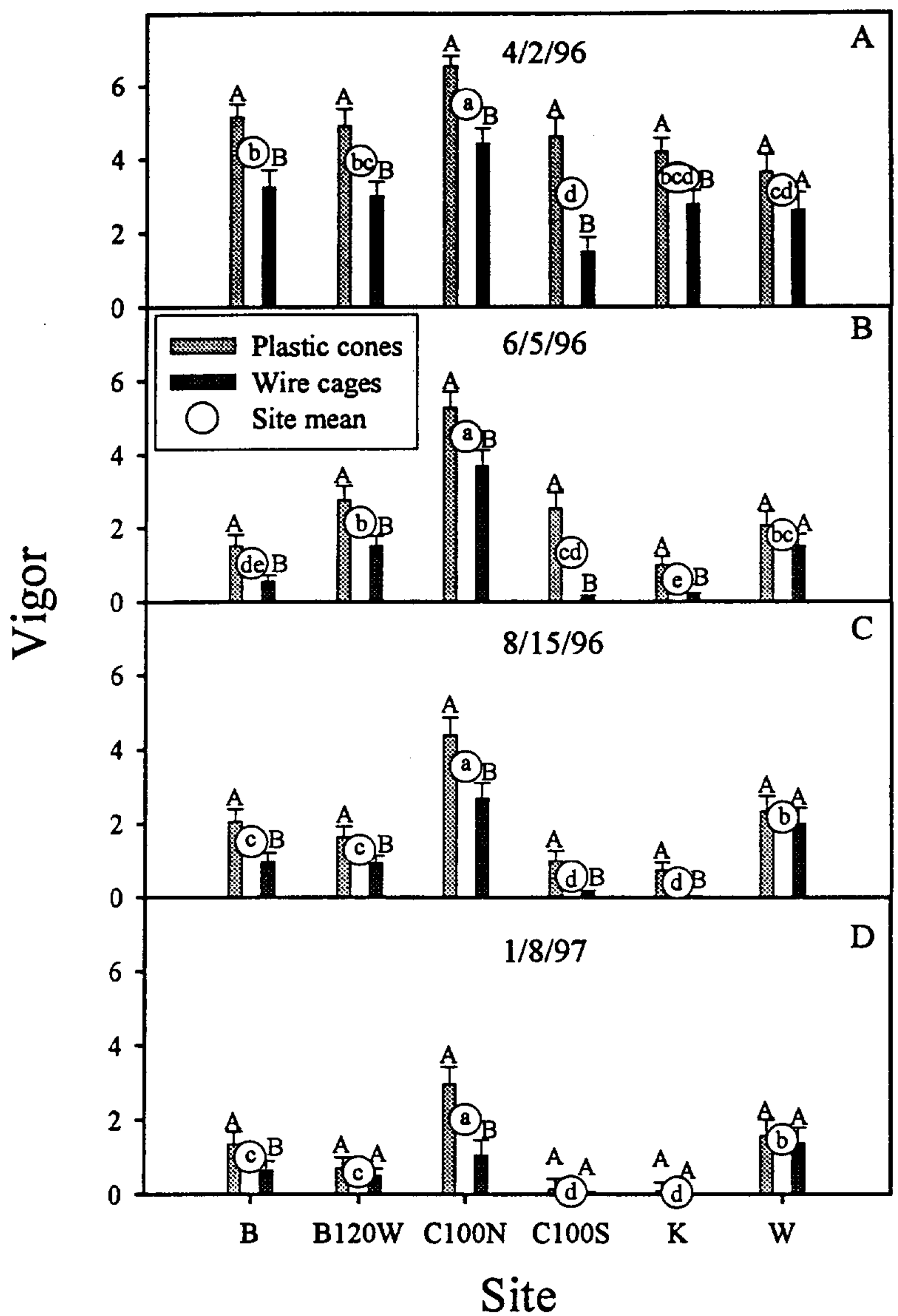

Figure 13. Mean vigor of the four shrub species in Figure 3, treated with plastic cones or wire cages for herbivory protection (bars) and site means (circles) on four dates at six sites in the Antelope Valley. Means associated with different letters within a site and date are different at p = 0.05.

1995 prior to transplanting, and exhibited the highest concentration of ammonium N, with low nitrate N (Table 8) in the upper soil profile. This site also exhibited the most abundant fungal hyphae and bacterial populations of the six locations (Table 8). These soil samples were taken from areas between the plants where no mulch was applied. Plant vigor was not affected by mulch treatment at this site on any evaluation date.

Table 8. Mean NH_4 and NO_3, bacterial counts, and hyphae fungal lengths (g $soil^{-1}$) for the soil surface layer (0-10 cm) on 4/19/96 (Transplant Experiment II). Means with the same letter are not significantly different at p = 0.05.

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

Site C100S was imbedded in an area which had undergone decades of agriculture (flood irrigated alfalfa/small grain). No seeded shrubs had become established in the earlier experiments, and the area had subsequently become covered with the invasive annual species, tumble mustard (*Sisymbrium altissimum* L.). This site exhibited the highest NO_3 N concentrations and the lowest bacterial populations, with few fungal hyphae present (Table 8). Survival and vigor of all transplanted species at this site declined steadily. By April 1997 evaluation, there were only two surviving individuals (of the 30 initial) of *A. polycarpa* and one of *A. canescens*.

