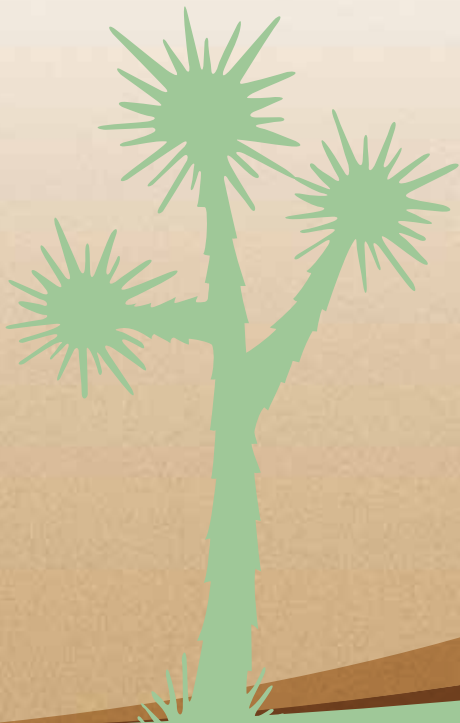


# Agricultural Guide

## to Controlling Windblown Sand and Dust



Information in this Guide applies to high elevation desert regions of Southern California. It is based on approximately 20 years of research conducted by the Dustbusters Research Group in the Antelope Valley of Northern Los Angeles County.



# Table of Contents

Summary . . . . .	3
Overview of the Problem . . . . .	4
History . . . . .	4
Why Dust Blows . . . . .	5
Effective Dust Control Measures . . . . .	6
Cost-Sharing Programs and Conservation Technical Assistance . . . . .	6
Specific Practices . . . . .	8
Cover Crops in Field Cropping Systems . . . . .	8
Stripcropping . . . . .	10
Agronomic Practices for Planting Cover Crops . . . . .	10
Cover Crops in Perennial Tree and Vine Systems . . . . .	11
Long Term Native Plant Cover . . . . .	11
Exposed Desert . . . . .	11
Wind Breaks . . . . .	11
Solid Fences . . . . .	12
Porous Fences . . . . .	12
Straw Bales . . . . .	12
Soil Surface Modification . . . . .	12
Berms . . . . .	13
Large Trees and Shrubs . . . . .	13
Surface Coverings . . . . .	14
Acknowledgments . . . . .	15
Resources Guide . . . . .	16
Appendix: Irrigation Requirements . . . . .	18
Dustbusters Research Group . . . . .	Back Cover

**Front Cover:** Blowing dust in the Antelope Valley has led to reduced visibility and serious traffic accidents. A number of techniques suppress blowing dust, even in very sandy areas.

**Back Cover:** California poppies, which are native vegetation, stabilize the soil.

# Summary

Growers in the high elevation Mojave Desert and other Southwestern U.S. locations encounter extended droughts, high winds, soil erosion, and other circumstances that result in blowing dust. Agricultural soils may be exposed briefly between crops, or as fields are fallowed for 1 to 3 years, grazed by sheep, or taken completely out of production. Any process that reduces vegetation cover also invites dust problems. Wind speeds in this area can exceed 50 mph. When the wind blows, dust from unprotected areas will follow.

Many public and private agencies are available to help growers manage their dust problems. In some cases, financial assistance is available. The techniques in this Guide may serve as a starting point. However, a comprehensive erosion management program may require consultation with experts.

Information in this Guide will assist growers with control of blowing sand and dust. It is based on almost 20 years of research conducted in Antelope Valley by the Dustbusters. It also provides information on cost sharing with federal agencies. Two other Guides have been prepared, one for homeowners and another for large area land managers. *The Homeowners Guide*, *Large Area Land Managers Guide*, and *Agricultural Guide* may be accessed at the Antelope Valley Air Quality Management District (AVAQMD) website at <http://www.avaqmd.ca.gov/>. Then click on “Windblown Dust Guidance”.

Growers in the Antelope Valley can contact one or more of the resources listed in the Resources Guide. Growers in other areas may also benefit from these resources or by contacting similar agencies in their own production areas.



**Figure 1:** The undisturbed desert is stable and is not a source of blowing dust.

# Overview of the Problem

## History

Many growers in the Antelope Valley remember the prolonged drought from 1985 to 1992 and the high winds up to 50 mph that propelled giant dust clouds across the Valley. Poor air quality intensified respiratory health problems, reduced visibility and triggered major highway accidents. Deep deposits of blown sand negatively impacted crop production and property values. (See Figures 2 and 3.)

Desert soils are typically crusted and protected from wind by scattered native vegetation. Soils are also protected by crops. Agricultural production in the Antelope Valley generally consists of rotations among forage crops (alfalfa, grains, hay), onions, carrots, and potatoes. Even areas of loose sand are protected if vegetation coverage is sufficient.

Vehicle traffic, construction activities, and agricultural production can damage or destroy vegetation, disrupt crusts, and lead to wind erosion. In agricultural production systems, some ground remains fallow for more than 1 year to reduce soil-borne pathogens or for economic reasons.



**Figure 2:** Land clearing for agricultural or other purposes can initiate a self-perpetuating cycle of disturbance.

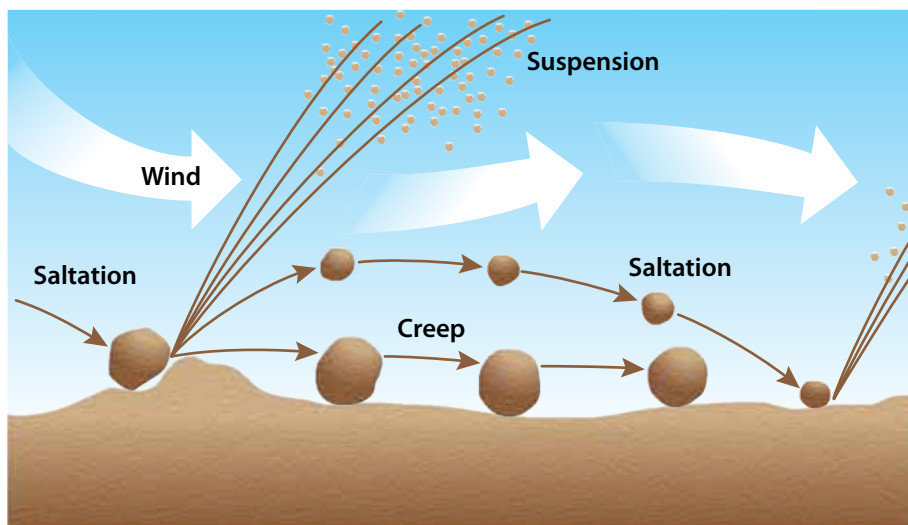


**Figure 3:** Blowing sand can bury crops or sandblast them.



## Why Dust Blows

For growers, blowing dust comes from two sources, land you own or lease and the land upwind of it. Sand blowing from upwind may cause your previously stable ground to begin to erode, as high winds pick up loose sand particles and bounce them along the ground. This saltation of sand and other coarse particles sandblasts the soil surface, eroding the stable crust, dislodging additional particles, and causing further erosion. Saltating particles can kill vegetation, scour stable land, and cause dust to be lofted into the air. (See Figure 4.) Wind rarely lifts sand higher than about 3 feet above ground. However, fine dust rises much higher, which eliminates any practical means of capture.



**Figure 4:** Wind erosion begins with particle creep (rolling) of large particles. Soon, saltation (bouncing) of sand particles begins. These energetic particles erode even stable soil, causing suspension of dust particles into the air.

As a grower, you may choose to implement procedures that control dust, in order to improve visibility, reduce wind erosion and loss of topsoil, minimize damage to roads and structures, and limit health impacts due to poor air quality. Effective dust control methods conserve your topsoil, protect your downwind cropped acreage, and support compliance with air quality regulations. Soils remain viable for production only when soil loss is held below about 5 tons per acre per year. Dust regulations require submittal of a Best Management Practice Plan that includes selection of Practices for Agricultural Operations specifically developed for control of fugitive dust in the Mojave Desert.

# Effective Dust Control Measures

Growers typically encounter dust problems with farmland, farm roads, equipment yards, and deep sand.

A number of dust control measures address these problems and have been evaluated in the Antelope Valley.

## **To establish an effective dust control program, determine:**

- ☼ How long protection needs to last
- ☼ Which crop will follow the protected period
- ☼ How much irrigation water will be available.



**Figure 5:** Irrigation may be the key to establishing vegetation for dust control.

Table 1 on the next page lists these measures and their associated U.S. Department of Agriculture Natural Resources Conservation Service (USDA/NRCS) Conservation Practice Codes.

## **Cost Sharing Programs and Conservation Technical Assistance**

Growers can receive conservation planning and technical assistance from the local NRCS office for dust control and a wide array of natural resource concerns, such as water quality, water conservation and wildlife. You may be able to receive financial assistance as well, through the local NRCS Environmental Quality Incentives Program (EQIP), which provides cost share funds to implement the Conservation Practices listed in Table 1. For Practice requirements, job sheets, and other information, contact the Lancaster Service Center of USDA/NRCS office at 661-945-2604.

The Conservation Reserve Program (CRP) is another cost share program. It encourages growers to voluntarily plant permanent areas of grass and trees on land that needs protection from erosion. This vegetative cover also serves as a windbreak. Additional information is available from the local USDA Farm Service Agency at 661-942-9549.

**Table 1: Dust control practices to consider in the Antelope Valley and their associated USDA/NRCS Conservation Practice and Reference Code**

Situation	Suggested Practices	Conservation Practice	USDA/NRCS Reference Code*
Farmland – high or low elevation	Cover crops – high or low value	Cover Crop	340
	Strip crops	Strip Cropping - Contact your local NRCS for guidance	585
		Cross Wind Trap Strips	489C
		Residue and Tillage Management - No Till / Strip Till / Direct Seed	329
	Mulch	Residue and Tillage Management - Mulch Till	345
	Native vegetation – buckwheat (only above valley floor)	Conservation Cover	327
	Roughened surface or furrows across the wind	Surface Roughening or Emergency Tillage	609
	Wind breaks and wind barriers	Windbreak / Shelterbelt Establishment	380
		Herbaceous Wind Barriers	603
	Mulch – wood chips or gravel	Mulching	484
Deep sand	Rice grass	Range Planting	550
	Wind breaks	Windbreak / Shelterbelt Establishment	380
	Mulch – wood chips or gravel	Mulching	484
Farm roads and equipment yards	Chemical coatings	Dust Control on Unpaved Roads and Surfaces	729
	Gravel		
	Paving		

**NOTE:** This list identifies the most common (but not all) Conservation Practices for growers. For information about additional options or for assistance, growers can contact the Lancaster Service Center of U. S. Department of Agriculture Natural Resources Conservation Service (USDA/NRCS) office at 661-945-2604. Additional resources are listed in the Resources Guide.

\* For more detailed information about these Conservation Practices, go to the USDA/NRCS website <http://www.ca.nrcs.usda.gov/>. Under Quick Access in left margin, select Electronic Field Office Technical Guide (eFOTG). Then click on California Map to select county. Page opens to display list of eFOTG sections in left margin. Select Section IV; then select Table of Contents. As an option, select Conservation Practices under the individual folders that appear under the Table of Contents heading.

# Specific Practices

## Cover Crops in Field Cropping Systems

Cover crops include grasses, legumes, and forbs for seasonal cover and other conservation practices. (See Figure 6.) They effectively reduce erosion from the wind. They can be used on all arable lands and even on very sandy ground with appropriate techniques.

Use cover crops when large acreage is leased and/or will be farmed in the near future. Cover crops add organic matter and nutrients to soil and may break disease cycles. Yields of subsequent crops may be significantly improved. Selection of a cover crop requires a cost-benefit analysis. Growers may select a cover crop based strictly on economic analysis or because it fits into their rotation in terms of equipment, planting dates, markets, or potential for hosting pests.

High value cover crops such as cowpea and *Sesbania* perform well in the Antelope Valley. They are relatively expensive to establish, but they improve soil quality and may provide a sizeable economic return. Consider using high value covers if the fallow period is only a few months and particularly if it is followed by high value vegetables.

Lower value cover crops such as cool season grains (i.e. barley, wheat) and warm season Sudangrass also perform well in this area. They are less expensive to establish but provide less benefit to soil than higher value options. However, they better resist degradation and therefore can stabilize land for up to 3 years.

Residue breakdown is critically important in cover crop selection. When vegetables follow a fallow period, avoid cover crops with high C:N ratios, such as cereals or Sudangrass. These crops slow residue breakdown and immobilize nutrients.

Mustard is a suitable cover crop for short term fallow farm land. It produces a low C:N ratio and breaks down quickly in the soil, releasing high levels of nitrogen. Mustard appears to enhance soil structure and increases yields of following crops such as carrots.



**Figure 6:** Even in sandy areas, it may be possible to install a cover crop such as barley, particularly with favorable rains or irrigation. Planting across the wind provides considerable suppression of blowing sand.

Although there is the potential for mustard residue to be a *Pythium* population host, research has shown definitive evidence that mustard cover crops increase cavity spot levels. Cover crops with similar properties are *Sesbania* and cowpeas.

Table 2 suggests cover crops for the Antelope Valley.

**Table 2: Suggested cover crops for the Antelope Valley**

Category	Type	Persistence	Crop Characteristics
Low cost	Cool season cereal grains	< 3 years	<b>Cereal Grains</b> – Easy to establish; marketable as forage. When planted in fall, may germinate on winter moisture. Without winter moisture, may need approximately 8 inches of irrigation. Suitable cereal grains include barley, wheat, and oats.  For information about current variety choices, contact agencies listed in Resources Guide.
Moderate cost	Cool season mustard	<3 months	<b>Mustard</b> – Short growing season; breaks down quickly in soil (<3 months). May suppress soil-borne nematodes, diseases, and in some cases weeds, but not a reliable substitute for Vapam fumigation. Returns applied N to soil but does not fix N.
High cost-high value	Cool season legume, vetch	<3 months	<b>Vetch</b> – Cool season legume; residue breaks down quickly (< 3 months). Adds N by fixation. Plant October – February.
Moderate cost	Warm season Sudangrass	< 3 years	<b>Sudangrass</b> – Warm season forage; plant after April. After harvest, stubble residue will hold soil and prevent it from blowing. For a grain crop during growing season, plant Sudangrass from late April through July. Requires supplemental irrigation. Can be chopped in summer and stubble will stabilize soil for remainder of season or subsequent seasons.
High cost-high value	Warm season legumes	< 3 months 3-6 months for <i>Sesbania</i>	<b>Legumes</b> (cowpeas, other beans, and <i>Sesbania</i> ) – Break down in soil quickly. Add N by fixation. Plant before August for maximum benefits.
High cost-high value	Perennial native shrubs	> 3 years	<b>Permanent cover species</b> – If land will be removed from cultivation for an extended period, consider planting saltbush ( <i>Atriplex spp.</i> ); California Buckwheat ( <i>Eriogonum</i> ); Rabbit brush ( <i>Chrysothamnus nauseosus</i> ); Indian rice grass ( <i>Oryzopsis hymenoides</i> ). May require starter irrigation and are inhibited by excess soil nitrogen. Will hold soil indefinitely once established.

**NOTE:** Table A1 in the Appendix provides recommended planting procedures for selected cover crops in the Antelope Valley.



## Stripcropping

Stripcropping consists of growing row crops, forages, small grains, or fallow in a systematic arrangement of equal width strips across the wind. (See Figure 7.) The practice can reduce costs and soil erosion and can protect growing crops from damage by wind-borne soil particles.



**Figure 7:** Strip cropping reduces expense while providing nearly all the benefit of a full cover crop.

The erosion-resistant (planted) and erosion-susceptible (unplanted) strips should be equal width, in multiples of the width of planting equipment, so that at least 50% of the ground is erosion resistant. No adjacent strips should be erosion-susceptible at the same time. When the strip orientation is not perpendicular to the wind, adjust the width, with the effective width measured along prevailing wind erosion direction and the minimum width determined by the width of the unplanted strip.

## Agronomic Practices for Planting Cover Crops

These variations on cover crop practices consist of managing the amount, orientation, and distribution of crop and other plant residue on the soil surface year round. The emphasis is on minimizing soil-disturbing activities to only those necessary to place nutrients, condition residue, and plant crops. All or part of the field may be cultivated, as appropriate.

Access roads may allow erosion and their width must be considered in laying out the resistant strips.

Table 3 provides recommended planting dates, seed rates, and depths for cover crops and native species in the Antelope Valley.

**Table 3: Recommended planting dates, seed rates, and depths for cover crops and native species in the Antelope Valley**

Crop	Planting Date	Seed Rate (lbs/acre)	Seed Depth
Cowpeas	May 1 - July 30	30 lbs	0.25-0.50 inches
<i>Sesbania</i>	May 1 - July 30	8 lbs	0.25 inches
Sudangrass	May 1 - July 30	50 lbs	1 inch
Native species	October - February	Dependent upon species. Consult seed company	Broadcast / drill 0.50 inches
Cereal grains	October - February	50 lbs	2 - 4 inches

### Cover Crops in Perennial Tree and Vine Systems

In orchards and vineyards, consider using cover crops as a dust control method. (See Figure 8.) Many orchards and vineyards are drip irrigated and are not set up for irrigation between crop rows. Thus, common cover crops for vineyards are annual grains or drought tolerant grasses. Plant these in fall or winter for germination on winter moisture. They do not require supplemental irrigation. When selecting a cover crop in perennial trees and vines, evaluate problems associated with insect control. Cover crops can host pests such as spider mites and leaf hoppers, as well as beneficial insects.



**Figure 8:** Prevent erosion between rows of permanent crops with a cover crop. The cover may be chosen to provide nitrogen or other horticultural benefits.

### Long Term Native Plant Cover

Consider using native species for fallow periods longer than 3 years and land to be removed from cultivation. These species provide the greatest sustainability and return the system as closely as possible to its natural state, which typically resists erosion. (See Table 2, “Perennial native shrubs” section.) For more information about native species, contact the Antelope Valley Resource Conservation District or the Lancaster Service Center of USDA/NRCS listed in the Resources Guide.

### Exposed Desert

Wind erosion may be reduced on rangeland open desert or other suitable locations through establishment of adapted annual or perennial vegetation such as grasses, forbs, legumes, or perennial shrubs and trees. This practice may be applied where desirable vegetation is below the acceptable level for dust suppression and natural reseeding to occur.

### Wind Breaks

Wind rarely lifts sand higher than 3 feet above ground. This allows wind breaks to trap blowing sand as it enters land from upwind areas or is blown from disturbed land. Wind breaks can be solid or porous barriers. (See Figures 9 and 10.) In either case they slow the wind and cause it to drop its burden of sand.

To keep the system functional as long as possible, remove or smooth sediment that accumulates along the edges.

### Solid Fences

Wood or concrete block fences are solid wind barriers. They collect blowing sand only on the barrier's upwind side. In general, little sand will pass the barrier until collected sand on the upwind side reaches the top of the fence. When sand begins to blow across the top, either increase fence height or remove the collected sand. Install these barriers along the upwind edge of your property.

### Porous Fences

Porous plastic fences are partial wind barriers. Openings in fences slow the wind and cause blowing sand to deposit mostly on the downwind side. Because the area of sand accumulation is larger than with solid fences, its depth is reduced and sand removal is required less frequently. However, little vegetation will grow where unstable sand accumulates.

These barriers may also be installed along the upwind edge of property or at intervals downwind across property. A 4-foot porous polyethylene sand fence will deposit blowing sand within about 40 feet of the fence.

### Straw Bales

Straw bales are often available on farms. Use these to erect solid or (by spacing them) porous barriers. These are most effective as wind breaks when they are at least 6 feet high.

### Soil Surface Modification

The soil surface can be modified by performing tillage operations that create random roughness. (See Figure 11.)



**Figure 9:** Porous wind fences are commercially available. They trap blowing tumbleweeds as well as sand. In areas with endangered species, such as the desert tortoise, openings should be provided at intervals to allow for continued natural migration of the animals.



**Figure 10:** The combination of wind fences and seeding of cover crops such as barley may reinforce each other. Even with poor establishment on very sandy ground, the combination may suppress wind erosion enough to initiate stabilization.



**Figure 11:** Tillage across the wind is very effective in controlling wind erosion. It may serve as an emergency measure or as preparation for seeding of native species.

Several techniques for roughening the soil surface may provide rapid suppression of wind erosion. Ripping soil to bring clods to the surface may be sufficient to disrupt wind and interrupt saltation of sand particles. Bedding or furrowing soil may also be effective, particularly across the wind. Blowing sand tends to collect in the furrow bottoms. Roughening is not effective in deep sand.