Plant survival and vigor at Site K (small plot) was as poor as at Site C100S (Fig. 12). This site, adjacent to site K (Experiment I), had been cropped to alfalfa and in 1994 volunteer alfalfa plants emerged. The higher ammonium concentration observed at this site (Table 8) may reflect remnant root biomass, though as at Site C100S, the soil had relatively high concentrations of NO_3 N and little fungal hyphae. The average NO_3 concentration at these two sites was 5.96 $\mu g\ g^{-1}$, compared with an average of 0.73 $\mu g\ g^{-1}$ over the other four sites. High N availability is often conducive to establishment of invasive, fast growing, nitrophilic species (West, 1991) such as *S. altissimum*, a vigorous competitor that does not form mycorrhizal associations (E. B. Allen, personal comm.).

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

Artificial wind barriers

Dispersed barriers

The mass of airborne particles at each collection height was significantly reduced by the dispersed barriers compared with the barren control plot at Site K, especially close to the soil surface (0.2 m; Fig. 14). During the particularly high wind collection period ending on Day of Year (DOY) 147 (1996), the differences between the treated and control plots were substantial. The suspended particle mass described highly significant negative exponential profiles over both plots ($r^2 = 0.96$ for the barren plot, and 0.99 for the barriers plot). While these profiles extended to the top of the sampling array over the control plot, there was little height dependence of mass above 1 m for the barriers plot (Fig. 14 inset). The reduced fetch between the barriers decreased the mass of particles in saltation near the soil surface (0.2 m; Fig. 14), and minimized entrainment into the bulk airstream.

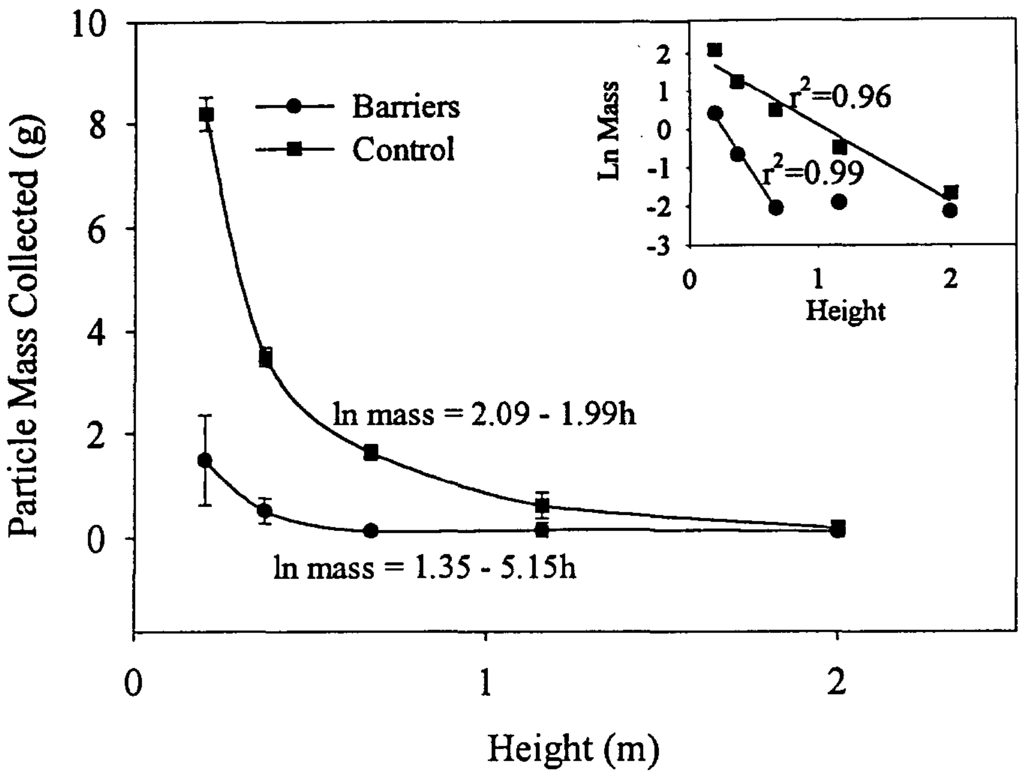

Figure 14. Vertical profiles of particulate mass collected at a loamy soil site in mid-Antelope Valley (Site K) on barrier and control plots for the sample period ending DOY 147, 1996.

The use of the piezo-electric impact sensor on one plot at Site K in 1996 allowed a direct determination of soil erosion wind velocity thresholds at the plot on which the discrete barriers were placed on a grid. The results from this sensor revealed a 20 minute average wind speed threshold at Site K of between 4 and 5 m s^{-1} (Fig. 15A).

An indirect method of determining threshold wind velocity based on regression of mass of dust on the summation of wind speeds above candidate thresholds was used to compare with the results from the impact sensor. No definite thresholds could be identified at Sites K and F due to small mass collections and the absence of high wind velocities to empower the regression technique. Wind velocities at Site A were typically higher than at the other sites and no barriers to wind flow were installed. The indirect method at this Site revealed a soil erosion threshold of about 5 m s^{-1}, close to that observed with the piezo-electric quartz sensor at Site K (Fig. 15B).

For comparison with previous estimates of threshold wind conditions yielding particulate emissions, our threshold wind velocity was converted to threshold friction velocity utilizing an approximate roughness length of z_0 = 1.0 cm (Grantz et al., 1995) and the consensus wind velocity threshold of 5.0 m s^{-1}, determined from the impact sensor data and the regression technique (Fig. 15). The calculated threshold friction velocity of 0.44 m s^{-1} compares well with reported threshold friction velocities of 0.45 m s^{-1} for overgrazed rangelands (Gillette and Passi, 1988), 0.45 m s^{-1} for the barren experimental plots at Site K in 1994 (Farber et al., 1996), and of 0.65 m s^{-1} for furrowed land at Site K in 1994 (Farber et al., 1996). During the windy season these values of threshold wind and friction velocities are likely to be exceeded in this location. The dispersed barriers would suppress saltation and reduce fugitive particulate emissions under these conditions.

Wind fences

Over the course of the sampling periods at Site F in 1992, there were no major sustained wind events, but there were two sampling periods in early April in which wind gusts exceeded 15 m s^{-1} and one period in which gusts approached 14 m s^{-1} resulting in significant soil movement (Table 9). The wind fences significantly decreased blowing sand under these high wind conditions, averaging 71%, 67%, and 54% control of particle collections at 0.2, 1.0, and 2.0 m above the ground, respectively (positions B vs. E in Figs. 1A and 16A; Table 9).

Averaged collections at all three heights over all sampling periods (Fig. 16A) indicates that much of the wind energy initiating saltation (0.2 m height) and maintaining suspension of particles (1.0 and 2.0 m height) was absorbed by the first fence. The reduction in wind velocity and carrying capacity caused deposition of the particles in the vicinity of this barrier. The longitudinal pattern of particle collection was similar at all three heights, though the mass at 0.2 m was nearly an order of magnitude greater than at 1.0 m, which was almost as much greater than at 2.0 m. This suggested a negative exponential vertical mass profile similar to that observed at Site K (Fig. 14). The log-linear relationships with sampling height were highly significant, (r^2=0.84, 0.96, and 0.82, for locations B, C, and D respectively; Fig. 16A). Analysis of the integrated air column burden of airborne particles suggests that the wind fences are effective in controlling wind blown particulate emissions.