### Berms

Berms provide more dramatic and long-lasting soil surface modification. (See Figure 12.) They are large mounds of earth built perpendicular to the wind. They may be stabilized with wood chips, vegetation, or other covering, or with wind fences. Berms slow the wind and cause sand to deposit mostly on the upwind side. Currently, wood chips are available free of charge from municipal waste sources.

To keep the system functional as long as possible, remove or smooth sediment that accumulates along the edges.



**Figure 12:** Berms are semi-permanent features on the landscape that provide effective reduction of blowing sand.

### Large Trees and Shrubs

Large vegetation, such as trees and shrubs, planted in a single or multiple rows, provides protection from blowing sand, similar to wind fences. (See Figure 13.) They also leave an attractive landscape feature after sand encroachment has been solved. To grow properly, vegetation needs moisture and protection from sandblasting. Plant vegetation along the downwind edge of a berm or other wind barrier. This will protect vegetation until it matures and begins to reduce wind speed on its own.



**Figure 13:** Wind barriers made up of permanent vegetation provide effective protection from blowing sand. They are too slow for emergency applications but provide long term beautification of the landscape.

Use trees to protect seedlings of other crops from sandblasting. However, the cost of establishing and maintaining tree covers can be high. Also, trees require supplemental water in the Antelope Valley, so evaluate water availability and maintenance of irrigation systems.



For more information about specific types of trees and shrubs, contact the Antelope Valley Resource Conservation District or Lancaster Service Center of USDA/NRCS listed in the Resources Guide. For irrigation requirements for evergreens, see Appendix Table A2.

## Surface Coverings

Dust control can be a problem on unpaved roads where there is vehicle and machinery traffic and on unpaved areas such as farmsteads, materials handling areas, equipment parking lots, and construction sites. Surface coverings can stabilize loose soil in these areas and may consist of almost anything that covers the sand and increases surface roughness. With the possible exception of wood chips, discussed below, these techniques would interfere with future cropping and should be avoided on land that will be returned to production.

Mulching involves applying plant residues, by-products, or other suitable materials produced off site to the land surface. Wood chips, gravel, or even plastic sheeting can be used as mulch. A thin layer (2-3 inches) of wood chips is a quick, easy way to temporarily stabilize small areas of accumulated sand while vegetation grows. This layer provides protection for up to 5 years. Currently, wood chips are available free of charge from municipal waste sources.

Gravel is more expensive and longer lasting than wood chips. It is most appropriate for roads and equipment yards.

Plastic mulches may be appropriate in permanent cropping systems, where they may offer additional benefits in moisture conservation and insect management.

Chemical dust suppressants are polymers that bind the soil surface, making it resistant to dislodging and saltation of sand particles. Other surface covering options include road base materials, road oils, oil and aggregates, and asphalt. For dust control, these products can be applied to roadways and equipment yards but not to production fields. The longevity and cost depends on the specific product.

For more information about dust control on unpaved roads and unpaved areas, visit the Western Regional Air Partnership (WRAP) at <http://www.wrapair.org/forums/dejf/fdh/index.html>.



# Acknowledgments

**The development and production of this Guide was funded by the following organizations. Without their contributions, publication of this Guide would not have been possible.**

- ☼ Antelope Valley Air Quality Management District/Mojave Desert Air Quality Management District
- ☼ Antelope Valley East Kern Water Agency
- ☼ Antelope Valley Resource Conservation District
- ☼ City of Lancaster
- ☼ City of Palmdale
- ☼ Kern County Air Pollution Control District/Desert Mountain Resource Conservation and Development Council
- ☼ Sanitation District of Los Angeles County
- ☼ Southern California Edison Company
- ☼ South Coast Air Quality Management District
- ☼ United States Department of Agriculture Natural Resources Conservation Service

We also wish to thank the many participants in the focus groups for reviewing and assisting with the information in this Guide.

## Disclaimer

The dust mitigation measures, research results, and conclusions and recommendations expressed in this Guide are solely those of its authors and contributors and are not necessarily endorsed by the many agencies, organizations, and companies who have supported and contributed to Dustbusters Research.

The user of this Guide must determine the appropriateness of a specific measure and must avoid creating fire, drainage, flood, or other safety issues when implementing dust mitigation measures. The user is advised to check with local agencies regarding safety and regulatory issues.

# Resources Guide

**The following is a list of organizations that can help you select and implement the most cost-effective dust mitigation measures to address your problem:**

Antelope Valley Air Quality Management District (AVAQMD) at **661-723-8070**; at website <http://www.avaqmd.ca.gov/>; or email [bbanks@avaqmd.ca.gov](mailto:bbanks@avaqmd.ca.gov).

Antelope Valley Resource Conservation District (AVRCD) at **661-945-2604**; at website <http://www.avrcd.org/>; or email [avrcd@carcd.org](mailto:avrcd@carcd.org).

Antelope Valley Resource Conservation District Nursery (AVRCD) at **661-942-7306**; at website <http://avrcd.org/nursery.htm>; or email [avrcd@carcd.org](mailto:avrcd@carcd.org).

Kern County Agricultural Commissioner at **661-868-6300**; at website <http://www.kernag.com/>; or email [agcomm@co.kern.ca.us](mailto:agcomm@co.kern.ca.us).

Lancaster Service Center of U. S. Department of Agriculture Natural Resources Conservation Service (USDA/NRCS) office at **661-945-2604**; website at <http://www.ca.nrcs.usda.gov/>.

Los Angeles County Agricultural Commissioner at **661-974-8801**; or at website <http://acwm.co.la.ca.us/>; or email [dbrackin@acwm.lacounty.gov](mailto:dbrackin@acwm.lacounty.gov).

U. S. Department of Agriculture Natural Resources Conservation Service (USDA/NRCS); website at <http://www.ca.nrcs.usda.gov/>.

University of California – Los Angeles County Cooperative Extension – Antelope Valley/Lancaster Office at **661-974-8824**; or at website <http://celosangeles.ucdavis.edu/>; or [asbiscaro@ucdavis.edu](mailto:asbiscaro@ucdavis.edu).

### **Other Sources of Information:**

The Antelope Valley Air Quality Management District website provides additional information that may help with your selection and implementation of cost-effective dust mitigation measures. Go to the website at <http://www.avaqmd.ca.gov/>; then select “Windblown Dust Guidance,” where you will find:

#### **Case Studies**

Provides descriptions of several successful windblown dust mitigation field case studies that have been conducted in the western Mojave Desert since 1992. During these case studies, several different dust mitigation strategies were developed, tested, and implemented.

#### **Publications**

Provides a list of peer reviewed open literature and conference papers. Also provides access to the complete papers.

#### **Extended Abstracts of Publications**

All peer reviewed publications have an abstract of approximately 300 words.

#### **Reports**

Provides a list of reports developed by the Dustbusters Research Group since 1992, organized by topic. Also provides access to the complete reports.

#### **WRAP**

You will also find information at the archived Western Regional Air Partnership (WRAP) at website <http://www.wrapair.org/forums/dejf/fdh/index.html>. WRAP provides access to the fugitive dust handbook developed by the Western Regional Air Partnership. This comprehensive handbook discusses the fugitive dust problem, mitigation solutions, and costs associated with the various control measures.

# Appendix: Irrigation Requirements

**Table A1: Recommended planting procedures for selected cover crops in the Antelope Valley.**

Type of Cover Crop	Suggestions for Stand Establishment
High cost cover (cowpeas)	<p>Pre-irrigate with 1-2 inches of water.</p> <p>Apply 150 units of N (ammonium sulfate).</p> <p>Irrigate for short durations of 2 hours per day for 2 weeks. For more information, contact the University of California Cooperative Extension listed in the Resources Guide.</p>
Low cost cover (cereal grain or Sudangrass)	<p>Place irrigation in field if needed or not expecting winter moisture; pre-irrigate with 1 inch. If irrigation will be limited, pre-irrigate with 2-3 inches.</p> <p>Irrigate 6-8 inches for season, if available.</p> <p>If sub-moisture is available, adjust drill depth to reach moisture. Grain will emerge from 3-4 inches deep.</p> <p>Apply 40 to 80 units of N only if irrigation is supplied.</p> <p>Do not irrigate prior to emergence because this reduces emergence. Replant if rain exceeds 0.5 inches or forms a crust.</p> <p>For Sudangrass, plant in May if possible. Will not emerge if planted after August. Irrigate for several weeks and fertilize for acceptable stand.</p>

**Table A2: Irrigation levels for establishment and maintenance of evergreen trees in the High Desert, expressed in gallons per tree per day. Data obtained near Victorville, California.**

Height of Tree (Feet)	WINTER Dec 21 - Mar 20			SPRING Mar 21- Jun 20			SUMMER Jun 21-Sep 20			FALL Sep 21 - Dec 20		
	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
3	0.2	0.2	0.3	0.4	0.6	0.9	1.3	1.5	1.3	0.9	0.5	0.3
6	0.3	0.3	0.5	0.7	1.1	1.9	2.6	3.0	2.6	1.9	1.1	0.5
9	0.5	0.5	0.8	1.1	1.7	2.8	3.9	4.5	3.9	2.8	1.5	0.8
12	0.6	0.6	1.1	1.4	2.3	3.7	5.2	6.0	5.2	3.7	2.0	1.1
15	0.8	0.8	1.4	1.8	2.9	4.7	6.5	7.5	6.5	4.7	2.6	1.4
18	0.9	0.9	1.6	2.2	3.4	5.6	7.7	9.0	7.7	5.6	3.1	1.6
21	1.1	1.1	1.9	2.5	4.0	6.5	9.0	10.5	9.0	6.5	3.6	1.9
24	1.2	1.2	2.2	2.9	4.6	7.4	10.3	12.0	10.3	7.4	4.1	2.2
27	1.4	1.4	2.4	3.2	5.1	8.4	11.6	13.5	11.6	8.4	4.6	2.4
30	1.5	1.5	2.7	3.6	5.7	9.3	12.9	15.0	12.9	9.3	5.1	2.7
33	1.7	1.7	3.0	4.0	6.3	10.2	14.2	16.5	14.2	10.2	5.6	3.0
36	1.8	1.8	3.2	4.3	6.8	11.2	15.5	18.0	15.5	11.2	6.1	3.2
39	2.0	2.0	3.5	4.7	7.4	12.1	16.8	19.5	16.8	12.1	6.6	3.5
42	2.1	2.1	3.8	5.0	8.0	13.0	18.1	21.0	18.1	13.0	7.1	3.8

Developed by R.T. Lanphier C.E.T.  
 USDA Soil Conservation Service  
 Provided courtesy of the Mojave Water Agency





## Dustbusters Research Group

In 1991, the Dustbusters Research Group formed a partnership to develop best management practices for mitigating wind erosion, reducing blowing dust, and improving air quality in the Antelope Valley. Since then, this Group has developed and implemented a land treatment program to minimize wind erosion through vegetative, physical, and chemical stabilization procedures.

This Group consists of private entities and federal, county, and city government representatives. For a complete listing of participants, go to the Antelope Valley Air Quality Management District's website at <http://www.avaqmd.ca.gov>.







◀ Author David Vaughn found widespread but non-uniform establishment of two saltbushes (*Atriplex canescens* and *A. polycarpa*) and California buckwheat (*Eriogonum fasciculatum*) throughout the EWP area. The shrubs suppressed fugitive dust over most of the formerly eroding area.

▼ From 1988 through 1991, barren lands in the western Mojave Desert were a major source of fugitive dust and fine particulate matter during periods of high wind.



**DustBusters reduce pollution, wind erosion . . .**

## Though difficult to achieve, revegetation is best way to stabilize soil

David A. Grantz   □   David L. Vaughn   □   Robert J. Farber   □   Bong Kim  
Tony VanCuren   □   Rich Campbell   □   David Bainbridge   □   Tom Zink

***Surface disturbance in arid regions — whether it results from abandoned agriculture, overgrazing or recreational activities — often sets the stage for wind-blown fugitive dust. Revegetation provides the most sustainable soil stabilization but is difficult to achieve in any given year. Widely varying environmental conditions and soil factors make direct seeding unreliable, and transplanting of nursery-grown shrubs does not assure plant establishment, even with supplemental irrigation. In occasional years plants can be successfully established, particularly *Atriplex canescens*, in the western Mojave Desert. Once vegetation becomes established, it successfully stabilizes the soil surface and reduces blowing dust. However, because successful establishment is infrequent, reliable mitigation of fugitive dust requires that other techniques be used as well.***

Expanding population, increased water and pumping costs, and mounting competition for water have induced more growers to periodically fallow land in arid and semiarid areas of California. This practice, and the abandonment of agriculture altogether in marginally productive sites, has become especially common during drought years. Areas that are abandoned, overgrazed or disturbed by recreational activities often become sources of fugitive dust and respirable particulate matter. Of particular concern to human health is "PM-10," particles below 10 microns in aerodynamic diameter, because they are small enough to deeply penetrate the lungs. Control of PM-10 originating from disturbed areas has been mandated as part of State and Federal Implementation Plans (SIP, FIP) for particulate air pollution.

The Antelope Valley of the western Mojave Desert (high) of California is an area of seasonally high winds blowing across extensive areas of barren, disturbed, fallowed and abandoned

land. Dust storms in this area have been visible from space. They reduce visibility, cause traffic accidents, inundate buildings and property and damage field and tree crops. Fine components of this fugitive dust have contributed to repeated violations of the State and National Ambient Air Quality Standards for particulate matter. Methods to stabilize these areas are urgently needed to protect the soil and atmospheric resources and to prevent harm to people and property.

Re-establishment of native vegetation is the most sustainable and economically attractive land stabilization strategy available, but low and unpredictable rainfall limits natural and facilitated revegetation success in desert areas. Without intervention, some plant species become established only once in every decade or even century, when environmental conditions of temperature, moisture, soil stability and nutritional status, as well as other poorly characterized factors, are favorable. The result is that disturbances created in these areas decades ago (such





A helicopter seeds fourwing saltbush, allscale saltbush, California buckwheat and California poppy.



California poppy (*Eschscholzia californica*) became established after the barley, providing additional vegetative cover as well as aesthetic appeal.

as covered-wagon trails and armored-vehicle tracks from World War II training exercises) remain barren and visible in the Mojave Desert today.

Attempts to revegetate these lands by direct seeding with or without associated tillage are common, but they fail in most years. However, since limited plant cover (20% to 30%) is typical of these regions and is sufficient to stabilize the soil, isolated areas of vegetation success may be adequate to stabilize the surface, and large homogeneous shrub populations may be unnecessary. The establishment of isolated plants — for example, by transplanting hardy nursery stock — may initiate development of islands of fertility that consolidate water and nutrients under plant canopies, improve soil tilth and microbial activity and begin sustainable successional processes leading to widespread shrub establishment.

The DustBusters Taskforce, a multiagency group convened to address these problems in the Antelope Valley, has investigated direct seeding, transplanting and various tillage interventions as possible mitigation strategies in the western Mojave Desert.

### Direct seeding

A stabilization protocol was applied in February 1992 through an innovative use of the USDA Soil (now Natural Resources) Conservation Service (NRCS) Emergency Watershed Protection (EWP) program. The 2,470-acre EWP area consisted of Rosamond and Hesperia series soils, with a variety of soil surface textures. In some areas there was an overburden of blown sand. Preparation of the site included burning the annual vegetation, leveling wind-deposited material and ripping and furrowing the soil perpen-

dicular to the prevailing winds. The furrows provided rapid but relatively short-lived suppression of fugitive dust in some areas but failed completely in sandy areas (Grantz et al. 1998).

The EWP strategy included a revegetation component applied with the tillage (table 1). A drought-resistant barley, *Hordeum vulgare*. 'Seco' or 'Solum', was drilled into the furrow bottoms to achieve a rapid vegetation cover in arable soils. Indian ricegrass [*Achnatherum hymenoides* (Roemer & Schultes) Barkworth], a native perennial bunchgrass, was seeded along with the barley in the furrow bottoms to provide rapid and sustainable cover in areas of deep shifting sand. An additional seed mixture of native shrubs and California poppy was broadcast by helicopter. Unusually heavy rainfall (2 to 3 times the 20-year average)

TABLE 1. Plant species, planting methods, and seeding rates used in the Emergency Watershed Protection program

Scientific name	Common name	Seeding method	Seeding rate†	
			kg/ha	lb/ac
<i>Atriplex canescens</i>	Four-wing saltbush	Aerial*	0.73	0.65
<i>Atriplex polycarpa</i>	Allscale saltbush	Aerial*	0.73	0.65
<i>Eriogonum fasciculatum</i>	California buckwheat	Aerial*	0.55	0.49
<i>Eschscholzia californica</i>	California poppy	Aerial*	0.1	0.09
<i>Achnatherum hymenoides</i> 'Paloma'	Indian ricegrass	Ground‡	1.1	0.98
<i>Hordeum vulgare</i> 'Seco' or 'Solum'	Barley	Ground‡	0.3	0.27

\*Broadcast by helicopter.

†Drilled in furrow bottoms.

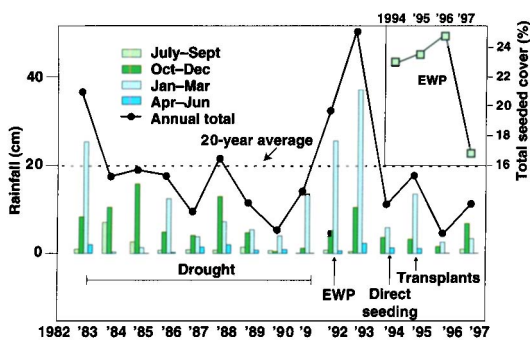
‡Nominal seeding rates.

TABLE 2. Control of fugitive dust at 3.3 feet above the ground by directly seeded vegetation in the Emergency Watershed Protection Program for periods with wind gusts above 34 mph

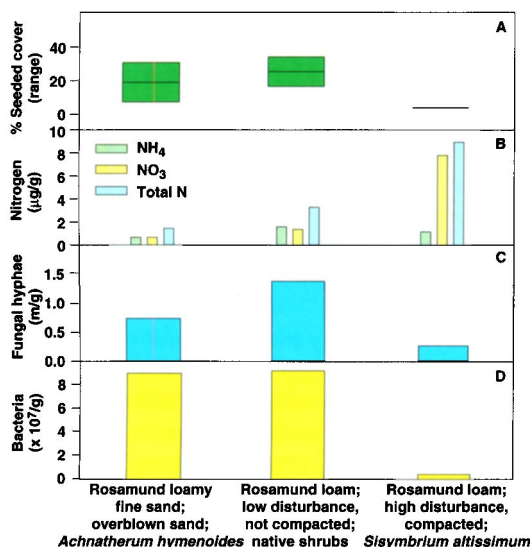
Dust collected		Control
Barren area	EWP area	
..... g .....		%
75.1*	0.380	99.5
0.47†	0.013	91.0

\*Drought conditions, 1992. Control area in western Antelope Valley.

†Wet conditions, 1994–1996 average. Control area in mid-Antelope Valley.



**Fig. 1.** Timeline of seasonal (colored bars) and annual total rainfall in the Antelope Valley during the drought, the EWP installation period and the subsequent return to drought conditions following the revegetation efforts. The dotted line shows 20-year average rainfall. Plant success in covering the soil by seeded EWP vegetation is shown for 1994–1997 (inset).



**Fig. 2.** Effect of soil type and level of disturbance on seeded plant performance (% ground cover) in 1997 following the EWP (A). Important determinants of plant cover were (per gram of soil) residual soil nitrogen (B), and fungal (C) and bacterial (D) colonization of the soil.

fell on the EWP area immediately following the direct seeding, and a dense ground cover of barley and perennial seedlings was successfully established in many areas.

Transects, randomly located throughout the 2,470-acre seeded area, were used to assess vegetative cover in June of 1994, 1995, 1996 and 1997. Ground cover of the seeded species increased slightly, from 23% in 1994 to about 25% in 1996, similar to typical values in the region, followed by a decrease to about 16% in June of 1997 (fig. 1). This decline was attributed to a

50% reduction in both California buckwheat and Indian ricegrass. In contrast, the *Atriplex* species were relatively stable. These results reflect important species differences in ability to survive conditions of limited soil water. In this area, Indian ricegrass is usually restricted to very sandy sites, and buckwheat to slightly higher elevations. In contrast, *Atriplex* spp. are naturally distributed widely throughout the valley floor in undisturbed areas.

Implementation of the EWP program on the most seriously disturbed areas of the Antelope Valley, combined with the resumption of rainfall at the end of the drought (fig. 1), resulted in reduced fugitive dust collected in our experiments (table 2). It also resulted in reduced maximum PM<sub>10</sub> concentrations in the atmosphere (measured at the Lancaster monitoring site), from 411 μg/m<sup>3</sup> (1989–1991 average) to 69 μg/m<sup>3</sup> (1992–1993 average). Although the relative composition and total percent ground cover by vegetation varied between the evaluation years, the control of fugitive dust relative to naturally occurring or experimentally imposed barren areas was substantial (>90%, table 2).