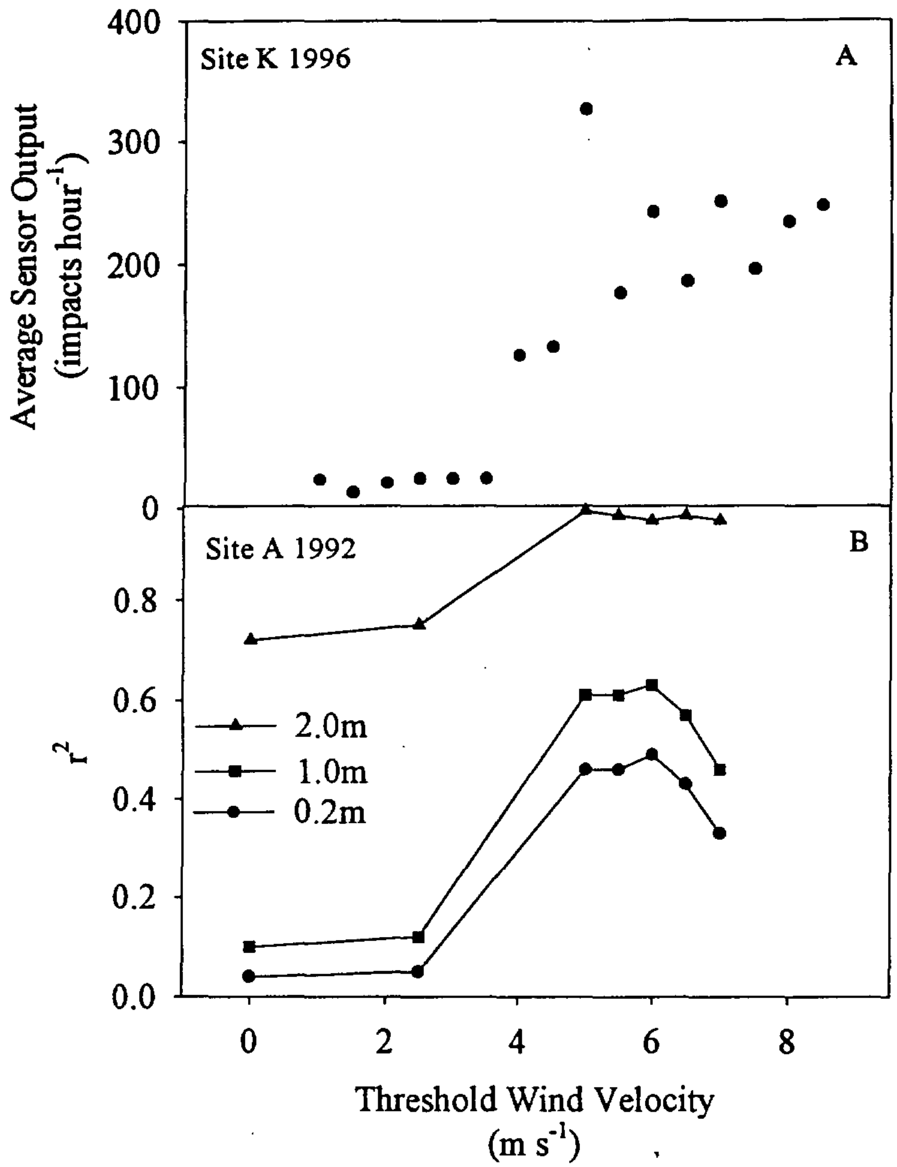

Figure 15. Threshold wind velocity analyses at (A) a loamy site in the mid-Antelope Valley (Site K) using a direct measure of saltation determined with a piezo-electric quartz impact sensor and simultaneous measurements of wind speed, and at (B) a loamy site in the upper Antelope Valley using a regression analysis of mass collected at three heights versus wind run summed above candidate threshold velocities. Regression coefficients were determined at all heights (solid lines) with n = 7.

Table 9. Mean wind speeds, maximum gust, and percent control by wind fences for three sampling periods at Site F in 1992.

Sample Period (Day Of Year) in 1992	Mean Wind Velocity ($m\ s^{-1}$)	Maximum Wind Gust ($m\ s^{-1}$)	Sampler Height (m)	Mass of sediment, Upwind (Position B, Fig. 1A) (g)	Mass of sediment, Downwind (Position E, Fig. 1A) (g)	Percent Control by Wind Fences
105 - 112	4.0	20.5	0.2	340.83	33.85	90.1%
			1.0	28.94	6.15	78.7%
			2.0	16.19	7.23	55.3%
112 - 119	2.7	15.2	0.2	7.61	1.17	84.6%
			1.0	2.02	.75	62.9%
			2.0	1.45	.57	60.7%
134 - 141	3.3	13.7	0.2	.253	.155	38.7%
			1.0	.209	.097	53.6%
			2.0	.183	.100	45.4%
Average			0.2			71.1%
			1.0			67.3%
			2.0			53.8%

The control site (Site A), equally sandy but without installed wind barriers, demonstrated the effectiveness of the wind fences at Site F. An array of BSNE samplers, placed at the same

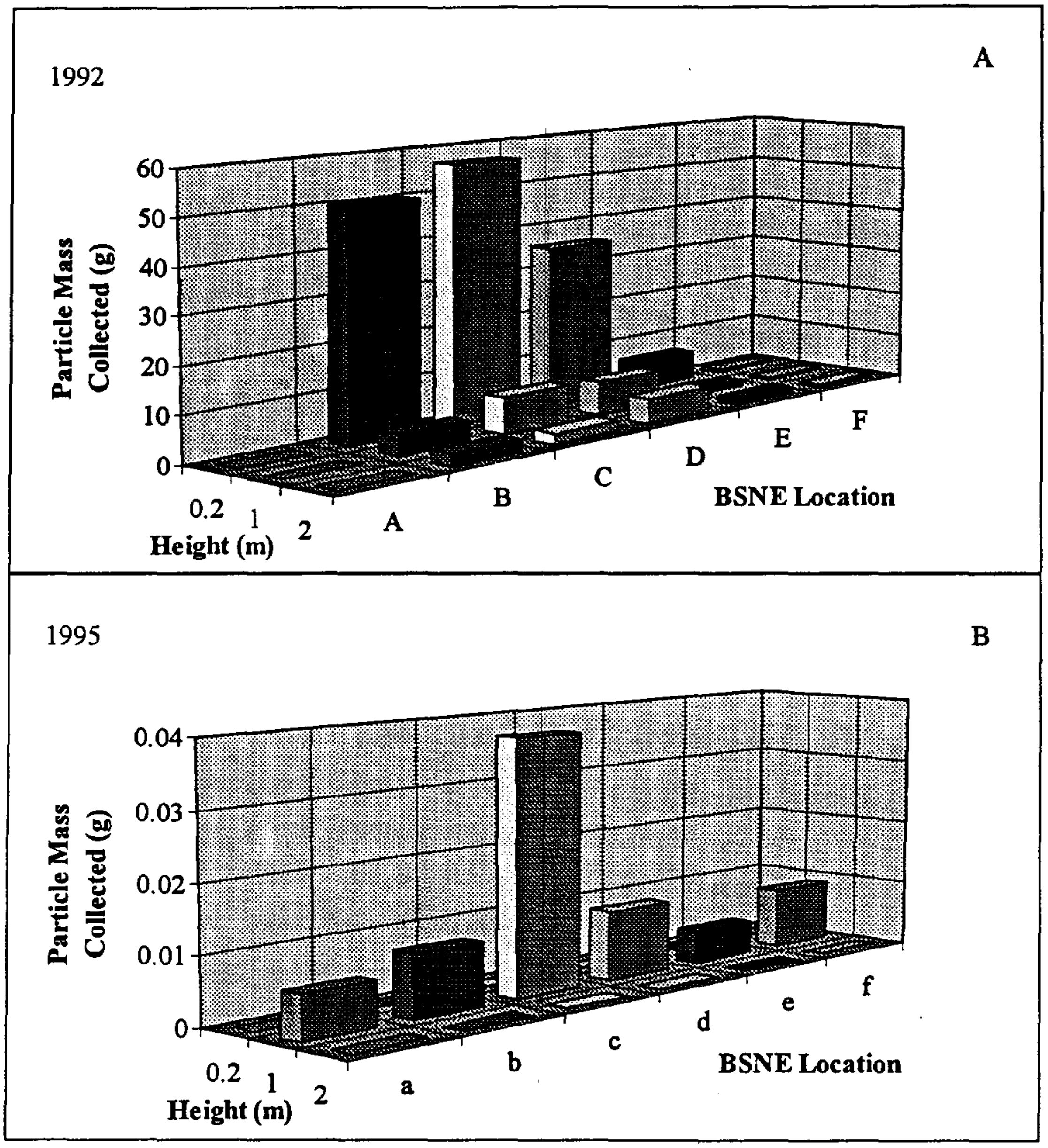

Figure 16. Distribution of particulate mass collected at a sandy site in the mid-Antelope Valley (Site F). (A) Vertical and longitudinal distribution along the transect of wind fences and sampler positions in place in spring 1992 shown in Fig. 1A. (B) Vertical and longitudinal distribution along the array in place in 1995 shown in Fig. 1A.

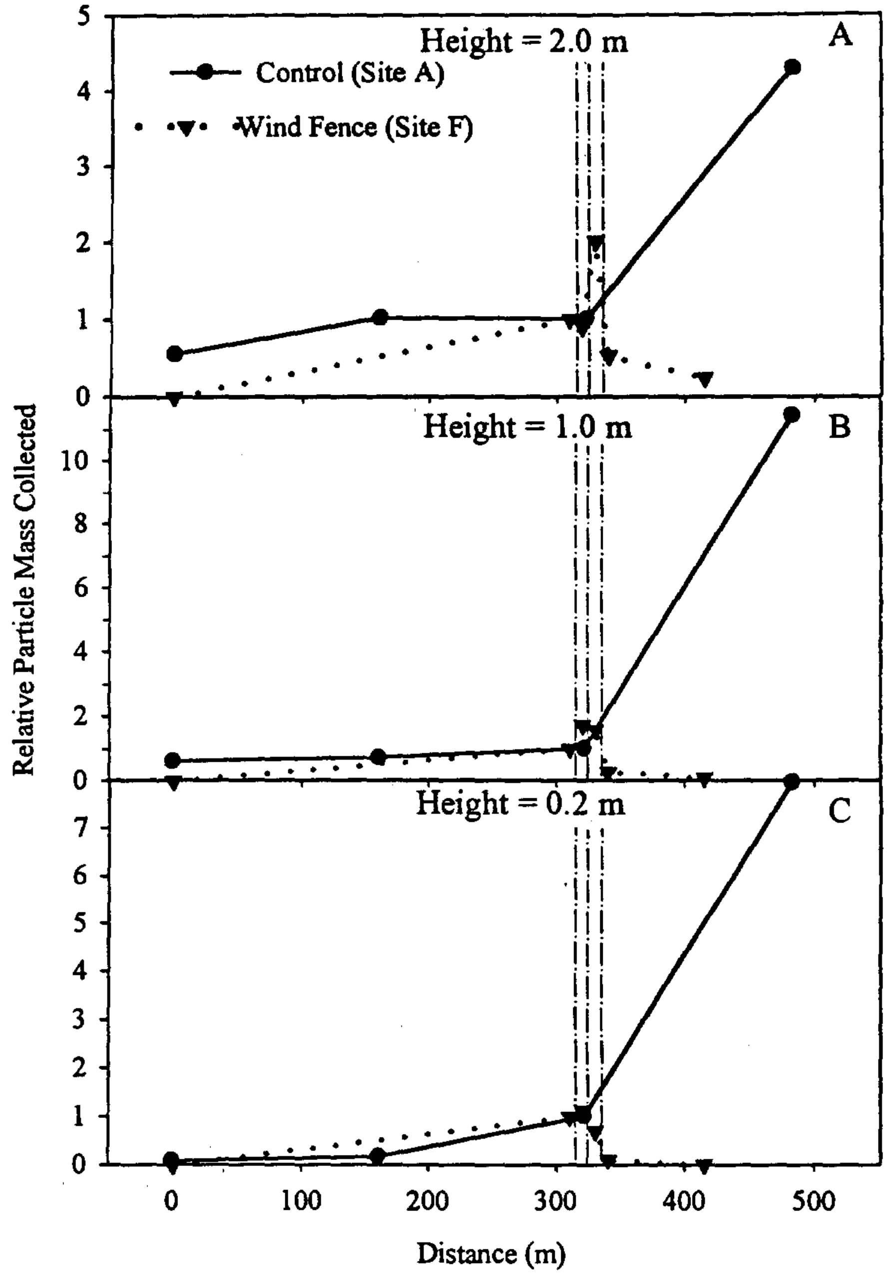

Figure 17. Longitudinal distribution of particulate mass collections at three sampler heights in spring 1992 at sandy sites with a single set of three parallel wind fences (prior to installation of two additional double fences, Fig. 1A; mid-Antelope Valley, Site F) and with no barriers (western Antelope Valley, Site A), demonstrating control of fugitive emissions by the parallel barriers.

heights as those at Site F, was deployed parallel with the prevailing winds along a fetch equivalent to that at Site F. The parallel wind barriers (present only at Site F; Fig. 17) resulted in a substantial decrease in suspended particles downwind of the fences. This was observed at all heights, but was especially pronounced at 0.2 m (Fig. 17C). Saltation was nearly eliminated. At a similar distance downwind from the leading edge of the erodible surface, transport at Site A increased substantially.