The success of the direct seeding was not uniform across the EWP area. To investigate possible differences in soil nitrogen (N) status and populations of microbiota, soil samples were obtained from three areas that represented different soil surface textures and levels of disturbance within the EWP area, and that differed visibly in EWP revegetation success. One area was overblown with sand and became dominated by Indian ricegrass. A second, low-disturbance area fostered good shrub establishment. A high-disturbance, compacted area retained no seeded cover and ultimately was colonized by a dense population of an invasive annual, tumble mustard (*Sisymbrium altissimum* L.) (fig. 2A).

The site-to-site variability was closely associated with soil conditions. The areas that responded well to direct seeding contained low concentrations of residual soil nitrogen (fig. 2B) and high concentrations of fungal hyphae (fig. 2C) and bacteria (fig. 2D), conditions normally associated with undisturbed desert ecosystems. In contrast,

the highly disturbed site, where none of the seeded species became established, contained low concentrations of fungal hyphae and bacteria and high residual N concentrations, particularly nitrate, reflecting former agricultural activities. Soils high in available N encourage invasion by rapidly growing nitrophilic species, while soils with low populations of mycorrhizal fungi inhibit shrub establishment and encourage invasion by nonmycorrhizal annuals such as *S. altissimum*. Preliminary soil sampling may be advisable prior to selection of revegetation protocols in arid regions.

In February 1994, attempts to duplicate the success of the EWP in large replicated plots (300 ft by 600 ft) failed in two of three experimental locations. Rainfall was not as favorable as in 1992 (fig. 1), although it was more typical of the region. The three sites were separated geographically to characterize the EWP as well as other areas of the Antelope Valley. One of the sites in which no establishment of the direct seeded vegetation took place was near the EWP area and contained soil types identical to those in the EWP, in which revegetation was successful in 1992. The other sites were located in the westernmost portion of the Antelope Valley. One yielded substantial plant establishment and one yielded no directly seeded plants, suggesting that location and soil characteristics have substantial but poorly understood effects on the success of direct seeding efforts. The EWP strategy, although highly successful in an unusually wet year, was not found to be reliably reproducible in other years or places.

A number of experimental treatments were imposed on the large plots, including a progression from undisturbed to minimally disturbed to highly disturbed soil surfaces, each representing a component of the original EWP protocol. Some of the treatments used a seed mixture similar to that used in the EWP. Existing vegetation on all of the large plots was burned. This was the only treatment applied to the control. Other plots received ripping and furrowing; ripping, furrowing and drilling the seed mix; broadcasting the seed mix without till-



age; rangeland drilling the seed mix without tillage; and rangeland drilling only seed of red brome, *Bromus rubens* L.

The least intrusive protocol, burning the annual vegetation followed by broadcasting the seed onto the barren but undisturbed soil surface, yielded the highest plant density and the richest species composition of any treatment tested (fig. 3). Rangeland drilling the seed mix, another low-disturbance protocol, resulted in lower densities of California buckwheat (*Eriogonum fasciculatum* Benth.), allscale saltbush [*Atriplex polycarpa* (Torrey) S. Watson] and rabbitbrush [*Chrysothamnus nauseosus* (Pallas) Britton], but higher densities of fourwing saltbush [*Atriplex canescens* (Pursh) Nutt]. Ripping and furrowing treatments followed by seeding (the EWP protocol) resulted in lower shrub densities and poorer species diversity (fig. 3). Ripping and furrowing without application of seed resulted in few shrubs, but dense populations of invasive annual species including tumble mustard, Russian thistle (*Salsola pestifer* Nelson) and the grasses, *Bromus rubens*, *B. tectorum* L. (cheatgrass) and *Schismus* spp. Soil disturbance is to be avoided in these areas to prevent mobilization of soil nitrogen and colonization by aggressive annual species.

The early successional species, *C. nauseosus*, although included in the seed mix, did not become established on any plot subject to soil disturbance (fig. 3D). In this area rabbitbrush is commonly observed to colonize barren land after range fire but resists establishment on soil surfaces that are barren due to wind erosion or other disturbance. Rabbitbrush established successfully on the control plot, which had been burned but to which no seed was applied (fig. 3D). This reflects seed that was blown in from an adjacent upwind area with a natural rabbitbrush population exceeding 1,200 plants per acre. Rabbitbrush establishment on ripped, furrowed or drilled plots was very poor, even though they were downwind of the same natural seed source. The plot that was burned but broadcast with rabbitbrush and other seed developed substantial, but lower, rabbitbrush density, reflecting competition from the saltbush and

buckwheat that were seeded. Rabbitbrush density decreased logarithmically with increasing distance from the native seed source.

Barren areas neighboring native rabbitbrush stands may require no intervention, except for removal of competing annual vegetation by burning. In the absence of a nearby seed source, however, repeated broadcasting of locally gathered seed may offer the greatest probability of establishment, while surface tillage reduces the probability of establishment to near zero. Our experience indicates that rabbitbrush should not be included in seed mixes nor be used to develop seedlings for transplanting, because it is difficult to germinate under nursery conditions, and because the copious bristles of the mature seed, which are ideal for wind dispersion, make it difficult to handle in seeding equipment.

### Transplanting

Following the failure to reproduce the success of the initial direct seeding experiment, a more reliable revegetation protocol was sought in transplants of nursery-grown seedlings. One species was evaluated in a single, large 4.2 acres plot, and several additional species were evaluated in small common garden plots at multiple locations throughout the Antelope Valley.

Seedlings were grown in high aspect 4-by-4-by-14-inch containers

(plant bands), in a sand/perlite/vermiculite mix with nitrogen and phosphorus added at 0.38 and 0.45 pounds per cubic yard, respectively. Two planting methods were tested: power-augering a hole 4 by 14 inches deep, and excavating a larger hole, 16 by 16 inches deep, by hand with a pickax. The latter method was conducive to planting by range fire crews with

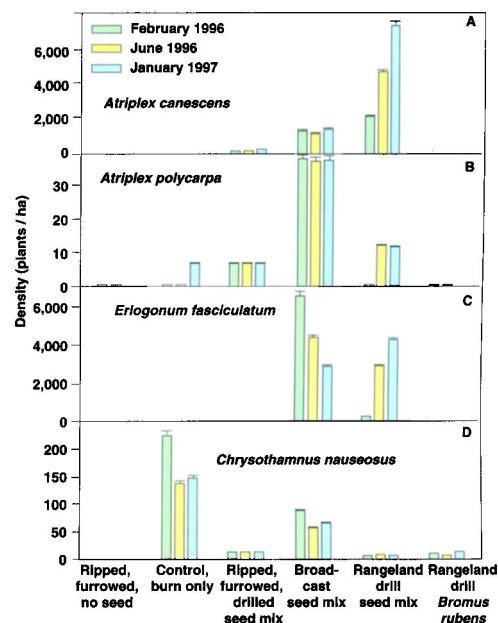


Fig. 3. Effect of alternative direct seeding methods and component soil manipulations on seeded plant performance (density) of native shrubs *A. canescens* (A), *A. polycarpa* (B), *E. fasciculatum* (C) and *C. nauseosus* (D).

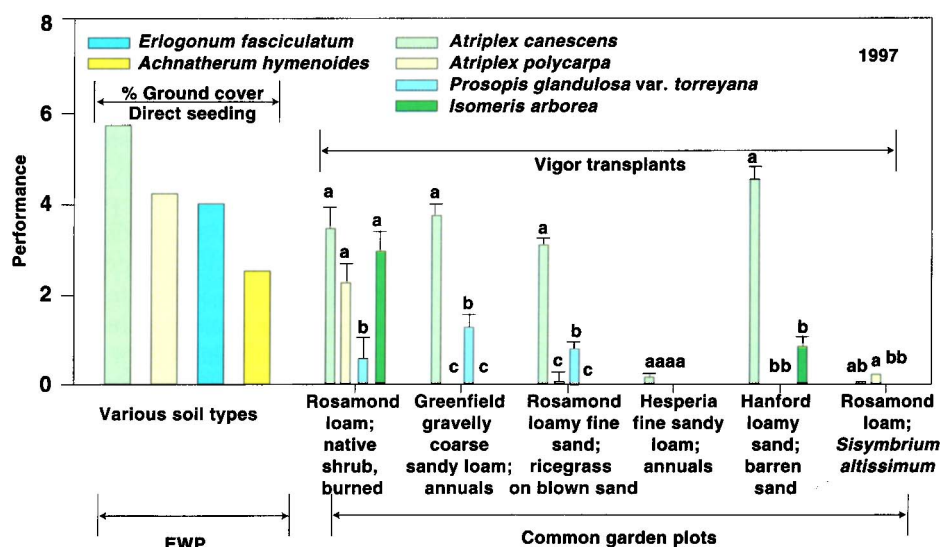


Fig. 4. Effect of plant species and soil type on performance of directly seeded species in the EWP area (% ground cover) and of transplanted species in the garden plots (plant vigor) in 1997.





**Above-average rainfall immediately following installation of the EWP led to rapid establishment of barley seeded in the furrow bottoms.**

revegetation experience. Approximately 0.5 gallon of water was added to each hole and allowed to drain. Plants were placed in the hole, the plant band removed and the hole back-filled and lightly compacted. An additional 0.25 gallon of water was added after planting. Two types of herbivory protection were randomly assigned to the transplants. Two-piece conical plastic tree shelters were commercially available, and cylindrical cages held in place with a metal rod driven into the ground were constructed on site from stucco wire.

A large plot of 780 transplants of honey mesquite [*Prosopis glandulosa* Torrey var. *torreyana* (L. Benson) M. Johnston] was installed in September 1995, spaced 30 by 7.5 ft. Each transplant received 0.5 gallon of supplemental irrigation on eight occasions during the year following transplanting. Plants were evaluated for vigor using a continuous rating scale (0 = dead to 8 = vigorous), on eight dates between planting and July 1997. Seven additional individuals of mesquite were transplanted adjacent to this plot into augered holes protected with larger wire cages. These individuals were irrigated weekly to evaluate potential growth.

The vigor of plants in augered holes (vigor = 1.58) was significantly greater than that of plants in hand-dug holes (vigor = 0.47;  $P < 0.001$ ). Similarly, the vigor of plants protected with plastic cones (vigor = 1.28) surpassed that of plants in wire cages (vigor = 0.60;  $P < 0.001$ ). Survival in early 1997 was 62%

among plants transplanted into augered holes protected by cones, compared with 10% in hand-dug holes protected with wire cages.

By July 1997, overall survival at this site had decreased to 16%, with average vigor of 0.2 and very small stature of the survivors. We removed herbivory protection from these plants in October 1996 and the new leaves and shoots of the

mesquite plants were intensely grazed by indigenous herbivores (e.g., black-tail jack rabbits, *Lepus californicus*), greatly reducing plant vigor.

Although these differences reveal that planting methods are important, plant performance in this environment is primarily limited by water availability. The seven mesquite transplants that received weekly irrigation exhibited 100% survival, had average vigor scores of 8.0 and grew to a large size. Where available, adequate supplemental irrigation improves the success of transplant revegetation efforts.

The smaller common garden plots were used to evaluate transplants of a variety of native species at six locations throughout the Antelope Valley. Plant spacing was 3.3 by 6.6 ft in the 82 by 39 ft plots. Transplants were about 10 inches tall at planting. Three mulch treatments (straw, wood chips and control) and two types of herbivory protection were evaluated with five replications at each site.

Fourwing saltbush was the most successful species in these tests, performing well in four of the six locations, paralleling its superior performance in the directly seeded EWP (fig. 4). Allscale and bladderpod performed well at only one site. Mesquite performed as poorly at each of these locations as it did in the large plot evaluation. Rabbitbrush performed poorly at all six locations (vigor = 0.9). No differences were observed between mulch treatments, while plants protected with cones performed better on average than those in wire cages.

Plant growth of most species was most vigorous at a minimally disturbed site that had been subjected to

an uncontrolled range fire just prior to transplanting. Rapid water infiltration indicated little compaction of the Rosamond loam soil at this site. In contrast, an adjacent site with Rosamond loam soil (fig. 4) exhibited slow water infiltration, suggesting soil compaction, and no shrub establishment. The plots are located in adjacent agricultural fields with different apparent use histories.

These two locations also exhibited contrasting revegetation success following the EWP direct seeding efforts in 1992 (fig. 2A). The burned site was in an area in which all seeded species became established, while the other site was in an area in which no seeded shrubs became established and which subsequently became covered with the invasive annual tumble mustard (*S. altissimum*). Soil analysis revealed higher  $\text{NO}_3\text{-N}$  concentrations and lower bacterial populations with less fungal hyphae at this site than in the neighboring site (fig. 2). Survival and vigor of transplanted as well as directly seeded plants are strongly influenced by these soil properties.

## Conclusions

There can be no guarantee of success in efforts to revegetate abandoned or disturbed lands in arid or semiarid regions, whether by direct seeding or by transplanting. Direct seeding with disruptive tillage succeeded in a year with late and above-average rainfall, but could not be repeated in more typical years. Alternative methods such as broadcast seeding on a burned but otherwise undisturbed soil surface may prove as successful without encouraging invasion by nitrophilic annual species.

The high rate of transplant mortality observed over 2 consecutive years of below-average precipitation suggests that the additional expense of nursery cultivation of seedlings for transplanting may not be warranted. Adequate supplemental irrigation may improve transplant survival and establishment. Narrow, deep planting holes that concentrate supplemental water and ensure good root-soil contact are superior to broad hand-dug holes. Plastic cones provided herbivory pro-

tection and beneficial microenvironmental effects that improved plant performance, but grazing of some species following removal of the cones may be catastrophic. Choice of species based on adaptation to the target environment and on feasibility of nursery production suggests that fourwing saltbush is recommended for transplanting and direct seeding interventions in this area, while rabbitbrush and mesquite are not recommended.

Soil nutrients and microorganisms reflect the level of soil disturbance and significantly affect the success of the seeding and transplanting efforts. High concentrations of available N encouraged invasion by aggressive annual species, suggesting that removal of residual N by cover cropping when feasible may facilitate long-term shrub establishment and soil surface stabilization.

In years of abundant rainfall, both direct seeding and transplanting are likely to be successful and thereby provide reliable suppression of fugitive dust for air quality mitigation. However, these are the periods during which fugitive dust is unlikely to contribute to particulate matter violations. In dry years, supplemental irrigation may facilitate long-term revegetation; otherwise, other mitigation strategies such as tillage and wind fencing should be applied with revegetation to achieve immediate and reliable control of soil erosion and fugitive dust emissions.

*D.A. Grantz is Plant Physiologist and Extension Air Quality Specialist and D.L. Vaughn is Staff Research Associate, Department of Botany and Plant Sciences and Statewide Air Pollution Research Center, UC Riverside; R.J. Farber is Senior Research Scientist, Environmental Research Division, Southern California Edison Company, Rosemead; B. Kim is Air Quality Specialist, South Coast Air Quality Management District, Diamond Bar; T. VanCuren is Air Pollution Research Specialist, California Environmental Protection Agency-California Air Resources Board, Sacramento; R. Campbell is District Conservationist, Natural Resources Conservation Service, Lancaster; D. Bainbridge is Environmental Studies Coordinator, United States International*



**In sandy areas, Indian ricegrass (*Achnatherum hymenoides*) became established where shrub establishment was poor, even when the shrubs were transplanted with protective plastic cones and wire cages.**

*University and T. Zink is Program Manager, Soil Ecology and Restoration Group, Department of Biology, San Diego State University.*

*Partial funding for this research was provided by California Environmental Protection Agency—California Air Resources Board and by South Coast Air Quality Management District.*

### Further reading

Bainbridge DA. 1993. Soil compaction: A critical problem in land restoration. *Land and Water* 37(1):42-3.

Carpenter DE, Barbour MG, Bahre CJ. 1986. Old field succession in Mojave Desert scrub. *Madroño* 33(2):111-22.

Farber RJ, Kim B, Ashbaugh L, et al. 1996. PM<sub>10</sub> air quality and micrometeorological measurements in Southern California's West Mojave Desert Antelope Valley. Paper No. 96-TP49A.06. 88<sup>th</sup> Annual Meeting & Exhibition of the Air and Waste Management Association, San Antonio, TX. June 1995.

Grantz DA, Vaughn DL, Farber RJ, et al. 1996. Stabilizing fugitive dust emissions in the Antelope Valley from abandoned farmlands and overgrazing. Paper No. 96-TP49A.05. 89<sup>th</sup> Annual Meeting & Exhibition of the Air and Waste Management Association, Nashville, TN. June 1996.

Grantz DA, Vaughn DL, Farber RJ, et al. 1998. Rapid methods to suppress fugitive dust and particulate air pollution from disturbed desert areas. *Cal Ag* 52(4):14-8.

Jackson LL, McAuliffe JR, Roundy BA. 1991. Desert restoration. *Restoration & Management Notes* 9(2):71-80.

Nakata JK, Wilshire HG, Barnes, CG. 1981. Origin of Mojave Desert dust storms



**Transplanted honey mesquite exhibited high mortality and low growth rate after nearly two years in the field, even with supplemental irrigation. Herbivory following removal of protection was severe.**

photographed from space on January 1, 1973. In: Pewe TL (ed.) *Desert Dust: Origin, Characteristics, and Effect on Man*. The Geological Society of America, Boulder, CO. p 223-32.

USDA, SCS. 1970. Soil survey, Antelope Valley area, CA. Soil Conservation Service, U.S. Department of Agriculture, Washington, D.C.

Wolfe SA, Nickling WG. 1993. The protective role of sparse vegetation in wind erosion. *Progress in Physical Geography* 17(1):50-68.

Zeldin MD. 1994. Approaches for controlling windblown dust emissions in Southern California desert areas. Paper No. 94-FA145.01. 87<sup>th</sup> Annual Meeting & Exhibition of the Air and Waste Management Association. Cincinnati, OH. June 1994.



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

David A. Grantz,\* David L. Vaughn, Robert J. Farber, Bong Kim, Lowell Ashbaugh, Tony VanCuren, Rich Campbell, David Bainbridge, and Tom Zink

### ABSTRACT

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

D.A. Grantz and D.L. Vaughn, Univ. of California at Riverside, Kearney Agric. Center, 9240 S. Riverbend Ave., Parlier, CA, 93648; R.J. Farber, Southern California Edison Co., P.O. Box 800, Rosemead, CA, 91770; B. Kim, South Coast Air Quality Management District, 21865 E. Copley Dr., Diamond Bar, CA, 91765; L. Ashbaugh, Crocker Nuclear Lab, Univ. of California, Davis, CA, 95616; T. VanCuren, California Air Resources Board, 2020 L Street, Sacramento, CA, 95812; R. Campbell, Antelope Valley Resource Conservation District, 44811 Date Avenue, Suite G, Lancaster, CA, 93534; and D.A. Bainbridge and T.A. Zink, Soil Ecology and Restoration Group, Dep. of Biology, San Diego State University, San Diego, CA, 92182. Received 11 June 1997. \*Corresponding author (david@uekac.edu).

Published in J. Environ. Qual., 27:960–967 (1998)

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

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

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

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

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

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

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

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

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

mass. Applicability of each is determined by cost and individual site requirements (Bainbridge et al., 1995).

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

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

## MATERIALS AND METHODS

### Plant Material

Five native plant species were chosen for evaluation. Honey mesquite, a deep-rooted, drought-resistant (avoiding and tolerant) leguminous species, is well adapted to drainages of both the high and low deserts of California. In some areas it has proven successful for stabilizing disturbed areas both by direct seeding and transplanting (Hickman, 1993; Bainbridge et al., 1993). Honey mesquite is considered endemic in this region but is now uncommon in the study area due to harvest for firewood and land clearing. Although capable of *Rhizobium* nodulation, this generally requires access to permanent fossil water tables for appreciable N<sub>2</sub> fixation (Rundel et al., 1982; Shearer et al., 1983), and is seldom observed on dry sites (Sprent, 1987) even following experimental irrigation (Virginia et al., 1989). The transplants used in this evaluation were not inoculated with *Rhizobium*.

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

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



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

Seedlings of all species were grown by the California Department of Forestry in Davis, CA, in high aspect 5 by 5 by 35.5 cm containers (plant bands; Bainbridge et al., 1994), in an artificial soil mix comprised of (by volume) 40% sand, 45% perlite, 5% vermiculite, 5% fir bark, and 5% coarse peat (L. Lippett, 1997, personal communication). Fertilizer (38–45–0; N–P–K; 590 g m<sup>-1</sup>) and gypsum (2950 g m<sup>-3</sup>) were added prior to planting.

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

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

### Weather Data

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

with SM192 solid state storage modules; Campbell Scientific Inc., Logan, UT).

### Experiment I

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

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

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

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

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

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

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

Site	Location	Elevation 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; coarse loamy, mixed, nonacid, thermic Xeric Torriorthents	Senescent annuals, low dense cover
C100S	34° 47' 28" N 118° 18' 45" W	752	Rosamond loam; fine-loamy, mixed (calcareous) thermic Typic Torrifluvents	Dense senescent cover <i>Sisymbrium altissimum</i>
C100N	34° 47' 30" N 118° 18' 45" W	752	Rosamond loam; fine-loamy, mixed (calcareous) thermic Typic Torrifluvents	Native desert shrub, barren from wildfire
B120W	34° 48' 17" N 118° 20' 24" W	765	Rosamond loamy fine sand; fine-loamy, mixed (calcareous) thermic Typic Torrifluvents	<i>Achnatherum hymenoides</i> (Roemer & Shultes) growing on overblown sand



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

### Experiment II

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

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

At each site (Table 1) the transplants were treated with one of three mulch treatments (straw, wood chips, and control) and one of two types of herbivory protection (plastic cones or wire cages), assigned randomly. The straw and wood chip mulches were applied to a depth of 8 to 10 cm in a circular pattern around the base of the plant (covering ca. 0.04 m<sup>2</sup>). 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  $\times$  protection applied randomly within rows. All transplants received either a cone or cage based on our previous experience in the study area. Protection was removed in October 1996 as above.

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

protection or mulch type within a site were evaluated only if main effects or interactions across all sites were significant.

Three randomly located soil samples (0–10 cm depth) were obtained from each of the six sites in April 1996 and analyzed for nitrate (NO<sub>3</sub>) and ammonium (NH<sub>4</sub>)–N levels (Keeney, 1982), and for bacterial and fungal populations (Anderson and Slinger, 1975; Trent, 1993; Conners and Zink, 1994). Soil data were analyzed by one-way ANOVA, and significant differences between site means were determined by Fisher's protected LSD.

## RESULTS AND DISCUSSION

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

### Experiment I—Large Plot Evaluation of Honey Mesquite

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

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

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

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

Vigor rating	Description
0	No leaves, stem brown, no green or purplish tissue evident
1	Stem partly green or purplish, no leaves present, no new growth
2	Stem partly green or purplish, no leaves present but new growth evident in axils
3	Stem wholly green or purplish, no leaves present, no new growth
4	Stem wholly green or purplish, no leaves present but new growth 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

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

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

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

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



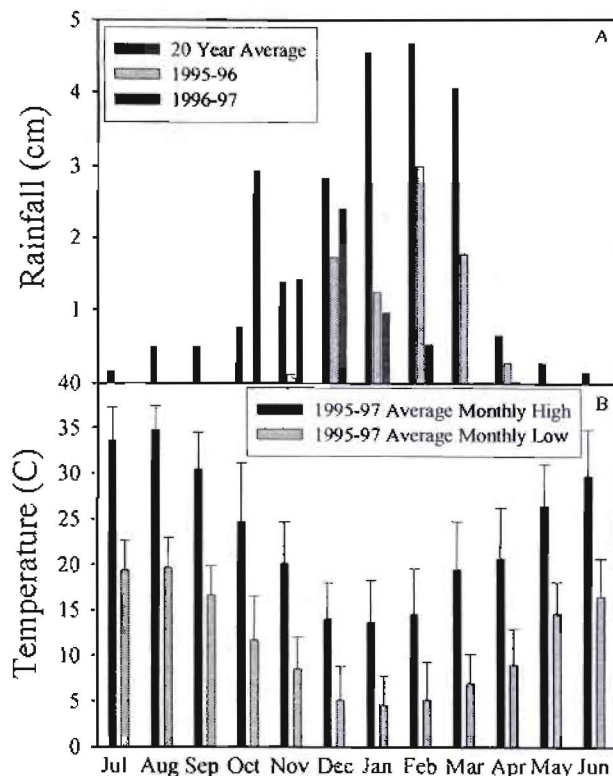


Fig. 1. Twenty-year average rainfall as measured at the Fox Field National Weather Service Station at Fox Field, Antelope Valley, and for the two years of transplant evaluations as measured by an on-site meteorological station (Panel A), and average monthly high and low temperatures from the same on-site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

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

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

Herbivory protection was removed from all plants in October 1996 when many individuals had emerged from their shelters. Above-average rainfall initiated establishment of annual species such as filaree [*Erodium cicu-*

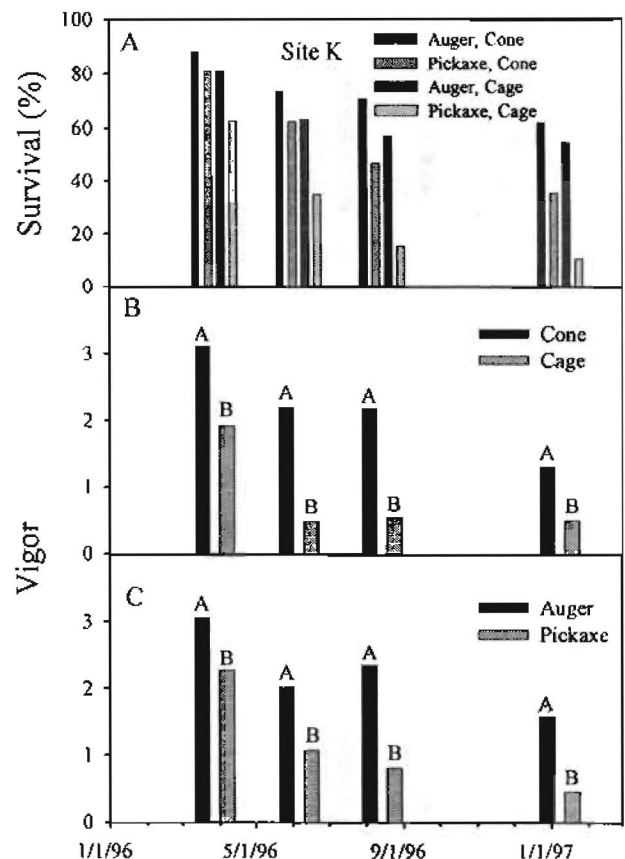


Fig. 2. Time course of survival (A) and vigor (B) of mesquite plants at Site K in the western Mojave Desert. Means associated with different letters within evaluation dates are different at  $P = 0.05$ .

tarium (L.) L'Hér] that could provide alternative forage for herbivores. Nonetheless, new leaves and shoots of honey mesquite were intensely grazed by indigenous herbivores with a subsequent decline in vigor in January 1997 (Fig. 2).

### Experiment II—Test of Species by Site

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

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

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

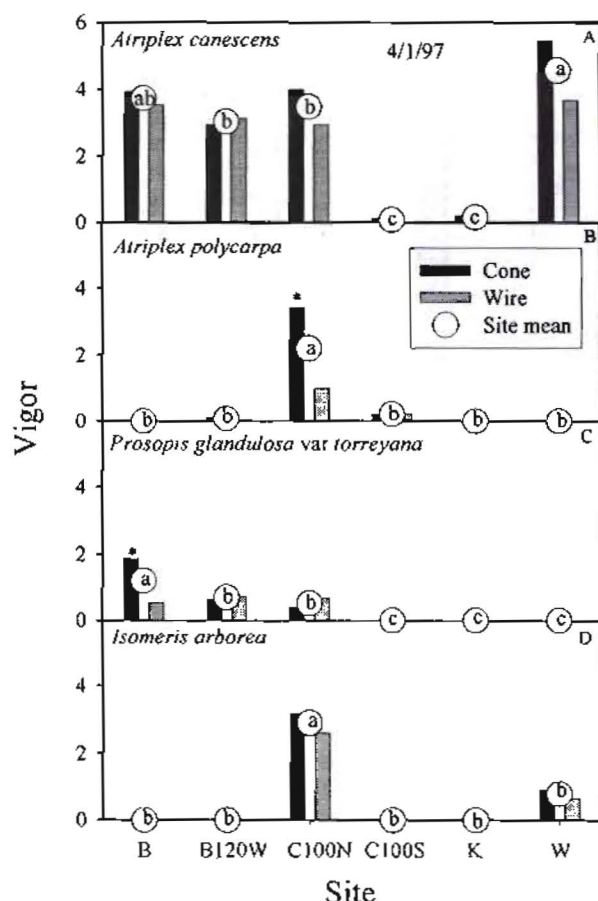


Fig. 3. Mean vigor of individual shrub species treated with plastic cones or wire cages for herbivory protection and species site means (bars and circles, respectively) on the April 1997 evaluation date. Site means associated with different letters are different at  $P = 0.05$ . Herbivory protection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

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

The six sites represented a range of soil types (Table 1) and land use history. Sites B120 W and C100S had land use histories similar to Site K, with alfalfa in rotation with small grains and sugar beet (*Beta vulgaris* L.) (J. Santos, 1997, personal communication). Site B was used for strip cropping of dryland barley (*Hordeum vulgare* L.) between 1948 and 1989 (B. Barnes, 1997, personal communication). Soil amendments, other than grain stubble, were not added at this site. Site C100N had not been subjected to agriculture in recent decades

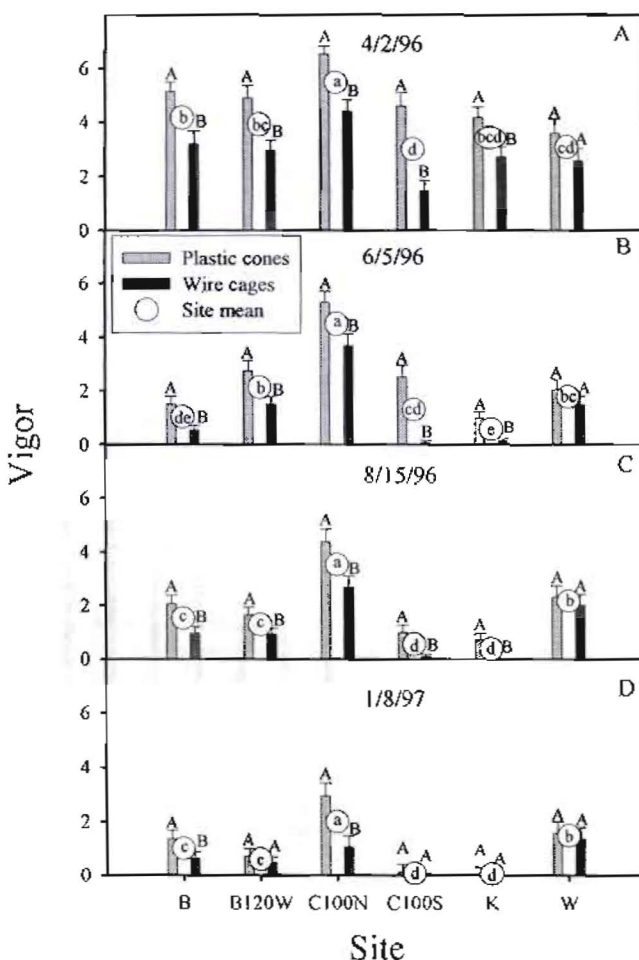


Fig. 4. Mean vigor of the four shrub species in Fig. 3, treated with plastic cones or wire cages for herbivory protection and site means (bars and circles, respectively) on four dates at six sites in the Antelope Valley. Means associated with different letters within a site and date are different at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

as mature saltbush scrub existed here prior to a natural wildfire in the winter of 1995 to 1996. The significant site differences in plant vigor (Fig. 3) are attributed largely to edaphic factors associated with disturbance arising from contrasting agriculture practices. The proximity of the sites suggests similar aerial environmental conditions.

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



Table 4. Mean ammonium ( $\text{NH}_4$ ) and nitrate ( $\text{NO}_3$ ), bacterial counts, and hyphae fungal lengths ( $\text{g soil}^{-1}$ ) for the soil surface layer (0–10 cm) on 19 Apr. 1996 (Exp. II).

Site	Mean $\text{NH}_4$	Mean $\text{NO}_3$	Bacteria	Fungal hyphae
	$\text{mg kg}^{-1}$	$\text{mg kg}^{-1}$	$10^6 \text{ g}^{-1}$	$\text{m g}^{-1}$
C100S	1.23ab	7.76a	34a	0.65c
K	1.62ab	4.16b	87a	0.39c
B	0.79ab	0.41c	75a	0.72c
C100N	1.92a	1.54bc	95a	2.66a
W	0.22b	0.35c	94a	1.06bc
B120W	0.66ab	0.60c	92a	0.70c

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

1995 prior to transplanting, and exhibited the highest concentration of  $\text{NH}_4\text{-N}$ , with low  $\text{NO}_3\text{-N}$  (Table 4) in the upper soil profile. This site also exhibited the most abundant fungal hyphae and bacterial populations of the six locations (Table 4). These soil samples were taken from areas between the plants where no mulch was applied. Plant vigor was not affected by mulch treatment at this site on any evaluation date.

Site C100S was imbedded in an area that had undergone decades of agriculture (flood irrigated alfalfa/small grain). No seeded shrubs had become established in the earlier experiments, and the area had subsequently become covered with the invasive annual species, tumble mustard (*Sisymbrium altissimum* L.). This site exhibited the highest  $\text{NO}_3\text{-N}$  concentrations and low bacterial populations, with few fungal hyphae present (Table 4). Survival and vigor of all transplanted species at this site declined steadily. By April 1997 evaluation, there were only two surviving individuals (of the 30 initial) of all-scale saltbush and one of fourwing saltbush.

Plant survival and vigor at Site K (small plot) was as poor as at Site C100S (Fig. 3). This site, adjacent to site K (Exp. I), had been cropped to alfalfa and in 1994 volunteer alfalfa plants emerged. The higher  $\text{NH}_4$  concentration observed at this site (Table 4) may reflect remnant root biomass, though as at Site C100S, the soil had relatively high concentrations of  $\text{NO}_3\text{-N}$  and little fungal hyphae. The average  $\text{NO}_3$  concentration at these two sites was  $5.96 \text{ mg kg}^{-1}$ , compared with an average of  $0.73 \text{ mg kg}^{-1}$  over the other four sites. High N availability is often conducive to establishment of invasive, fast-growing, nitrophilic species (West, 1991) such as *S. altissimum*, a vigorous competitor that does not form mycorrhizal associations (E.B. Allen, 1997, personal communication).

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

## CONCLUSIONS

The high rate of plant mortality observed over two consecutive years of low but not atypical precipitation,

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

## ACKNOWLEDGMENTS

The authors acknowledge L. Lippett of the California Department of Forestry for expert assistance in nursery production of the plant material used in this research, P. Kindig and B. Barnes for generous use of their land, and E.B. Allen and M. Zeldin for many helpful discussions. This work was funded by the California Air Resources Board under contract no. 94-337. This paper has been reviewed by the staff of the California Air Resources Board and has been approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Air Resources Board, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

## REFERENCES

- Allen, E.B. 1991. Temporal and spatial organization of desert plant communities. p. 193–208. In J. Skujinš (ed.) *Semiarid lands and deserts: Soil resource and reclamation*. Marcel Dekker, New York.
- Allen, M.F. 1988. Belowground structure: A key to reconstructing a productive arid ecosystem. p. 113–135. In E.B. Allen (ed.) *The reconstruction of disturbed arid lands*. Westview Press, Boulder, CO.
- Allen, M.F., and M.G. Boosalis. 1983. Effects of two species of VA mycorrhizal fungi on drought tolerance of winter wheat. *New Phytol.* 93:67–76.
- Allen, M.F., and J.A. MacMahon. 1985. Impact of disturbance on cold desert fungi: Comparative microscale dispersion patterns. *Pedobiologia* 28:215–224.
- Anderson, J.R., and J.M. Slinger. 1975. *Euromiumchelate and fluores-*



- cent brightener staining of soil propagules and their photomicrographic counting. *Soil Biochem.* 7:205–215.
- Bainbridge, D.A., M. Fidelibus, and R. MacAller. 1995. Techniques for plant establishment in arid ecosystems. *Restoration Manage. Notes* 13(2):190–197.
- Bainbridge, D.A., N. Sorensen, and R.A. Virginia. 1993. Revegetating desert plant communities. p. 21–26. *In* T. Landis (coord.) *Proc., Western Forest Nursery Assoc. Meet., Fallen Leaf Lake, CA.* USDA Forest Service Gen. Tech. Rep. GTR RM-221.
- Bainbridge, D.A., and R.A. Virginia. 1990. Restoration in the Sonoran Desert of California. *Restoration Manage. Notes* 8(1):3–14.
- Bilbro, J.D., and D.W. Fryrear. 1995. Techniques for controlling fugitive dust emissions generated on cultivated land by the wind. Paper 95-MP12.01. *Air and Waste Manage. Assoc. Annu. Meet., Nashville, TN.* 18–23 June 1995. *Air and Waste Management Assoc., Pittsburgh, PA.*
- Bleak, A.T., N.C. Frischnecht, A.P. Plummer, and R.E. Eckert. 1965. Problems in artificial and natural revegetation of the arid shadscale vegetation zone of Utah and Nevada. *J. Range Manage.* 18:49–65.
- Boyer, J.S. 1985. Water transport. *Annu. Rev. Plant Physiol.* 36: 473–516.
- Carpenter, D.E., M.G. Barbour and C.J. Bahre. 1986. Old field succession in Mojave Desert scrub. *Madroño* 33(2):111–122.
- Connors, K., and T.A. Zink. 1994. Europium staining for soil ecosystems disturbance evaluation. *Restoration Manage. Notes* 12(2): 211–212.
- Cox, J.R., H.L. Morton, T.N. Johnson, G.L. Jordan, S.C. Martin, and L.C. Fierro. 1982. Vegetation restoration in the Chihuahuan and Sonoran Deserts of North America. *Agric. Res. and Manuals* no. 28. USDA Agric. Res. Serv., Tucson, AZ.
- Farber, R., B. Kim, L. Ashbaugh, D.A. Grantz, D.L. Vaughn, E. Roberts, T. Zink, D. Bainbridge, T. VanCuren, J. Watson, B. Dean, and R. Campbell. 1996. PM10 Air quality and micrometeorological measurements in Southern California's West Mojave Desert Antelope Valley. Paper no. 96-TP49A.06. *Air and Waste Management Assoc. Annu. Meet., Nashville, TN.* June 1996. *Air and Waste Management Assoc., Pittsburgh, PA.*
- Grantz, D.A., D.L. Vaughn, R. Farber, B. Kim, M. Zeldin, E. Roberts, L. Ashbaugh, T. VanCuren, J. Watson, B. Dean, P. Novack, R. Campbell, D. Bainbridge, and T. Zink. 1998. Seeding native plants to restore desert farmland and mitigate fugitive dust/PM<sub>10</sub>. *J. Environ. Qual.* (In press.)
- Harley, J.L., and S.E. Smith. 1983. *Mycorrhizal symbiosis.* Academic Press, New York.
- Hickman, J.C. (ed.). 1993. *The Jepson manual: Higher plants of California.* Univ. of California Press, Berkeley.
- Horn, H.S. 1974. The ecology of secondary succession. *Annu. Rev. Ecol. Syst.* 5:25–37.
- Jackson, L.L., J.R. McAuliffe, and B.A. Roundy. 1991. Desert restoration. *Restoration Manage. Notes* 9(2):71–80.
- Keeney, D.R. 1982. Nitrogen—Available indices. p. 711–733. *In* A.L. Page et al. (ed.) *Methods of soil analysis. Part 2.* SSSA, Madison, WI.
- McAuliffe, J.R. 1986. Herbivore-limited establishment of a Sonoran Desert tree, *Cercidium microphyllum*. *Ecology* 67(1):276–280.
- Powell, D.L. 1980. Mycorrhizal infectivity of eroded soils. *Soil Biol. Biochem.* 12:247–250.
- Romney, E.M., A. Wallace, and R.B. Hunter. 1987. Transplanting of native shrubs on disturbed land in the Mojave Desert. p. 50–53. *In* A. Wallace et al. (ed.) *Symp. on Shrub Ecophysiology and Biotechnology,* Logan, UT. 30 June–2 July 1987. USDA For. Serv. Gen. Tech. Rep. INT-256.
- Rundel, P.W., E.T. Nilsen, M.R. Sharifi, R.A. Virginia, W.M. Jarrell, D.H. Kohl, and D.B. Shearer. 1982. Seasonal dynamics of nitrogen cycling for a *Prosopis* woodland in the Sonoran Desert. *Plant Soil* 67:343–353.
- SAS Institute. 1988. *SAS/STAT user's guide.* SAS Inst., Cary, NC.
- Shanan, L., N.H. Tadmor, M. Evenari, and P. Reingier. 1970. Microcatchments for improvement of desert range. *Agron. J.* 62:445–448.
- Shearer, G.D., D.H. Kohl, R.A. Virginia, B.A. Bryan, J.L. Skeeters, E.L. Nilsen, M.R. Sharifi, and P.W. Rundel. 1983. Estimates of N<sub>2</sub> fixation from variation in natural abundance of <sup>15</sup>N in Sonoran Desert ecosystems. *Oecologia* 56:365–373.
- Sprent, J.I. 1987. Problems and potentials for nitrogen fixation in deserts. p. 1049–1062. *In* E.E. Whitehead et al. (ed.) *Arid lands: Today and tomorrow.* Westview Press, Boulder, CO.
- Trappe, J.M. 1981. Mycorrhizae and productivity of arid and semi-arid rangelands. p. 581–599. *In* J.T. Manassah and E.J. Briskey (ed.) *Advances in food producing systems for arid and semi-arid lands.* Academic Press, New York.
- Trent, J. 1993. Rhizosphere formation and hydraulic lift in Indian rice grass: Rhizosphere composition and nitrogen fixation. Ph.D. diss. San Diego State Univ., San Diego in conjunction with Univ. of California, Davis.
- U.S. Department of Agriculture. 1970. Soil survey, Antelope Valley area, CA. SCS-USDA, Washington, DC.
- Virginia, R.A., and D.A. Bainbridge. 1987. Revegetation in the Colorado Desert: lessons from the study of natural systems. p. 52–63. *In* J.P. Rieger and B.K. Williams (ed.) *Proc. of the 2nd Native Plant Revegetation Symp. Society for Ecological Restoration and Management,* Madison, WI.
- Virginia, R.A., W.M. Jarrell, W.G. Whitford, D.W. Freckman, and M.R. Jenkins. 1989. Response of Chihuahuan Desert mesquite dunes to supplemental water. *Bull. Ecol. Soc. Am.* 70:287–288.
- West, N.E. 1981. Nutrient cycling in desert ecosystems. p. 301–324. *In* D.W. Goodall and R.A. Perry (ed.) *Arid-land ecosystems: Structure, functioning, and management.* Vol. 2. Cambridge University Press, Cambridge.
- West, N.E. 1989. Spatial pattern-functional interactions in shrub dominated plant communities. p. 283–305. *In* C.M. McKell (ed.) *The biology and utilization of shrubs.* Academic Press, San Diego.
- West, N.E. 1991. Nutrient cycling in soils of semiarid and arid regions. p. 295–332. *In* J. Skujinš (ed.) *Semiarid lands and deserts: Soil resource and reclamation.* Marcel Dekker, New York.
- Whitford, W.G., E.F. Aldon, D.W. Freckman, Y. Steinberger, and L.W. Parker. 1989. Effect of organic amendments on soil biota of a degraded rangeland. *J. Range Manage.* 42:56–60.
- Zink, T.A. 1994. The effects of recalcitrant organic amendment on disturbed coastal sage and creosote scrub habitats of Southern California. M.S. thesis. San Diego State Univ., San Diego, CA.