Between 1992 and 1995, cyclic establishment and die-back of winter annuals had occurred in all areas of Site F. These were primarily Tumble mustard (*Sisymbrium altissimum* L.) and Russian thistle. At any given time during Spring 1995 there were newly germinated as well as senescent individuals of both species, as well as intermittent occurrences of filaree (*Erodium cicutarium* (L.) L'Hér), cheatgrass (*Bromus tectorum L.*), prickly lettuce (*Lactuca serriola* L.), and red brome (*Bromus rubens* L.). There was never any large mass of particles collected in the follow-up evaluation in 1995, but the wind fences in combination with the scattered ground cover were effective in preventing wind erosion at Site F (Fig. 17B).

Wind fences 50 m apart were evaluated at sites X and W as possible methods for economically controlling very large areas, where dense networks of barriers would be cost-prohibitive. The widely separated wind fences at Sites X and W were established across sandy areas known to have been barren and periodically eroding since at least 1991. Soil types were similar to those that resisted revegetation in other areas of Antelope Valley. BSNE samplers were deployed in an array at 1.0 m height from 13 April to 30 May, 1994. The barriers were effective in reducing airborne particle collections at 1.0 m (Fig. 18). Mass collected upwind of the first fence was not different in the control plot and barrier plot. At each position the mass of particles was significantly greater in the control plot (Fig. 18) despite low masses of collected material at all locations associated with establishment of winter annual plant species.

Furrows

Furrowing is commonly used for controlling wind erosion in arid as well as more mesic environments. The resulting complex and rough soil surface exposes more aggregated particles to the wind and increases the wind speed required to initiate particle movement. Dislodged particles