# Plant and Environment Interactions

## Seeding Native Plants to Restore Desert Farmland and Mitigate Fugitive Dust and PM<sub>10</sub>

David A. Grantz,\* David L. Vaughn, Rob Farber, Bong Kim, Mel Zeldin, Tony VanCuren, and Rich Campbell

### ABSTRACT

Windblown fugitive dust contributes to violations of air quality standards for particulate matter <10  $\mu\text{m}$  aerodynamic diameter (PM<sub>10</sub>). In the western Mojave Desert of California, approximately 1070 ha of previously tilled or over-grazed land impacted downwind metropolitan areas by wind-driven emissions of dust. A protocol of furrowing across the wind and direct seeding of three native perennial shrubs and a bunch grass helped reduce fugitive dust emissions in this area by more than 95%. Seeded species varied from 35 to 97% of living plant cover in individual years, reflecting rainfall patterns. In areas of deep sand, Indian ricegrass (*Achnatherum hymenoides* Roemer & Shultes) outperformed the shrubs, while fourwing saltbush [*Atriplex canescens* (Pursh) Nutt.] exhibited the most widespread establishment. This revegetation was achieved in an anomalous year with above average and late rainfall that eliminated early competition from annual species and later fostered abundant shrub growth. This success was not reproducible in more normal years, when minimal disturbance protocols such as broadcasting of seed on the untilled soil surface were as effective and less costly. We conclude: (i) direct seeding can lead to plant establishment in favorable years, but is likely to fail in any given year, (ii) direct seeding should be implemented with little soil disturbance, (iii) the native fourwing saltbush is the most likely species to become established in this environment, and (iv) unpredictable rainfall and temperature require that direct seeding be backed up with alternative strategies to achieve reliable dust and PM<sub>10</sub> mitigation in arid environments.

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 groundwater 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 1980s and early 1990s, seasonally high winds created dust storms that contributed to repeated violations of the PM<sub>10</sub> national ambient air quality standards in downwind urban areas (e.g., Lancaster, CA; South Coast Air Quality Management District, 1989, 1990, 1991, unpublished data). 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 erodible 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.

Favorable conditions for natural plant establishment occur once every 7 to 15 yr on the arid salt desert shrublands of the North American Great Basin (Bleak et al., 1965) and once in 4 yr 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 yr (Cox et al., 1982). While secondary succession may result in mature Mojave Desert creosote bush scrub within approximately 65 yr (Carpenter et al., 1986), it may take up to 180 yr for recovery of species diversity in severely disturbed sites (Webb et al., 1983). Thus, reliance in restoration programs on rainfall and direct seeding in these areas will fail in most years (Jackson et al., 1991).

Full recovery of vegetation to a pre-disturbance condition is hindered by the permanent changes imposed by agriculture. The preexisting network of ephemeral streams in this area 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 substantially altered the physical and biotic characteristics of the edaphic environment, including substantially reducing populations of important symbionts such as vesicular-arbuscular mycorrhizal fungi (Bainbridge, 1993; Bainbridge and Virginia, 1990). Irreversible changes in hydrology (surface and groundwater) and

D.A. Grantz and D.L. Vaughn, Univ. of California at Riverside, Kearney Agric. Center, 9240 S. Riverbend Ave., Parlier, CA 93648; R.J. Farber, Southern California Edison Company, P.O. Box 800, Rosemead, CA 91770; B. Kim and M. Zeldin, South Coast Air Quality Management District, 21865 E. Copley Dr., Diamond Bar, CA 91765; T. VanCuren, California Air Resources Board, 2020 L Street, Sacramento, CA 95812; R. Campbell, Antelope Valley Resource Conservation District, 44811 Date Avenue, Suite no. G, Lancaster, CA 93534. Received 19 Feb. 1997. \*Corresponding author (david@uckac.edu).

the widespread establishment of exotic plant species (e.g., Russian thistle, *Salsola pestifer*) also contribute to difficulties in restoration to a pre-disturbance condition.

In February 1992, with funding from the USDA Soil (now Natural Resources) Conservation Service (NRCS), an 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<sub>10</sub> 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 broadcast of slowly developing but sustainable native perennial shrubs.

Here 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.

## MATERIALS AND METHODS

This study incorporates results of three distinct experiments. First, the EWP program 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 program, 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 lat, and between 118°17'50" and 118°20'43" W long, with a mean elevation of approximately 760 m. Soils were of the

Rosamond (fine-loamy, mixed [calcareous], thermic Typic Torrifluvents) and Hesperia (coarse-loamy, mixed, nonacid, thermic Xeric Torriorthents) 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 disturbing 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 1) 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, a perennial bunchgrass widespread throughout rangelands of the western USA, and well adapted to sandy soils in temperate deserts (Young et al., 1994), was also drilled along with the barley in the furrow bottoms.

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, and 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 (Bonham, 1989, p. 25–26) 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; Bonham, 1989, p. 119–123) 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

**Table 1. Plant species, planting methods, and seeding rates used in the Emergency Watershed Protection program (EWP).**

Scientific name	Common name	Seeding method	Seeding rate† kg ha <sup>-1</sup>
<i>Atriplex canescens</i>	Four wing saltbush	Aerial‡	0.73
<i>Atriplex polycarpa</i>	Allscale saltbush	Aerial	0.73
<i>Eriogonum fasciculatum</i>	California buckwheat	Aerial	0.55
<i>Eschscholzia californica</i>	California poppy	Aerial	0.1
<i>Achnatherum hymenoides</i> cv. Paloma	Indian ricegrass	Ground§	1.1
<i>Hordeum vulgare</i> cv. Seco or Solum	Barley	Ground	0.3

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

‡ Broadcast by helicopter.

§ Drilled in furrow bottoms.



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 3-yr period.

### Control Areas for 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, a fine-loamy, mixed, thermic Typic Haploxeralf) 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 to 1996 a control site closer to the EWP area was established. A large (183 by 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 by 183 m. Treatments were chosen to represent a range of candidate approaches to stabilizing these abandoned farmlands (Table 2), including evaluation of the individual components of the combination EWP protocol. These included nondisturbing (burning existing vegetation and broadcasting seed), minimally disturbing (burning and rangeland drilling seed), and highly disturbing (ripping, furrowing, and drilling seed) treatments. Four of these eight treatments (treatments 3, 4, 5, and 6) used the same seed mixture (similar to that used in the EWP), with pure live seed applied at 0.40 (fourwing saltbush), 0.26 (allscale saltbush, *Atriplex polycarpa*), 0.27 (California buckwheat, *E. fasciculatum*), and 0.20 kg ha<sup>-1</sup> (rubber rabbitbrush, *Chrysothamnus 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. 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; p. 144–147).

To evaluate a broader range of vegetation than could be accommodated in LP, nine plant species were seeded in a 3 × 3 Balanced Lattice Design (nine treatments in incomplete blocks of three experimental units, with four replications yielding 36 plots per location; Cochran and Cox, 1957). Experimental units (plots) were 2 by 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 four locations, two with loamy and two with sandy soils in March 1994, and two additional lattices (one irrigated with 0.8 cm weekly for 3 wk) at each location in November 1994.

The species used were those in the EWP program (fourwing saltbush, allscale saltbush, Indian ricegrass, and California buckwheat) plus rubber rabbitbrush and red brome, *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, creosote bush [*Larrea tridentata* (DC.) Cov.], a large perennial shrub native to the area, and asexually propagated vetiver (*Vetiveria zizanioides*), a subtropical grass used to control soil erosion by water (National Research Council, 1993). Vetiver, 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 GP, with or without irrigation.

### Fugitive Dust

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). 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 diam. 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).

Table 2. 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.†
3	Ripped, furrowed, and drilled with the seed mix.†,‡
4	Ripped, furrowed, and drilled seed in strips, one pass across the wind at 50, 100, and 150 m from the upwind edge of plot.§
5	Broadcasted the seed mix without tillage.‡
6	Rangeland drilled the seed mix.‡
7	Rangeland drilled <i>Bromus rubens</i> .
8	Rangeland drilled the seed mix in a pattern of intersecting strips; seed 1 pass, skip 2 in both directions.

† Emergency Watershed Protection program (EWP) specifications required ripping to a minimum of 0.3 m deep and between 0.46 to 0.51 m wide (shank separation), and furrowing 0.91 to 1.02 m wide (furrow centers).

‡ Seed mix differed from that used in the EWP (cf. Table 3).

§ Strip width was 5.5 m.

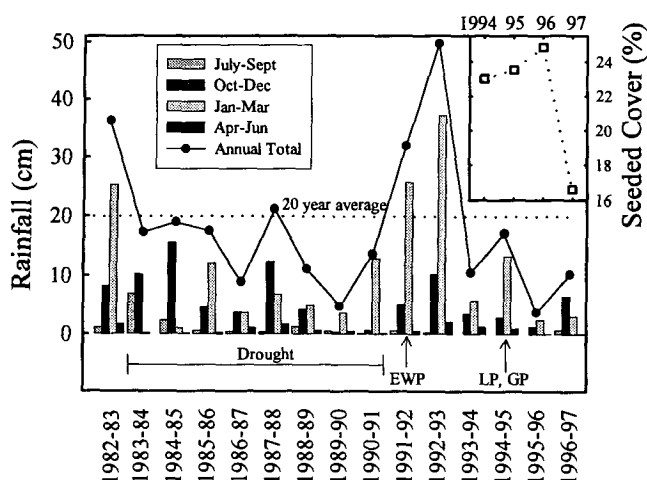


Fig. 1. Quarterly (bars) and annual total (solid circles) rainfall at Lancaster, CA, from July 1982 through June 1997. The prolonged drought, and time of installation of the Emergency Watershed Protection (EWP) program, and of the large plots (LP) and common garden plots (GP) are shown. The total percent of ground area covered by the directly seeded shrub species declined following a period of low rainfall (inset).

## RESULTS AND DISCUSSION

### Revegetation in the Emergency Watershed Protection

Immediately following establishment of the EWP in February 1992, abundant rainfall (200% of normal) was received (Fig. 1) 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 emissions (Table 3). Between 1992 and 1995 exceedances of the California state standard for  $PM_{10}$  ( $50 \mu g m^{-3}$ , 24 h avg.) at the Lancaster monitoring site were reduced to only five exceedance days per year on average, compared with 25, 22, and 11 d in the preceding 3 yr. 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. 1 and inset). The differences in percent cover of seeded perennial species observed between the years 1995 and 1997

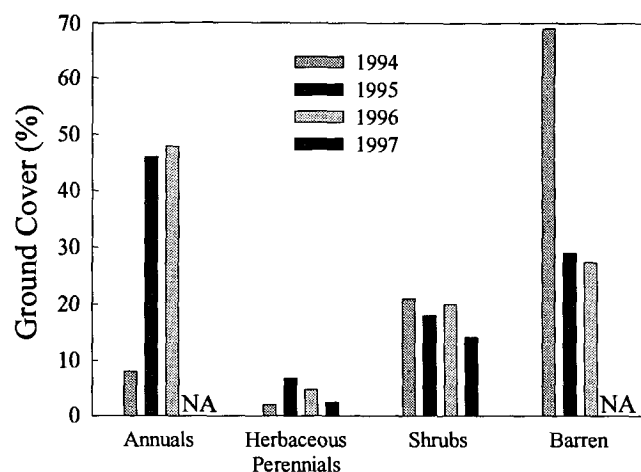


Fig. 2. Percent of the ground surface covered by plant type or barren soil averaged over 4 yr and all areas of the Emergency Watershed Protection (EWP) program. (NA, data not available).

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. 2), 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 fourwing saltbush and gray ephedra (*Ephedra nevadensis* S. Watson) averaged  $46 \pm 3.8\%$ . The barren areas observed in 1994 were mostly ( $>66\%$ )  $<2.0$  m in length, with only 6%  $>8.0$  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.

The plant cover observed in the EWP area in 1994 consisted of the seeded woody shrubs fourwing saltbush (7%), allscale saltbush (7%), and the smaller but more numerous California buckwheat (7%), with about 2% cover attributed to the seeded perennial bunchgrass, Indian ricegrass, and 8% annual species, including the invasive Russian thistle (6%). The seeded California poppy, though observed in 1992, was uncommon in the EWP area by 1994, with no intercepts on any transect.

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*

Table 3. Mass of fugitive dust collected at 1.0 m height downwind of the emergency watershed protection (EWP) program 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  $15 m s^{-1}$ .

Collection period Year (DOY)	Mean wind velocity	Maximum wind gust	Sampler height	Dust collected		Control at EWP
				Control	EWP	
				g		
<hr/>						
	m s <sup>-1</sup>		m			%
1992 (105–112)	4.0	20.5	1.0	75.1†	0.38	99.5
1994 (136–155)	4.2	19.7	1.0	0.05‡	0.003	94.1
1995 (155–162)	4.15	19.6	1.0	0.54‡	0.01	82.0
1996 (97–104)	5.23	24.4	1.0	0.81‡	0.026	96.8

† 1992 control was a naturally occurring barren area upwind of the EWP site.

‡ 1994 to 1996 control was a plot at Site K kept barren by removing annual vegetation as necessary by burning or light disking.

and *Schismus* spp. This was accompanied by a proportional decrease in barren area, while shrub covered area decreased slightly (Fig. 2). 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. 2) is of particular note. In contrast to the rainfall in 1994–1995 (86% of normal), in 1995–1996 rainfall was meager (19% of normal) and poorly timed, falling early in the season (Fig. 1). 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 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, nonliving but still standing biomass contributes substantially to stabilizing the surface against wind erosion (Wolfe and Nickling, 1993).

A significant ( $P < 0.02$ ) time  $\times$  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. 3). On average, adequate establishment of the four seeded perennial species occurred across the EWP area, though Indian ricegrass 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 allscale saltbush was much slower to establish than fourwing saltbush. The smaller statured California buckwheat 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 inter-

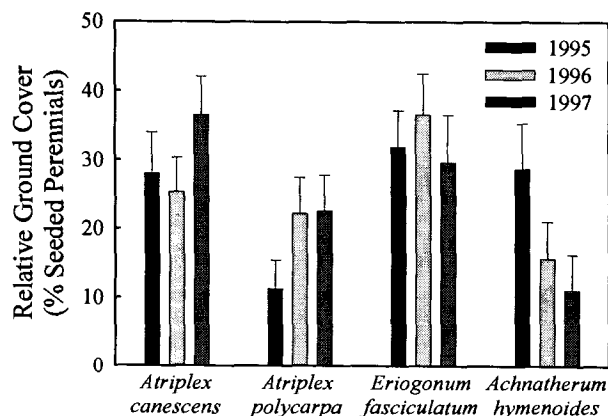


Fig. 3. Ground cover by seeded perennial species relative to the total area covered by all seeded perennial species, averaged over all areas of the Emergency Watershed Protection (EWP) program.

actions 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 1995–1996 winter contributed to the death of many small (height  $< 0.5$  m) individuals of fourwing saltbush as initially larger shrubs outcompeted the smaller individuals. Between 1994 and 1996 the relative composition of the *Atriplex* spp. generally increased while that of *Eriogonum* and *Achnatherum* spp. declined (Fig. 3).

Variability in shrub cover between individual transects within the EWP area was associated with differences in soil classification (Fig. 4 and 5A) and soil fertility and microbiology (Fig. 5B, 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 effect 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  $\times$  plant species interaction ( $P < 0.01$ ). *Eriogonum* spp. performed significantly better on the Rosamond fine sandy loam and *Achnatherum* spp. significantly better on the Rosamond loamy fine sand than on other soil types. Time averaging reduced between-species differences to a nonsignificant level. When the time factor was specifically included, the significant three-way interaction of time  $\times$  species  $\times$  soil type demonstrated that the changes in vegetative

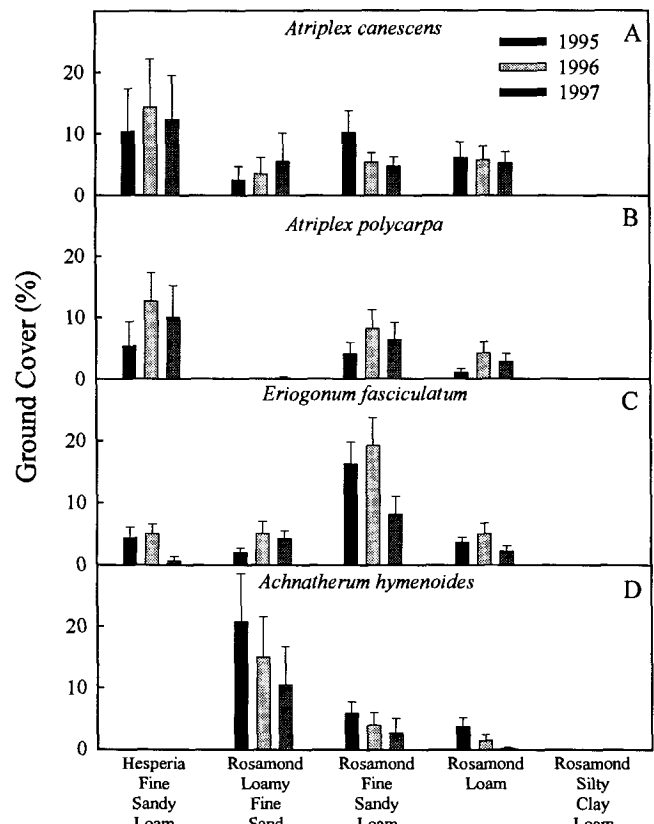


Fig. 4. Percent of the ground surface covered by individual seeded species by soil type within the Emergency Watershed Protection (EWP) area (bars not visible are near zero).

ground cover with time differed between species in different soil types (Fig. 4).

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 Indian ricegrass was restricted to these sandy areas, where it outperformed all other seeded species (Fig. 4D). No transect intercepts were encountered with allscale saltbush on sand, though fourwing saltbush 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* spp. performing best on the Hesperia series (Fig. 4A, B) and California buckwheat competing best on the Rosamond series soils (Fig. 4C).

Within the EWP area sites with these two predominant soils contained the lowest concentrations of residual nitrogen (Fig. 5B) from previous agricultural amendments and the highest concentrations of fungal hyphae ( $0.70$  and  $1.30 \text{ m g}^{-1}$ , respectively; Fig. 5C) and of bacteria ( $9.2$  and  $9.4 \times 10^7 \text{ g}^{-1}$ , respectively; Fig. 5D). 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 cy-

cling (West, 1991). In the heavier soil, Rosamond silty clay loam, none of the seeded species became established (Fig. 4), and the soil had much lower concentrations of fungal hyphae ( $0.3 \text{ m g}^{-1}$ ) and bacteria ( $3.4 \times 10^7 \text{ g}^{-1}$ ). 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. 5). 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 tumble mustard.

### Evaluation of Alternative Stabilization Strategies

The direct seeding protocol used in the EWP was repeated in LPs and approximated in small common GPs, 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 LP locations (Sites B and K), and at all GP 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 three LP 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. 6; 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. 6; Panels A–D), of any protocol tested. In February 1996, California buckwheat exceeded  $6000 \text{ plants ha}^{-1}$  on this plot, approximately 6 cm tall, though later the density decreased substantially (Fig. 6C) with below average rainfall (Fig. 1). Establishment of the annual species tumble mustard 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 California buckwheat, allscale saltbush, and rubber rabbitbrush, but higher densities of fourwing saltbush than in the

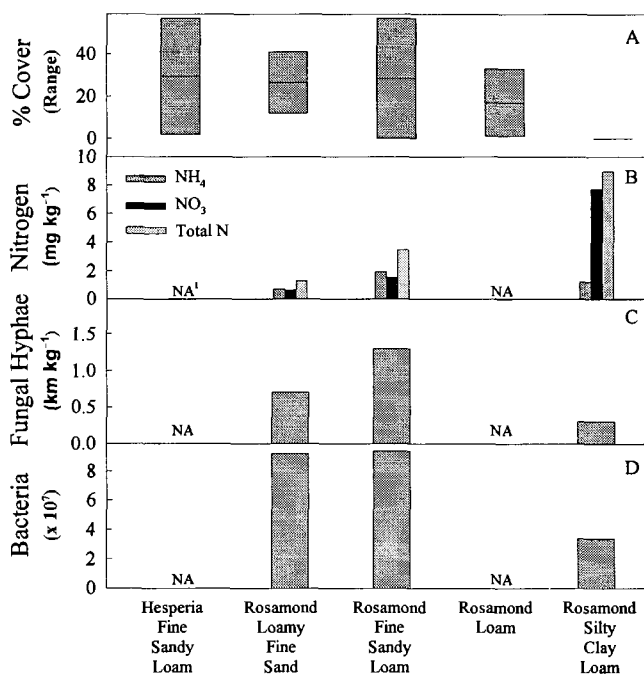


Fig. 5. (A) Variability in total plant cover (horizontal lines, mean; bars, range) between transects within each soil type in the Emergency Watershed Protection (EWP); (B) soil and abundance of ammonium, nitrate, and total N; (C) soil fungal biomass; and (D) soil bacterial populations. (NA, data not available).

broadcast treatment (Fig. 6). 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 fourwing saltbush in this relatively nondisruptive 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. 6), 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 red brome, cheatgrass (*B. tectorum* L.), and *Schismus* spp., resulted in a dense population of annual species.

Rangeland drilling the seed mix in intersecting strips resulted in areas with no seed, and areas with one- and two-fold the normal seeding rate, with corresponding resultant plant densities. Areas receiving no seed (and no disturbance; Fig. 7A) 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. 7B) excellent establishment of fourwing saltbush was obtained, along with moderate establishment of the other shrubs, with only moderate invasion by annual seedlings. Areas receiving

the twofold rate (Fig. 7C) attained seeded shrub densities (primarily fourwing saltbush) that were very high, along with nearly complete suppression of annual species. While all four shrub species used in the seed mix except rubber rabbitbrush 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 rubber rabbitbrush 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. 7A).

The most successful establishment of this shrub at Site G occurred on the control plot and in the nonseeded 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. 6). The natural establishment of this species in these areas was attributed to seed that was blown in from an adjacent undisturbed area with a natu-

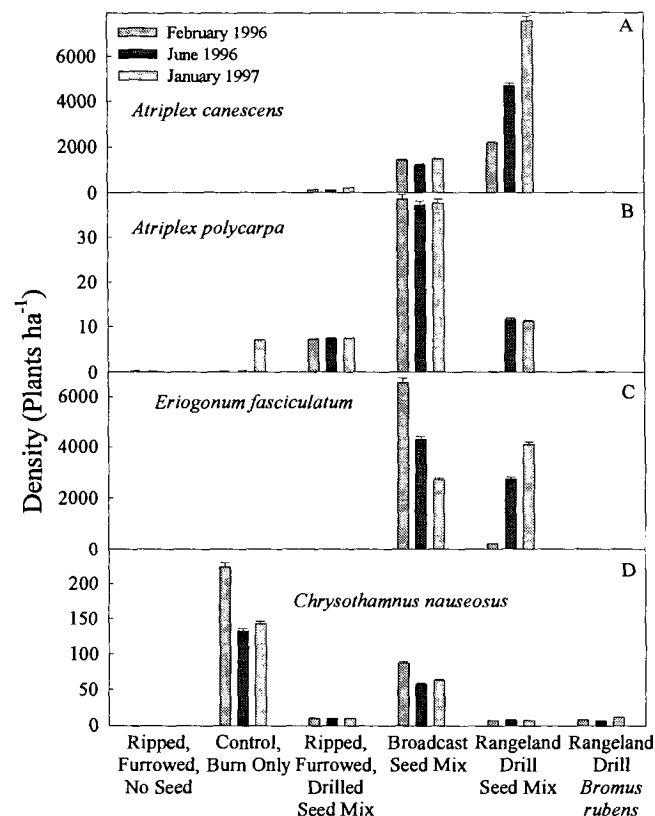


Fig. 6. Plant density of individual seeded perennial species (A–D) at Site G resulting from the six contrasting fugitive dust stabilization protocols, on three sample dates. (Bars not visible are near zero).

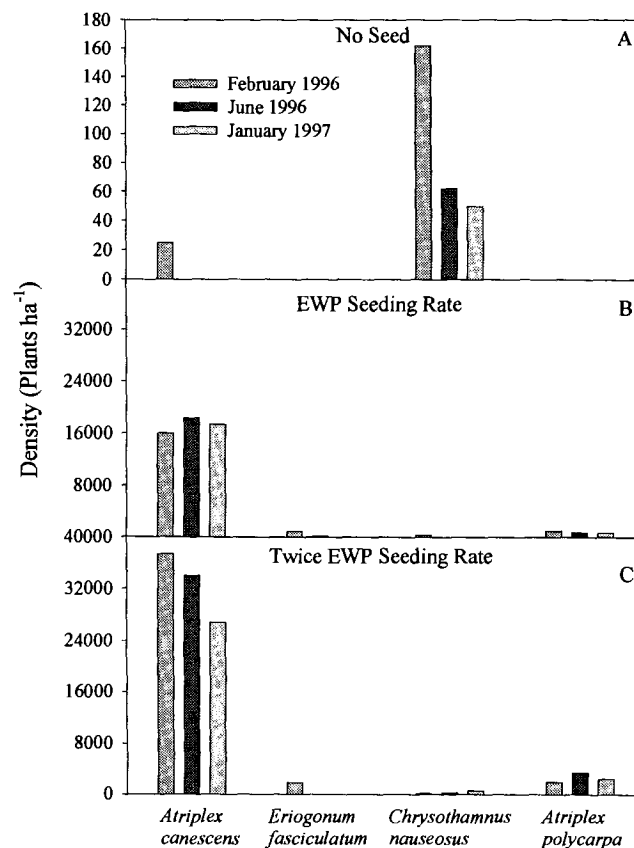


Fig. 7. Effect of seeding rate (A–C) on plant density of the four individual seeded perennial species at Site G. The plot was burned and received no seed (A) except in strips that received the Emergency Watershed Protection (EWP) seeding rate (B) or twice this rate (C) where perpendicular seeded strips intersected. (Bars not visible are near zero).

ral rabbitbrush density of  $3083 \pm 79$  plants  $\text{ha}^{-1}$ . 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. 6D) 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. 6D), even though they were also downwind of the natural seed source.

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. 8). 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 3 yr in the ripped and furrowed EWP area did not encounter a single individual of rubber rabbitbrush, though the species is ubiquitous in surrounding areas. During revegetation along the Los Angeles aqueduct (Kay, 1979) 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.

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, 1997, 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 allscale

saltbush. 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 Emergency Watershed Protection

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 3) is attributed principally to tillage across the wind, before significant shrub establishment.

The ripping component of the EWP protocol brought nonerodable soil aggregates to the surface, thereby increasing surface roughness and providing wind-sheltered areas in which moving particles were trapped (Bilbro 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 shear 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.

During 1994–1996 several factors (Grantz et al., 1996) combined to result in low levels of fugitive dust emissions from the EWP area (Table 3). 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. 1). 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

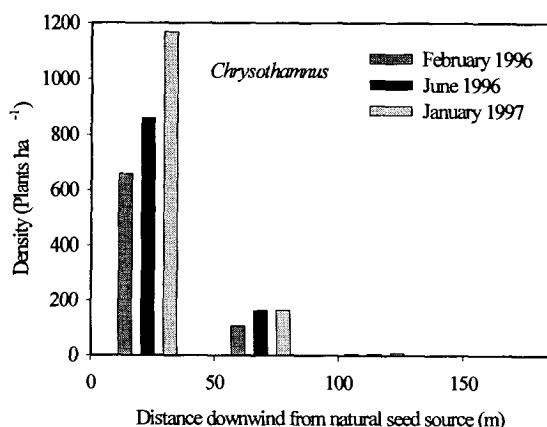


Fig. 8. Plant density of rubber rabbitbrush at Site G in the burned but unseeded areas between three parallel strips receiving the Emergency Watershed Protection (EWP) protocol, as a function of distance from a natural upwind seed source. (Bars not visible are near zero).



by more than 80% (Table 3). During periods of lower wind speed (not shown) smaller dust samples were more variable but suggested similar levels of control.

## CONCLUSIONS

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 outcompete 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, fourwing saltbush was the shrub species most likely to become established. While allscale saltbush performed adequately in most soil types, in sandy soils only fourwing saltbush 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, generally nonvegetative protocols in arid environments.

## ACKNOWLEDGMENTS

This work was supported by the California Air Resources Board under contract no. 92-347 and the South Coast Air Quality Management District under Contract no. C92155. This paper has been reviewed by the staff of the California Air Resources Board and has been approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the South Coast Air Quality Management District or the Air Resources Board, nor does mention of trade names or commercial products constitute endorsement or recommendation for use. The EWP revegetation program was funded by the U.S. Department of Agriculture, Soil Conservation Service (now Natural Resources Conservation Service) through the Emergency Watershed Protection Program. The authors are grateful to J. Egan for providing the *Vetiveria zizanioides* transplants, to Dr. D.W. Fryrear for providing the

design of the BSNE samplers, and to B. Dean, Herb Spitzer and Clyde Sims of the USDA, NRCS and the Los Angeles County Fire Department for coordinating the EWP installation and providing information on the reseeded protocols.

## REFERENCES

- Allen, M.F. 1988. Belowground structure: A key to reconstructing a productive arid ecosystem. p. 113-135. *In* E.B. Allen (ed.) The reconstruction of disturbed arid lands. Westview Press, Boulder, CO.
- Bainbridge, D.A. 1993. Soil compaction: A critical problem in land restoration. *Land Water* 37(1):42-43.
- Bainbridge, D.A., and R.A. Virginia. 1990. Restoration in the Sonoran Desert of California. *Restoration Manage. Notes* 8(1):3-14.
- Bilbro, J.D., and D.W. Fryrear. 1995. Techniques for controlling fugitive emissions generated on cultivated land by the wind. Paper no. 95-MP12.01. Air and Waste Management Assoc. Annual Meeting, San Antonio, TX. June, 1995. Air and Waste Management Assoc., Pittsburgh, PA.
- Bleak, A.T., N.C. Frischnecht, A.P. Plummer, and R.E. Eckert. 1965. Problems in artificial and natural revegetation of the arid shadscale vegetation zone of Utah and Nevada. *J. Range Manage.* 18:49-65.
- Bonham, C.D. 1989. Measurements for terrestrial vegetation. John Wiley & Sons, New York.
- Call, C.A., and B.A. Roundy. 1991. Perspectives and processes in revegetation of arid and semi-arid rangelands. *J. Range Manage.* 44:543-549.
- Carpenter, D.E., M.G. Barbour, and C.J. Bahre. 1986. Old field succession in Mojave Desert scrub. *Madroño* 33(2):111-122.
- Cochran, W.G., and G.M. Cox. 1957. Lattice designs. p. 396-438. *In* Experimental designs. John Wiley & Sons, New York.
- Cox, J.R., H.L. Morton, T.N. Johnson, G.L. Jordan, S.C. Martin, and L.C. Fierro. 1982. Vegetation restoration in the Chihuahuan and Sonoran Deserts of North America. *Agric. Rev. and Manuals* no. 28. USDA Agric. Res. Serv., Tucson, AZ.
- Farber, R., B. Kim, L. Ashbaugh, D. Grantz, D. Vaughn, E. Roberts, T. Zink, D. Bainbridge, T. VanCuren, J. Watson, B. Dean, and R. Campbell. 1996. PM<sub>10</sub> air quality and micrometeorological measurements in southern California's West Mojave Desert Antelope Valley. Paper no. 96-TP49A.06. Air and Waste Management Assoc. Annual Meet., Nashville, TN. June, 1996. Air and Waste Management Assoc., Pittsburgh, PA.
- Grantz, D.A., D.L. Vaughn, R. Farber, B. Kim, E. Roberts, L. Ashbaugh, J. Watson, B. Dean, R. Campbell, T. VanCuren, T. Zink, and D. Bainbridge. 1996. Stabilizing fugitive dust emissions in the Antelope Valley from abandoned farmlands and overgrazing. Paper no. 96-TP49A.05. Air and Waste Management Assoc. Annual Meeting, Nashville, TN. June, 1996.
- Harley, J.L., and S.E. Smith. 1983. Mycorrhizal symbiosis. Academic Press, New York.
- Jackson, L.L., J.R. McAuliffe, and B.A. Roundy. 1991. Desert restoration. *Restoration Manage. Notes* 9(2):71-80.
- Kay, B.L. 1979. Summary of revegetation attempts on the second Los Angeles aqueduct. *Mojave Revegetation Notes* 22:1-24.
- Krebs, C.J. 1989. Ecological methodology. HarperCollins, New York.
- National Research Council. 1993. Vetiver grass: A thin green line against erosion. National Academy Press, Washington, DC.
- SAS Institute. 1988. SAS/STAT user's guide. SAS Inst., Cary, NC.
- Silcock, R.G. 1986. Strategies for plant introduction and reseeded of semiarid pastoral lands. p. 268-274. *In* P.J. Ross et al. (ed.) Rangelands: A resource under siege. Australian Acad. Sci., Canberra.
- Stout, J.E., and D.W. Fryrear. 1989. Performance of a windblown-particle sampler. *Trans. ASAE* 32(6):2041-2045.
- Trappe, J.M. 1981. Mycorrhizae and productivity of arid and semi-arid rangelands. p. 581-599. *In* J.T. Manassah and E.J. Briskey (ed.) Advances in food producing systems for arid and semi-arid lands. Academic Press, New York.
- U.S. Department of Agriculture. 1970. Soil survey, Antelope Valley Area, CA. Soil Conservation Service, USDA, Washington, DC.
- Webb, R.A., H.G. Wilshire, and M.A. Henry. 1983. Natural recovery of soils and vegetation following human disturbance. p. 279-302. *In* Environmental effects of off-road vehicles. Springer-Verlag New York, New York.

- West, E.W. 1991. Nutrient cycling in soils of semiarid and arid regions. p. 295–332. *In* J. Skujins (ed.) Semiarid lands and deserts: Soil resource and reclamation. Marcel Dekker, New York.
- Wolfe, S.A., and W.G. Nickling. 1993. The protective role of sparse vegetation in wind erosion. *Prog. Phys. Geogr.* 17(1):50–68.
- Young, J.A., R.R. Blank, W.S. Longland, and D.E. Palmquist. 1994. Seeding Indian ricegrass in an arid environment in the Great Basin. *J. Range Manage.* 47:2–7.
- Zeldin, M.D. 1994. Approaches for controlling windblown dust emissions in southern California desert areas. Paper no. 94-FA145.01 presented at the 87th Annual Meeting and Exhibition of the Air and Waste Management Assoc., Cincinnati, OH. 19–24 June 1994.

February through May is the critical time for wind erosion in Kansas, but wind erosion can happen any time when high winds occur on smooth, wide fields with low vegetation and poor soil structure. The loss of soil through blowing dust dramatically decreases the productivity of soils (Li et al., 2007). Dust contains the majority of soil organic matter and fine particulates that allow soils to hold water and nutrients. Dust also can have significant economic, human and animal health, and safety impacts.

The most effective wind erosion control is to ensure a protective cover of residue or growing crop throughout the critical erosion period. Control measures such as strip cropping, residue management, reduced tillage, grass strips, and windbreaks are effective management methods for reducing erosion because they increase the surface roughness or reduce surface wind speeds. However, these prevention methods must be planned at least a season in advance.

Under some conditions, cropland can be quite susceptible to wind erosion. Burning or removing crop residues for forage creates a particularly serious hazard. Winter wheat and other fall-planted crop fields also may be susceptible during periods of low cover in the winter and early spring. This is particularly true after a drought year or after other crop failures. Marginally productive cropland may not produce sufficient residue to provide protection from wind erosion. In addition, overgrazed or poorly vegetated rangeland may be subject to wind erosion.

It is important to monitor field conditions and identify fields with conditions susceptible to erosion. These conditions include low vegetative cover and a high proportion of erodible-sized clods (less than 1 millimeter, or about the thickness of a dime). Treating potential problems before they occur is preferred to reacting after a field is actively eroding. Once soil movement has started, it is difficult to avoid further damage. Prompt action, however, may prevent a small erodible spot from damaging an entire field or adjacent fields.

## Legal Aspects

Kansas law (Kan. Stat. Ann. §2-2001 through 2-2009) addresses wind erosion control. If soil is blowing off any property in quantities large enough to cause erosion damage, damage on land downwind, or injury to the public health, soil blowing must be lessened or stopped. If the landowner cannot or will not stop wind erosion in a timely manner, county commissioners are authorized to have emergency wind erosion control performed (Kan. Stat. Ann. §2-2004). County commissioners can create a soil-drifting fund from which costs of erosion control can be paid. To create the fund, the county commissioners can levy a tax against all taxable tangible personal property of the county. (Kan. Stat. Ann. §2-2007).

Alternatively, the commissioners, after notice and a hearing, can recover the cost of any emergency tillage by levying a special assessment against the land.



**Figure 1.** Emergency tillage across 50 percent of the field (Photo credit: USDA-ARS Engineering & Wind Erosion Research Unit).



**Figure 2.** Tillage implement with very wide spaced shanks, making clods to roughen the soil surface. (Photo credit: John Smith, University of Nebraska).

The special assessment is not to exceed \$3 per acre for each acre on which work is done for any one year, unless such amount is not adequate to cover the actual cost of the work (Kan. Stat. Ann. §2-2008 (b))

## Emergency Control

### *Mulching*

If wind erosion has started, it can be reduced by mulching with manure or other anchored plant materials such as straw or hay. To be effective, at least 1.5 to 2 tons per acre of straw or grass or 3 to 4 tons per acre of corn or sorghum stover are needed to control areas of erosion. Residue can be spread by hand, spreader, or other mechanical equipment. A stubble puncher or disk set straight may be used to anchor residue and prevent it from being blown away.

Wet manure application should be 15 to 20 tons per acre and not incorporated into the soil.

Care should be taken to not add wheel paths parallel to the wind direction as the mulch is applied. Traffic areas and wheel paths can contribute to wind erosion.

Generally, mulches are only practical for small areas, so mulching is most effective when applied before the soil starts to move. Producers should scout fields to identify areas that might be susceptible to wind erosion if they plan to use mulch or manure as a control. Signs to look for include low residue quantity, or residue that is broken off from the plant.

### *Emergency Tillage Basics*

Emergency tillage is a last resort that can be effective if done promptly with the right equipment. The goal of emergency tillage is to make the soil surface rougher by producing resistant clods and surface ridges. A rough surface reduces wind speed. The larger clods and ridges resist movement and provide traps to catch moving soil particles.

Chisels with single or few tool ranks are frequently used to roughen the soil surface. For emergency tillage,

the chisel point and speed and depth of operation combination that produces the roughest surface with the largest number of firm clods resistant to falling apart when dry,

should be used. Finding the right combination might take some experimentation. The depth of tillage usually affects clod stability more than travel speed, but optimum depth is highly dependent on soil conditions (i.e., moisture) and compaction. Deeper tillage passes often can produce more resistant clods than shallow passes.