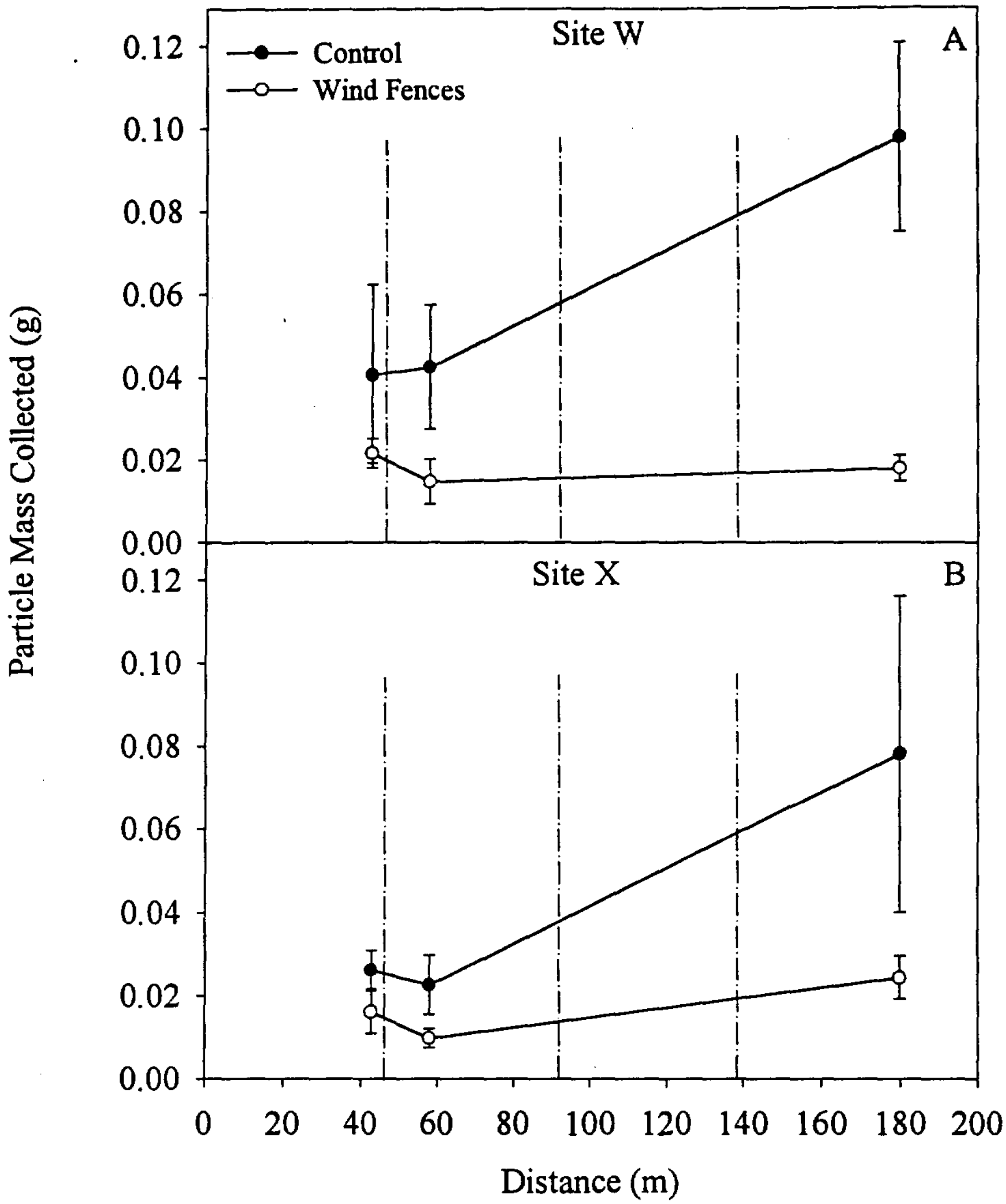

Figure 18. Longitudinal distribution of particulate mass collections sampled at 1.0 m height in adjacent barrier and control plots between 20 April and 8 May 1994, at two sandy locations in the western Antelope Valley. (A) Site W and (B) Site X.

also become trapped in wind-protected locations, suppressing saltation and interrupting the chain reaction that leads to massive dust emissions.

For the weekly sampling periods that resulted in measurable dust collection, the furrows at Site K in 1995 reduced fugitive dust at all heights (Table 10), ranging from a 93% reduction near the soil surface to a 24-33% reduction above 1.0 m. The furrows significantly increased the threshold friction velocity, a measure of wind speed needed for dust emissions, from about 45 to about 65 cm s^{-1}. Heavy soils that readily form aggregates are more likely to respond to a furrowing treatment than sandy soils. In situations of arable soil overburdened with windblown sand furrowing may be ineffective, while deep ripping may be effective in bringing large aggregates to the surface and reducing dust emissions.

Table 10. Control by furrows of fugitive dust at Site K in 1995 for those weeks when measurable fugitive dust was collected by the BSNE samplers.

No. of weekly samples	Mean Wind Speed (m s^{-1})	Max Wind Gust (m s^{-1})	Sampler height (m)	Average Percent Control
3	3.6	19.6	0.20	93%
3	3.6	19.6	0.37	76%
3	3.6	19.6	0.67	66%
6	4.4	25.2	1.0	56%
3	3.6	19.6	1.16	24%
3	3.6	19.6	2.00	33%

The common agronomic practice of furrowing across the wind was successful in rapidly reducing fugitive dust and soil erosion from this fallow field in the Antelope Valley. However, a general disadvantage of such tillage in the Antelope Valley and other arid areas, is that it discourages establishment of desirable native perennial shrubs such as *Atriplex* spp. and rabbitbrush (*Chrysothamnus nauseosus*), and encourages invasion by nitrophilic annuals such as

Russian thistle. Nevertheless, the rapid stabilization of furrowing may promote revegetation of some highly unstable sites since continual surface erosion also inhibits shrub establishment.

Conclusions

Seeding

Rapid initial control of emissions may be achieved by furrowing across the wind and rapid establishment of exotic annual species such as barley. However, the associated soil disturbance fosters invasion by annual species, and prevents natural reestablishment of native rabbitbrush that may occur without intervention in some areas. A protocol of removing competition by annual species through burning, without soil disturbance, may allow natural recolonization from upwind seed stores. Natural reestablishment of native perennial vegetative cover in arid regions will not occur in dry periods when fugitive dust is a problem. It may also be precluded in wet years by abundant rapid growth of annual species which out-compete slowly growing perennials. Thus intervention will often be required. Successful vegetative establishment, even for optimal direct seeding protocols imposed with minimal soil disturbance, remains uncertain in any given year. No protocol was found, even with supplemental irrigation, that guaranteed revegetation success. The vegetative cover achieved in the EWP intervention in a year of high rainfall was comparable to that observed in old field successional areas of Mojave Desert scrub. Both natural and reestablished vegetation was effective in suppressing fugitive dust emissions.

Over all tests in all areas, *A. canescens* was the shrub species most likely to become established by direct seeding. While *A. polycarpa* performed adequately in most soil types, in sandy soils only *A. canescens* became established. In these sandy areas the perennial bunchgrass species, Indian ricegrass, became established. Overall, soil surface texture exerted minimal influence on species survival. Fungal hyphae and bacterial populations were highest in areas of good shrub establishment and lowest in areas dominated by annuals.

Direct seeding remains a high risk, but sometimes unavoidable, technique to stabilize these areas. When reliable, rapid suppression of dust emissions, for nuisance mitigation or air quality standard attainment, is required, direct seeding must be backed up by alternative protocols in arid environments.

Transplanting

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

Artificial barriers

Wind barriers were effective in reducing airborne, soil-derived particles, by suppressing wind erosion and fugitive emissions from a variety of surface conditions in a hard-to-stabilize arid area. Widely spaced discrete barriers (individual, dispersed roughness elements simulating small shrubs) were effective in reducing wind blown soil at heights up to 2.0 m compared to fully barren surfaces. Wind fences installed perpendicular to the prevailing winds were also effective in reducing saltation near the soil surface, and reducing collected airborne particles downwind of the fences by approximately 90%. An indirect, statistically based method of determining erosion wind speed thresholds yielded reasonable values compared to directly measured values, and to micrometeorological determinations of threshold friction velocity at this site. These thresholds are likely to be exceeded in this area. Furrows installed perpendicular to the prevailing winds reduced emissions by greater than 50% at heights up to 1.0 m. Establishment of wind barriers can be expected to result in significant reductions of airborne particulate matter. This may beneficially impact nearby structures subjected to blowing coarse particle sand, as well as regional particulate air quality.