## Emergency Tillage: Sandy Soils

Loose sandy soils require a different tillage approach to effectively control erosion. On sandy soils, clods cannot be formed that will be sufficiently resistant to erosion. Erosion resistance is achieved through building ridges and furrows in the field to provide adequate protection. A 14-inch moldboard lister spaced

40 to 50 inches apart (or an 8-inch lister on 20- to 24-inch spacings) is needed to create sufficient surface roughness. The first listing pass should be shallow, not more than about 4 to 5 inches deep. Then, when additional treatment is needed, the depth should become progressively deeper. Alternatively, for the second treatment the original ridge may be split. The addition of manure to the ridged surface may be beneficial.

## Emergency Tillage on Soils and Residues: Spacing Strategies

Performing emergency, clod-forming tillage across the field is effective. Tillage passes should be made perpendicular to the direction of the prevailing wind causing the erosion (Table 1). The success of emergency tillage is highly dependent on climatic, soil, and cover conditions. There are different tried-and-true strategies that can be used for the different soil types.

*Clayey soils:* Research shows a narrow chisel (2 inches wide) on 24- to 54-inch spacings and oper-

### Tips for Effective Emergency Tillage

1. Watch the weather forecast for periods of high winds (greater than 25 miles per hour), particularly when surface soils are dry.
2. Assess residue and plant cover before the wind begins blowing, and take preventive action with emergency tillage. It is much easier to prevent the problem from starting than to stop erosion after it begins. If you wait, the soil only gets drier, losing moisture needed to form clods.
3. Use the combination of tractor speed, tillage depth, and shovel size that produces the roughest surface with the most resistant clods. If wind erosion is anticipated, do some test tillage beforehand to see what tillage tool, depth, and speed provides adequate clods and surface roughness.
4. Always start at the upwind location when the field is blowing. A sufficient area upwind of the eroding spot should be tilled in addition to the area presently blowing.
5. Till in a direction perpendicular to the prevailing wind direction (Table 1). For row crop areas, it may be necessary to compromise direction and follow the row pattern. Maintain as much anchored stubble in the field as possible.



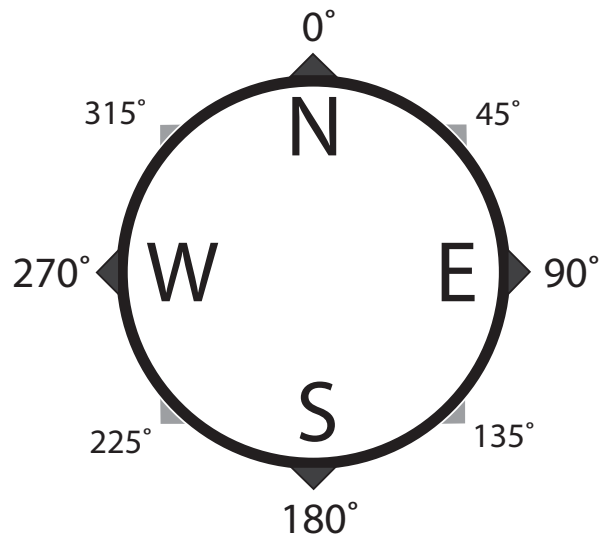
*Loamy soils:* A medium, 4-inch wide shovel can be effective for medium-textured soils (loamy soils). Narrower spacings should be used where there is no cover and wider in areas of partial cover, such as in growing crops or plant residue. If the erosion conditions recur or persist, a second, deeper chiseling should split the first spacing. For example, if the first chiseling was done on 24-inch spacings and clod-forming tillage was necessary to keep the field from blowing, the second tillage pass should happen in such a way that the implement is operated in the same direction as the first tillage, but the shanks should be run 12 inches over from the previous pass.

It is often not necessary to till the entire field, but rather, it is effective to perform emergency tillage passes across 50 percent of the field (till a pass, skip a pass, repeat). A narrow chisel spacing (20 to 24 inches) is best for this method. If 50 percent of the area has been tilled and wind erosion persists, the omitted strips can be emergency tilled in a second operation to make tillage full cover. If a second tillage pass is needed, it should be at a greater depth than the first pass. Wide chisel spacings are used in the full-field coverage method. The space between chisel grooves can be chiseled later should wind persist.

Sometimes emergency tillage to prevent the loss of valuable topsoil is necessary on fields that are growing



**Figure 3.** A field in southwestern Kansas with major wind erosion damage. (Photo credit: DeAnn Presley)



**Figure 4.** *Compass points with degree increments.*

[illegible]

insured crops because of poor residue cover or poor stands of crops (often winter wheat after a dry year). Producers should check with their crop insurance providers regarding insurance rules when considering emergency tillage on a growing wheat crop.

Studies in southwest Kansas and Manhattan demonstrate that by using a 40-inch chisel spacing, operated at 4 to 6 inches deep, wheat yields were reduced by 5.5 bushels per acre where the shanks ran over the wheat plants. Overall, however, the wheat yield was reduced by 1 bushel per acre on the entire field. Emergency tillage on a growing winter wheat crop does not significantly reduce wheat yields of an established crop; therefore, if wheat fields start blowing, emergency tillage is a short-term, viable option.

### **Emergency Tillage: Speed and Direction**

All tillage operations should be perpendicular or across the direction of the prevailing or eroding wind (Table 1). For most of Kansas, this means that emergency tillage should be performed in an east-west direction. Since winds can deviate from the prevailing

directions, forecast wind directions and speeds should be taken into consideration in determining actual tillage directions. The best wind erosion control is created with maximum surface roughness when resistant clods cover a major portion of the surface. Research shows that lower travel speeds of 2 to 3 miles per hour generally produce the largest and most resistant clods. Speeds of 5 to 7 miles per hour, however, produce the greatest roughness. Because clod resistance is usually reduced at higher speeds, the effect may not be as long-lasting as at lower speeds. Thus, higher speeds are recommended where erosion is already in progress, while lower speeds might be a better choice in anticipation of erosion.

### **References**

Li, J., Okin, G. S., Hartman, L. J. & Epstein, H. E. Quantitative assessment of wind erosion and soil nutrient loss in desert grasslands of southern New Mexico, USA. *Biogeochemistry* **85**, 317-332, doi:10.1007/s10533-007-9142-y (2007).

#### **DeAnn Presley**

Soil Management Specialist  
Agronomy

#### **Ed Brokesh**

Machinery Systems Specialist  
Biological and Agricultural Engineering

#### **John Tatarko**

USDA-ARS Engineering & Wind  
Erosion Research Unit

#### **Peter Tomlinson**

Environmental Quality Specialist  
Agronomy

Brand names appearing in this publication are for product identification purposes only. No endorsement is intended, nor is criticism implied of similar products not mentioned.

Publications from Kansas State University are available at: [www.ksre.ksu.edu](http://www.ksre.ksu.edu)

Publications are reviewed or revised annually by appropriate faculty to reflect current research and practice. Date shown is that of publication or last revision. Contents of this publication may be freely reproduced for educational purposes. All other rights reserved. In each case, credit DeAnn Presley, et al., Emergency Wind Erosion Control, Kansas State University, March 2013.

### **Kansas State University Agricultural Experiment Station and Cooperative Extension Service**

MF2206

March 2013

K-State Research and Extension is an equal opportunity provider and employer. Issued in furtherance of Cooperative Extension Work, Acts of May 8 and June 30, 1914, as amended. Kansas State University, County Extension Councils, Extension Districts, and United States Department of Agriculture Cooperating, John D. Floros, Director.

**NATURAL RESOURCES CONSERVATION SERVICE**  
**CONSERVATION PRACTICE STANDARD**

**SURFACE ROUGHENING**

(Ac.)

**CODE 609**

**DEFINITION**

Performing tillage operations that create random roughness of the soil surface

**PURPOSE**

- Reduce wind erosion
- Reduce dust emissions into the air
- Protect plants from abrasion by wind-blown particles.

**CONDITIONS WHERE PRACTICE APPLIES**

On soils that have a surface layer suitable for clod formation and have a high potential for wind erosion due to lack of surface cover. This practice should not be used as a primary erosion control practice.

This practice applies on soils whose surface layer has a wind erodibility factor (I) value of 104 or less (see the National Agronomy Manual, Exhibit 502-2).

**GENERAL CRITERIA APPLICABLE TO ALL PURPOSES**

Tillage operations done for this purpose will produce random roughness (RR) values (inches) large enough to achieve a 25% reduction in the potential erosion rate (soil "I" value), **OR** reduce wind erosion during the management period by 25% as determined by the most current wind erosion technology.

The random roughness ( $K_{rr}$ ) value used to

estimate wind erosion shall be determined from Table 1. Random roughness ( $K_{rr}$ ) shall be equal to or less than 0.75. The shaded area shows the RR – "I" factor combinations that meet the 25% reduction criterion.

**Table 1.**  $K_{rr}$  from Random Roughness (RR) and "I" Factor Values<sup>1</sup>

RR (in)	I = 104	I = 86	I ≤ 56
0.2"	1.0	1.0	1.0
0.4"	0.95	0.86	0.70
0.6"	0.88	0.76	0.51
0.8"	0.82	0.68	0.40
1.0"	0.78	0.62	0.34
1.2"	0.74	0.57	0.30
1.4"	0.72	0.54	0.27
1.6"	0.69	0.51	0.24

<sup>1</sup>Note-I factor values >134 have a  $K_{rr}$  = 1.0, & the I of 134 soil will not reach a 25% reduction at any RR.

Random Roughness (RR) values shall be estimated from the field operation table for random roughness [see the National Agronomy Manual Part 502, Exhibit 502-7], or estimated using the roughness pictures in Agriculture Handbook 703 Appendix C, pages 339 to 347.

**Criteria to Protect Plants from Abrasion by Wind Blown Soil Particles**

Tillage operations for this purpose will produce random roughness sufficient to reduce or eliminate surface creep (roller phase) and saltation during crop emergence and early crop development.

Roughness created shall reduce the soil loss for the first growth period after planting the crop to the soil loss listed in National Agronomy Manual Table 502-4,

## **CONSIDERATIONS**

This practice should be used when a well-planned and properly applied wind erosion control system fails for reasons beyond the control of the producer. These situations may exist when a low residue-producing crop is harvested too late in a growing season to produce sufficient residue cover, or when the planned erosion control system fails to control erosion during a high wind event.

Wide spacing of chisel points or skip chiseling (alternate chiseled/non-chiseled strips) for the first operation may permit salvaging part of a growing crop of small grain and leave undisturbed soil for later operations, if needed.

Spacing and depth of chisel operation are important to obtain uniform distribution of clods on the surface. Close spacing at shallow depths generally pulverizes the soil, and does not produce enough random roughness to decrease the soil-blowing potential.

Proper tillage equipment matched to the crop being grown and soil is important. In general, chisels or narrow sweeps may reduce potential soil blowing on loamy or fine textured soils. Roughening the soil surface with a lister/bedder or wide shovels on chisel shanks is more effective on soils whose surface layer has a wind erodibility factor (I) value of 104 and 86.

Emergency tillage (surface roughening) can be done on soil that has an "I" factor greater than 104 using deep tillage, when soil moisture is adequate to create a stable aggregate (clod) and when finer soil material can be brought to the surface.

Perform the initial tillage operation as soon as erosion starts, or as soon as it is evident that the existing cover or surface roughness is

inadequate to control erosion below an acceptable level.

Begin surface roughening operations on the windward (up wind) edge of the field.

Ridging associated with the tillage is very important to controlling wind erosion. Tillage that creates ridging is done perpendicular to the direction of damaging wind. See conservation practice standard Cross Wind Ridges 588 for criteria to use ridging.

Surface crusts generally reduce soil erodibility. However, certain smooth, crusted soils with loose grains (sand size particles) on the soil surface may cause crusts to abrade rapidly. These soils include loamy fine sands and sandy loams that have significant portions of sand on the surface when crusted. They also include certain calcareous loams, silt loams, and silty clay loams that tend to form sand sized aggregates in the surface when crusted.

## **PLANS AND SPECIFICATIONS**

Plans and specifications for establishment of this practice shall be prepared for each field or treatment unit according to the conditions and criteria in this standard. Specifications shall be recorded using approved specification sheets, job sheets, narrative statements in the conservation plan, or other acceptable documentation.

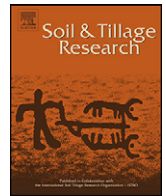
## **OPERATION AND MAINTENANCE**

This practice will be performed as soon as possible when there is inadequate cover to protect the soil from potential wind erosion events or when a crusted soil condition occurs as sensitive crop is emerging and inadequate crop residues are present.

## **REFERENCES**

USDA, Natural Resources Conservation Service, National Agronomy Manual, 3<sup>rd</sup>. Ed., October 2002. Part 502 Wind Erosion.





# Friction velocity and aerodynamic roughness of conventional and undercutter tillage within the Columbia Plateau, USA

Brenton Sharratt<sup>a,\*</sup>, Guanglong Feng<sup>b</sup>

<sup>a</sup> USDA-Agricultural Research Service, 213 LJ Smith Hall, WSU, Pullman, WA 99164, United States

<sup>b</sup> Department of Biosystems Engineering, Washington State University, Pullman, WA, United States

## ARTICLE INFO

### Article history:

Received 31 March 2009

Received in revised form 14 August 2009

Accepted 18 August 2009

### Keywords:

Wind erosion

Air quality

Dust emissions

Conservation tillage

## ABSTRACT

Friction velocity ( $u_*$ ) and aerodynamic roughness ( $z_o$ ) at the soil–plant–atmosphere interface affect wind erosion, but no attempts have been made to quantify these parameters as affected by tillage systems within the Columbia Plateau region of the Pacific Northwest United States. Wind velocity profiles above adjacent field plots (>2 ha), with plots subject to conventional or undercutter tillage during the summer fallow phase of a winter wheat–summer fallow rotation, were measured over 50 high wind events (wind velocities in excess of  $6.4 \text{ m s}^{-1}$  at a height of 3 m) during 2005 and 2006 near Lind, Washington to determine  $u_*$  and  $z_o$  of tillage treatments. Wheat stubble plots were subject to either conventional (disks) or undercutter (wide V-shaped blades) tillage in spring and then periodically rodweeded prior to sowing winter wheat in late summer. Prior to sowing,  $u_*$  for conventional and undercutter tillage respectively averaged  $0.36$  and  $0.46 \text{ m s}^{-1}$  in 2005 and  $0.38$  and  $0.40 \text{ m s}^{-1}$  in 2006 while  $z_o$  for conventional and undercutter tillage respectively averaged  $2$  and  $7 \text{ mm}$  in 2005 and  $2$  and  $4 \text{ mm}$  in 2006. The aerodynamically rougher surface of undercutter tillage was predicted to suppress vertical dust flux; this was collaborated with observations in the field where undercutter tillage reduced dust flux as compared with conventional disk tillage. Undercutter tillage, therefore, appears to be an effective management practice to roughen the surface and thereby suppress dust emissions from agricultural land subject to summer fallow within the Columbia Plateau.

Published by Elsevier B.V.

## 1. Introduction

Wind erosion removes fertile topsoil and is therefore a concern for global societies in maintaining food and fiber production for future generations. Wind erosion damages crops as a consequence of saltating particles sandblasting seedlings (Fryrear, 1986) and can impair visibility and human health as a result of increasing the atmospheric dust load through the emission of fine particulate matter from soils. In fact, windblown dust has caused vehicular accidents as a result of reduced visibility (Hudson and Cary, 1999) and has contributed to exceedance of the US Environmental Protection Agency ambient air quality standard for PM<sub>10</sub> (particulate matter  $\leq 10 \mu\text{m}$  in diameter) within the Columbia Plateau region of the Pacific Northwest United States (Sharratt and Lauer, 2006).

Wind erosion is initiated when friction velocity ( $u_*$ ) exceeds the threshold friction velocity. Threshold friction velocity is the minimum friction velocity, at the height where momentum is absorbed by surface roughness elements, that is required to initiate

movement of an aggregate or particle resting on the soil surface; aggregate or particle movement is achieved when drag and lift forces overcome gravitational and inter-particle cohesive forces acting on the aggregate or particle at the soil surface. While threshold friction velocity is governed by the size, shape, and mass of aggregates or particles at the soil surface, threshold friction velocity is also influenced by soil surface water content and crusting, surface roughness, and biomass cover. Friction velocity, however, is governed by the apparent roughness of the surface and atmospheric convection or stability (Stull, 2000). The apparent roughness of an agricultural field is comprised of roughness cast by aggregates on the soil surface, tool marks or ridges created by tillage implements, and vegetation protruding above the soil surface. Abatement of wind erosion of an agricultural field, therefore, can be attained by altering soil surface characteristics (e.g. size of aggregates, biomass cover).

Developing strategies to mitigate wind erosion is imperative to conserving the soil resource and improving air quality within the Columbia Plateau. In the drier part (annual precipitation <300 mm) of this region, about 1.5 million ha of land is managed in a winter wheat–summer fallow rotation. Conventional summer fallow generally entails cultivating soils with sweeps, disks, or cultivators after wheat harvest in late summer and again the

\* Corresponding author. Tel.: +1 509 335 2724; fax: +1 509 335 3842.  
E-mail address: [Sharratt@wsu.edu](mailto:Sharratt@wsu.edu) (B. Sharratt).

following spring and then rodweeding the soil to control weeds prior to sowing winter wheat in late summer (Schillinger, 2001). Although conventional tillage practices are very effective in conserving soil water during the fallow phase of the rotation, soils are very susceptible to erosion during summer fallow because multiple tillage operations degrade soil aggregates and bury crop residue.

The United States Department of Agriculture-Natural Resource Conservation Service has recently promoted the use of an undercutter tillage implement for reducing wind erosion within the Columbia Plateau (Burnham, 2007). The undercutter implement, with wide, over-lapping, V-shaped blades, minimizes soil inversion and disturbance that otherwise occurs with a plow or disk. Retention of crop residue or large aggregates on the soil surface as a result of less soil disturbance by the undercutter implement may better protect the soil surface against the forces of wind. No studies have examined the impact of this conservation tillage implement on aerodynamic surface characteristics that affect wind erosion and dust emissions from agricultural soils in the region. The objective of this study was to assess  $u_*$  and aerodynamic roughness ( $z_o$ ) of soils subject to conventional and undercutter tillage during the summer fallow phase of a winter wheat–summer fallow rotation.

## 2. Materials and methods

This study was conducted at field sites located within the low precipitation zone (<300 mm annual precipitation) of the Columbia Plateau region of the Pacific Northwest United States (Fig. 1). Fields were in a winter wheat–summer fallow rotation when the fallow phase of the rotation began after harvest of wheat in July 2004 and 2005. Field sites were located 12 km southwest of Lind, Washington on a Shano silt loam (Andic Aridic Haplustoll) in 2004 and 14 km southeast of Lind, Washington on a Ritzville silt loam (Andic Aridic Haplustoll) in 2005. Shano silt loam is comprised of 34% sand, 56% silt, and 10% clay whereas Ritzville silt loam is comprised of 21% sand, 65% silt, and 14% clay. Organic matter content of both soils was 1%. Adjacent plots were established at the field site after wheat harvest each year with plots subject to either conventional tillage or undercutter tillage during the fallow phase of a winter wheat–summer fallow rotation. Conventional tillage practices were those used by the wheat growers who owned and managed the field sites. Field plots were 200 m × 100 m in 2004 and 200 m × 200 m in 2005.

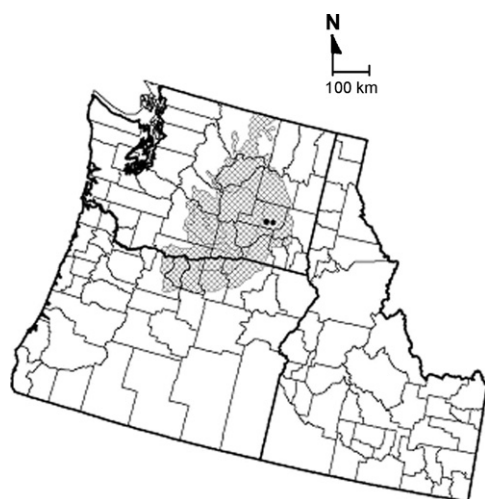


Fig. 1. Location of field sites in 2005 and 2006 (dots) within the Columbia Plateau region (shaded area) of the Pacific Northwest United States.

Table 1

Dates of field operations and precipitation during the 2005 and 2006 field campaigns.