Recommendations

1. The most effective long term surface stabilization in the Antelope Valley, and similar arid regions, is through revegetation with sustainable native shrub vegetation.

- Direct seeding is more cost effective and nearly as reliable as transplantation of nursery grown materials.
- Fourwing saltbush, *Atriplex canescens*, proved to be the most generally adapted plant species tested. Rabbitbrush, *Chrysothamnus nauseosus*, was difficult to propagate and to seed in the field using available seed dispensing devices and should be avoided. Honey mesquite, *Prosopis glandulosa* var *Torreyana*, did not perform well in extensive trials on a heavy soil, nor on lighter soils in less intensive tests, but did respond favorably to abundant irrigation.

2. Revegetation was effective in mitigating fugitive dust when plants became established. However, this was uncertain and failed in most years, and required some time. Thus for emergency or urgent fugitive dust problems a mechanical solution should be applied instead of, or in addition to, revegetation.

- Windfences and furrows erected across the prevailing winds were highly effective in suppressing fugitive dust
- Scattered roughness elements, consisting in our test of plastic cones designed for herbivory protection of transplanted seedlings, proved very effective in reducing emissions of fugitive dust. Other available objects could prove just as effective, including discarded tires, large stones, etc. Unsightly objects could be removed once surface stabilization has led to the onset of shrub establishment.

3. Future research is required to develop new mitigation techniques, to enhance the reliability of current techniques, particularly revegetation, and to evaluate sites for potential emissions of fugitive dust.

- Wind tunnel studies may be useful as a screening technique for determining the conditions under which particular soils may emit fugitive dust, and for assaying the effectiveness of mechanical surface modifications in suppressing emissions. These could then be tried on large scale experimental plots.

- Seedbed ecology. Microenvironmental conditions in the soil surface layers are poorly characterized, but appear to control biological responses such as germination and root growth. Soil physical and chemical characteristics and microbial populations (primarily VAM fungi and bacteria) may be measured and correlated with biological responses, in widescale correlative and focused mechanistic research. Detailed information on seed and seedling responses to the variety of conditions observed in arid regions could aid in development of models predicting desirable plant species and probabilities of successful plant establishment.
- Old field ecology. The timecourses and processes of shrub reestablishment following disturbance are not well characterized. Particularly, invasion of stabilized but barren sites by rabbit brush could be exploited more effectively in mitigation programs. Information on the interaction of Russian thistle (*Salsola pestifer*) and soil microbiota could be of interest to reseeding programs.
- Plant physiology. Differences in water and nutrient acquisition, rates of photosynthetic gas exchange, seasonal carbon allocation to roots, etc. may provide information that is useful in choosing plant materials for specific areas. This information may also enhance revegetation success by suggesting site preparation, seasonal and irrigation requirements.
- Extension and outreach. Further demonstration projects will be required to convince local land owners and managers to adopt recommended treatments.
- Economics. Explicit measures of the cost effectiveness of different techniques should be addressed. Appropriate units could be tons of dust suppressed per dollar of mitigation investment.

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Appendix

Appendix

In conjunction with the research conducted under Contract 94-337, a micrometeorological station was operated at a secure site (118° 35' 15" W, 34° 51' 00" N) from 6 April 1994 through 17 January 1997. Ten 3.5" PC compatible, 1.44 Mb disks have been submitted with the Final Report, and contain the micrometeorological data. The data files are in Excel 7.0 for Microsoft Windows. Sensors were interrogated at 1 Hz, and reported as 20 minute averages.

Table A. Description of micrometeorological variables.

Column	Data Entry	Units
A	Year	
B	Day of Year (DOY)	
C	Hour-minute (HHMM)	
D	Battery Voltage (of datalogger)	Volts
E	Wind Speed (WS) at 2.0 m	$m\ s^{-1}$
F	Wind Direction (WD) at 2.0 m	degrees from true North
G	Wind direction standard deviation (WD St Dev)	degrees
H	Maximum wind speed (Max WS)	$m\ s^{-1}$
I	Time of maximum wind speed	HHMM
J	Wind speed standard deviation (WS St Dev)	$m\ s^{-1}$
K	Rainfall	inches
L	Solar radiation	$W\ m^{-2}$
M	Temperature at 2.0 m	degrees Celsius
N	Relative humidity at 2.0 m	%

Table B. Start and end times for the micrometeorological data files submitted with the final report on ARB Contract 94-337.

File name	Data Year	Start DOY	Start HHMM	End DOY	End HHMM
AV Mmet A.xls	1994	96	1420	262	2220
AV Mmet B.xls	1994	262	2240	365	2340
AV Mmet C.xls	1995	1	0000	119	0040
AV Mmet D.xls	1995	119	0100	230	0020
AV Mmet E.xls	1995	230	0040	342	0300
AV Mmet F.xls	1995-96	342	0320	88	0540
AV Mmet G.xls	1996	88	0600	217	0900
AV Mmet H.xls	1996	217	0920	328	0020
AV Mmet I.xls	1996-97	328	0040	73	1240
AV Mmet J.xls	1997	73	1300	170	1220