Year	Calendar date	Day of year	Field operation	Precipitation <sup>a</sup> (mm)
2005	May 5	125	Tillage	
	May 6	126	Fertilize	
	May 10	130	Rodweed	
	May 15	135		2.3
	May 20	140		3.6
	May 21	141		6.4
	June 5	156		4.6
	July 8	189		9.9
	July 9	190		1.8
	July 21	202	Rodweed	
	August 17	229		2.0
	August 31	243	Sow	
2006	April 30	120	Tillage	
	June 2	153	Fertilize	
	June 13	164		1.5
	June 14	165		5.6
	June 24	175	Rodweed	
	August 6	218	Rodweed	
	August 27	239	Sow	
	September 21	264		2.5
	October 16	289		3.6

<sup>a</sup> Days with precipitation  $\geq 1.3$  mm during the period of high wind observations in 2005 (12 May to 18 October) and 2006 (6 June to 20 October).

The wheat stubble plots remained undisturbed after harvest in 2004 while wheat stubble plots in 2005 were harrowed twice after harvest to incorporate weed seed. In early May 2005 and late April 2006, stubble plots were tilled to a depth of 0.1 m using either a double disk or undercutter implement. The undercutter implement had 0.81-m wide V-shaped blades spaced 0.7 m apart. After tillage, fertilizer was injected at a depth of 0.1 m into the soil with shanks spaced 0.45 m apart on 6 May 2005 and 2 June 2006. In 2005, both plots were rodweeded at a depth of 0.1 m on 10 May and 21 July prior to sowing winter wheat in rows spaced 0.45 m apart with a deep furrow drill on 31 August. In 2006, both plots were rodweeded on 24 June and 6 August prior to sowing winter wheat on 27 August with a deep furrow drill. Field operations during 2005 and 2006 are summarized in Table 1.

### 2.1. Estimating $u_*$ and $z_o$

Friction velocity and  $z_o$  were estimated from wind velocity profiles obtained during high wind events capable of causing wind erosion. A high wind event was defined by a threshold wind velocity of  $6.4 \text{ m s}^{-1}$  at a height of 3 m; an event was initiated when wind velocity exceeded the threshold for 10 consecutive minutes and terminated when wind velocity was lower than the threshold for 10 consecutive minutes. The field plots were instrumented to monitor wind velocity and air temperature at heights of 0.1, 0.5, 1, 2, 3, and 6 m above the soil surface in each plot. Wind velocity was measured using 3-cup anemometers (model 014A, Met One, Grants Pass, Oregon). Air temperature was measured using non-aspirated, shielded, fine-wire thermocouples. Instrumentation was installed at the leeward position (northeast corner) in the plots. In 2005, land to the south of both plots and to the west of the undercutter tillage plot was cropped to winter wheat while the west end of the conventional tillage plot abutted the undercutter tillage plot. In 2006, land to the west of both plots was cropped to winter wheat while the southern boundary of the undercutter tillage plot bordered a ravine (10 m deep and 50 m wide) and the southern boundary of the conventional tillage plot abutted the undercutter tillage plot. Friction velocity and  $z_o$  were assessed only for high wind events that had prevailing winds between  $190^\circ$  and  $260^\circ$  to ensure a fetch, or length of field with known and similar surface characteristics, of at least 100 m in 2005

**Table 2**

Soil surface characteristics of conventional and undercutter tillage during the 2005 and 2006 field campaigns.

Soil characteristic	Tillage treatment	Date of sampling <sup>a</sup>						
		2005			2006			
		7 June	25 July	14 September	6 June	28 June	9 August	6 September
Standing stubble (g m <sup>-2</sup> )	Conventional	4	5	21	4	4	5	2
	Undercutter	38	68	31	13	12	17	5
Prostrate residue cover (%)	Conventional	35	30	9	22	18	15	12
	Undercutter	55	50	11	40	42	46	29
Silhouette area index (m <sup>2</sup> m <sup>-2</sup> )	Conventional	0.01	0.01	0.02	0.01	0.01	0.01	0.003
	Undercutter	0.04	0.08	0.02	0.02	0.02	0.03	0.006
Random roughness (mm)	Conventional	11.7	15.0	10.4	13.8	10.8	7.2	11.0
	Undercutter	18.1	14.9	8.8	13.8	10.7	10.0	8.3

<sup>a</sup> Date of sowing was 31 August 2005 and 27 August 2006.

and 200 m in 2006. Maximum fetch over this range of prevailing wind directions was 225 m in 2005 and 285 m in 2006. Sensors were monitored every 10 s with data averaged and recorded every minute during a high wind event. An automated weather station was also deployed at the leeward position in the conventional tillage plot to measure relative humidity, precipitation, and solar radiation.

Wind velocity within the inertial sublayer of the surface boundary layer can be described by the log wind profile:

$$u_z = \left(\frac{u_*}{k}\right) \ln\left(\frac{z}{z_0}\right) \quad (1)$$

where  $u_z$  is wind velocity (m s<sup>-1</sup>) at height  $z$  (m) and  $k$  is von Karman's constant (0.4). Estimation of  $u_*$  and  $z_0$  in Eq. (1) can be obtained from a knowledge of the wind velocity profile under conditions of neutral atmospheric stability. Although neutral stability typically occurs during high winds (Oke, 1987), we verified the existence of neutral stability using the Richardson's number (Stull, 2000):

$$Ri = \frac{(g/T)(\partial T/\partial z)}{(\partial u/\partial z)^2} \quad (2)$$

where  $Ri$  is Richardson's number,  $g$  is the gravitational constant (9.8 m s<sup>-2</sup>),  $T$  is air temperature (K), and  $\partial T$  and  $\partial u$  are the respective change in temperature (K) and wind velocity (m s<sup>-1</sup>) with height  $\partial z$  (m). Stability conditions were classified according to Thom (1975) with neutral stability defined by  $Ri$  between  $-0.01$  and  $0.01$ . Both  $u_*$  and  $z_0$  were obtained under conditions of neutral stability from wind velocity measurements at no fewer than three heights that were resolved to lie within the logarithmic region of the inertial layer. These parameters were estimated by linear regression analysis of  $u$  versus  $\ln(z)$ ; accordingly,  $u_*$  is the ratio of  $k$  to regression slope and  $z_0$  is the exponent of the regression intercept. For all profiles, the coefficient of determination of the relationship was  $>0.98$ .

## 2.2. Estimating dust flux

Friction velocity influences vertical dust flux ( $F$ ) according to (Gillette and Passi, 1988):

$$F = \gamma u_*^3 (u_* - u_{*t}) \quad (3)$$

where  $\gamma$  is an empirical dust coefficient and  $u_{*t}$  is the threshold friction velocity (m s<sup>-1</sup>). Vertical flux of dust occurs only when  $u_*$  exceeds  $u_{*t}$ . The  $u_{*t}$  of tillage treatments was estimated based upon known soil surface characteristics (Table 2) and empirical equations described by Shao (2000).

Soil surface characteristics measured after tillage, fertilizing, and sowing at three random locations in each tillage treatment

included biomass of standing stubble and prostrate (i.e. flat) residue, silhouette area index (SAI), prostrate residue cover, and ridge and random roughness. Biomass of stubble and residue was assessed by collecting, drying, and weighing above-ground stubble and prostrate residue from 0.25 m<sup>2</sup> areas within each plot. SAI was determined according to:

$$SAI = \frac{1}{A} \sum (dh) \quad (4)$$

where the summation is for all standing stubble elements of height  $h$  and diameter  $d$  within the sampling area  $A$ . A pin or roughness meter was used to measure prostrate or flat residue cover and soil surface random roughness. The pin meter was comprised of 40 equidistant pins (spacing of 25 mm) that protruded and moved vertically through holes in a steel frame mounted on the soil surface (Wagner and Lindstrom, 1996). The pins were in a retracted position until lowered to the soil surface for measuring residue cover and random roughness. Residue cover was calculated as the percent of pins whose feet (6-mm diameter) overlaid prostrate residue elements. Random roughness was determined as the standard deviation among pin elevations after correcting for slope (Currence and Lovely, 1970). Oriented or ridge roughness was only apparent after sowing wheat; ridges created by the deep furrow drill were characterized by roughness, associated with height and spacing of ridges, according to Zingg and Woodruff (1951).

Threshold friction velocity was estimated from standing stubble and prostrate residue biomass of tillage treatments prior to sowing because differences in crop residue characteristics were more apparent and consistent than differences in other surface characteristics between treatments prior to sowing (Table 2). According to Shao (2000):

$$u_{*t} = u_{*tss} f(\lambda) f(rc) \quad (5)$$

where  $u_{*tss}$  is the threshold friction velocity of a smooth, dry, unconsolidated, and bare soil surface and  $f(\lambda)$  and  $f(rc)$  are respective correction functions for standing stubble and prostrate residue cover. The correction function for standing stubble is:

$$f(\lambda) = \sqrt{\{(1 - m\alpha\lambda)(1 + m\beta\lambda)\}} \quad (6)$$

where  $m$  is a constant ( $\sim 0.5$ ) that accounts for non-uniformity in shear stress caused by roughness elements,  $\alpha$  is the ratio of stubble element basal area to stubble element frontal area,  $\beta$  is the ratio of stubble to soil surface drag coefficients, and  $\lambda$  is silhouette area index (total stubble frontal area to soil surface area). Stubble height prior to sowing was  $\sim 0.1$  m for both treatments. The drag coefficient for stubble was 0.45 (Campbell, 1986) and for a smooth soil surface was 0.0033 (Raupach et al., 1993). Data presented by Hagen (1996) were used to derive the correction function for



prostrate residue cover as:

$$f(rc) = (1 + 1.92rc - 2.092rc^2 + 0.866rc^3)^2 \quad (7)$$

where  $rc$  is the fraction of soil surface covered by prostrate residue. The  $u_{*TSS}$  was estimated to be  $0.15 \text{ m s}^{-1}$  based upon Bagnold's scheme (Bagnold, 1941) for a surface comprised of particles with a mean diameter of  $100 \mu\text{m}$ .

### 2.3. Statistical analysis

Regression analysis and paired  $t$ -tests were performed to compare  $u_*$  and  $z_o$  of conventional and undercutter tillage. Each pair of  $u_*$  or  $z_o$  determinations obtained during a high wind event was used to test (paired  $t$ -test) whether significant differences existed between the mean  $u_*$  or  $z_o$  obtained for conventional disk and undercutter tillage across all high wind events.

## 3. Results and discussion

### 3.1. High wind event characteristics

A total of 38 and 55 high wind events, with each event characterized by wind velocities at a 3-m height exceeding  $6.4 \text{ m s}^{-1}$ , occurred during the respective period of observation in 2005 (12 May to 18 October) and 2006 (6 June to 20 October). Persistent SW ( $190$ – $260^\circ$ ) winds were observed during 45 and 87% of these events in subsequent years whereby a fetch with known surface characteristics of at least 100 m in 2005 and 200 m in 2006 was maintained upwind of the instrumentation for the duration of the high wind event. Power failures and plant debris lodged against sensors precluded obtaining quality wind data for three and six high wind events characterized by SW winds over the period of observation in successive years. In addition, neutral stability did not occur during six high wind events characterized by SW winds in 2006; for these events,  $Ri$  varied from  $-0.014$  to  $-0.033$ . For high wind events characterized by SW winds and neutral stability in 2005 (14 events) and 2006 (36 events), the maximum 1-min wind velocity observed at a height of 3 m was  $13.0 \text{ m s}^{-1}$  in 2005 (occurred on 6 July) and  $14.5 \text{ m s}^{-1}$  in 2006 (occurred on 16 June). The maximum duration of a high wind event was 597 min in 2005 and 906 min in 2006 (these events occurred on 29 August in both years).

### 3.2. Friction velocity

Friction velocity ranged from  $0.31$  to  $0.49 \text{ m s}^{-1}$  for conventional tillage and from  $0.43$  to  $0.58 \text{ m s}^{-1}$  for undercutter tillage across all high wind events in 2005. In 2006,  $u_*$  ranged from  $0.34$  to  $0.56 \text{ m s}^{-1}$  for conventional tillage and from  $0.33$  to  $0.56 \text{ m s}^{-1}$  for undercutter tillage across all high wind events. Excluding the anomalously high wind events on 6 and 8 July 2005 (days 187 and 189) and 16 June 2006 (day 167),  $u_*$  was generally lower prior to sowing than after sowing both years (Fig. 2). For example,  $u_*$  for high wind events prior to and after sowing was respectively  $0.36$  (standard error or SE =  $0.02$ ) and  $0.44$  (SE =  $0.01$ )  $\text{m s}^{-1}$  for conventional tillage and  $0.46$  (SE =  $0.02$ ) and  $0.51$  (SE =  $0.01$ )  $\text{m s}^{-1}$  for undercutter tillage in 2005. In 2006,  $u_*$  prior to and after sowing was respectively  $0.38$  (SE =  $0.01$ ) and  $0.48$  (SE =  $0.01$ )  $\text{m s}^{-1}$  for conventional tillage and  $0.40$  (SE =  $0.01$ ) and  $0.53$  (SE =  $0.01$ )  $\text{m s}^{-1}$  for undercutter tillage. Some variation in  $u_*$  occurred across high wind events prior to sowing as well as after sowing (Fig. 2). Changes in  $u_*$  prior to sowing were largely associated with changes in atmospheric flow characteristics (e.g. velocity, orientation to roughness elements) across high wind events as large variations in  $u_*$  occurred over periods of time in

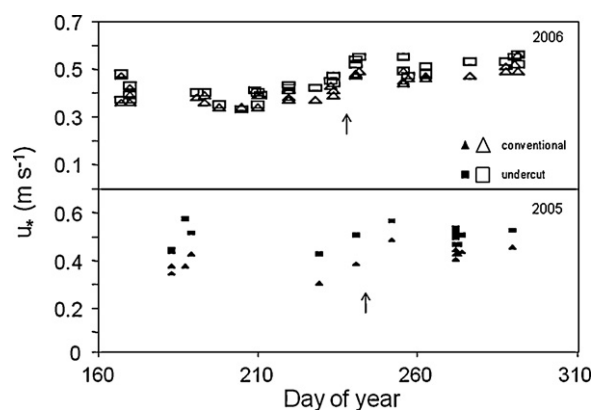


Fig. 2. Friction velocity ( $u_*$ ) of conventional and undercutter tillage during high wind events in 2005 and 2006. The arrows indicate dates of sowing both years.

which the soil surface was not disturbed by field operations and precipitation. This is exemplified by differences in  $u_*$  of  $0.03 \text{ m s}^{-1}$  for conventional tillage and  $0.14 \text{ m s}^{-1}$  for undercutter tillage between days 183 and 187 in 2005 during which time there was no precipitation or tillage (Table 1). Similarly in 2006, differences in  $u_*$  of  $0.11 \text{ m s}^{-1}$  for both conventional and undercutter tillage occurred between days 167 and 170 and differences in  $u_*$  of  $0.06 \text{ m s}^{-1}$  for both conventional and undercutter tillage occurred between days 220 and 234 during which time there was no precipitation or tillage (Table 1).

Friction velocity for undercutter tillage prior to sowing in 2005 (Fig. 2) appeared anomalous for the 6 and 8 July (days 187 and 189) high wind events; these extreme  $u_*$  ( $0.58$  and  $0.52 \text{ m s}^{-1}$ , respectively) were determined from wind velocity profile data containing the highest velocities (mean wind velocity at 6-m height was respectively  $9.2$  and  $8.7 \text{ m s}^{-1}$  during the events) of all events in 2005. After sowing in 2005,  $u_*$  of conventional and undercutter tillage appeared to decline with time; slope estimates of  $u_*$  versus day of year after sowing were  $-0.0009 \text{ m s}^{-1} \text{ d}^{-1}$  for conventional tillage and  $-0.0012 \text{ m s}^{-1} \text{ d}^{-1}$  for undercutter tillage. The apparent decline in  $u_*$  with time was contrary to our assumption that  $u_*$  would increase with time after sowing due to an increase in aerodynamic roughness of the surface and absorption of kinetic energy by the plant canopy during growth of winter wheat (wheat attained a height of  $0.2 \text{ m}$  at the end of the observation period both years). The decline in  $u_*$  with time after sowing in 2005 was not associated with any variation in mean wind velocities, as wind velocities at 6-m height ranged from  $7.1$  to  $7.7 \text{ m s}^{-1}$  across all high wind events after sowing. The decline in  $u_*$  with time after sowing, however, was likely influenced by a high  $u_*$  on 9 September (day 252). In fact, by omitting  $u_*$  on 9 September,  $u_*$  of conventional and undercutter tillage appeared to increase with time (slope estimates of  $u_*$  versus day of year were  $0.0014 \text{ m s}^{-1} \text{ d}^{-1}$  for conventional tillage and  $0.0015 \text{ m s}^{-1} \text{ d}^{-1}$  for undercutter tillage). The anomalously high  $u_*$  on 9 September was likely due to winds being more orthogonal to the NS ridges or seed rows on 9 September than on subsequent days. Winds on 9 September were from the WSW ( $239^\circ$ ) while winds for all events thereafter were more parallel to the ridges being from the SSW ( $191$ – $216^\circ$ ).

Friction velocity of conventional and undercutter tillage prior to sowing in 2006 was highest for the 16 June (day 167) high wind event. The high  $u_*$  ( $0.47 \text{ m s}^{-1}$  for conventional tillage and  $0.48 \text{ m s}^{-1}$  for undercutter tillage) corresponded with the highest wind velocities (mean wind velocity at 6-m height was  $10.0 \text{ m s}^{-1}$  during the event) observed across all high wind events in 2006. After sowing in 2006,  $u_*$  appeared to increase with time as the slope of the relationship between  $u_*$  and day of year was positive

for both conventional ( $0.0009 \pm 0.0003 \text{ m s}^{-1} \text{ d}^{-1}$ ) and undercutter tillage ( $0.0003 \pm 0.0003 \text{ m s}^{-1} \text{ d}^{-1}$ ). These temporal trends after sowing, however, were only significant ( $P < 0.05$ ) for conventional tillage. An increase in  $u_*$  with time after sowing was likely due to continued development of wheat and not due to variation in mean wind velocity or wind direction across high wind events. Although the highest  $u_*$  for both tillage treatments ( $0.56 \text{ m s}^{-1}$ ) after sowing occurred in association with the highest wind velocities (mean wind velocity at 6-m height was  $9.1 \text{ m s}^{-1}$ ) at the end of the period of observation on 19 October 2006 (day 292), temporal trends in  $u_*$  after removing this singular  $u_*$  from linear regression analysis remained significant for conventional tillage. Mean wind velocities at 6-m height across all other high wind events after sowing in 2006 ranged from  $7.4$  to  $8.6 \text{ m s}^{-1}$ , with higher velocities ( $>8.2 \text{ m s}^{-1}$ ) occurring within the first 20 d after sowing. In addition, an increase in  $u_*$  with time after sowing in 2006 was not imposed by a change in wind direction to a more orthogonal orientation to the NS ridges since there was no association between  $u_*$  and wind direction after sowing; in fact, there was a tendency for southwesterly winds to shift to a more southerly direction with time (slope of wind direction versus day of year was  $-0.31 \pm 0.26^\circ \text{ d}^{-1}$ ) after sowing.

Friction velocity was generally higher for undercutter tillage than for conventional tillage during high wind events in 2005 and 2006 (Fig. 4). Indeed,  $u_*$  was greater for undercutter tillage than for conventional tillage during all high wind events in 2005 and during 31 of the 36 high wind events in 2006. The slope estimate of the relationship between  $u_*$  for undercutter tillage and conventional tillage across all high wind events in 2005 and 2006 (Fig. 4) was not different from unity ( $P < 0.05$ ) in both years, but the intercept of the relationship was significant ( $P = 0.02$ ) in 2005. A paired  $t$ -test further indicated that differences in  $u_*$  between tillage treatments were significant ( $P < 0.01$ ) both years. Although  $u_*$  was estimated from mean wind velocities during a high wind event, the variability or error in  $u_*$  was examined during singular high wind events (those that lasted  $>6 \text{ h}$ ) by computing  $u_*$  for each 1 min period during an event. These 1 min  $u_*$  values were then sorted by wind velocity categories of 6–7, 8–9, and 10–11  $\text{m s}^{-1}$  at a height of 6 m. The standard error in  $u_*$  was then computed for each wind velocity category. Standard error in  $u_*$  varied little between tillage treatments, wind velocity categories, and years. For a singular high wind event, the standard error in  $u_*$  was about  $0.005 \text{ m s}^{-1}$ .

### 3.3. Aerodynamic roughness

Changes in the apparent roughness of the surface due to sowing winter wheat are distinguishable in the observed trend of  $z_o$  (Fig. 3). Aerodynamic roughness prior to and after sowing was respectively 2 (SE = 0.3) and 8 (SE = 0.6) mm for conventional tillage and 7 (SE = 0.5) and 15 (SE = 1) mm for undercutter tillage in 2005. In 2006,  $z_o$  prior to and after sowing was respectively 2 (SE = 0.2) and 7 (SE = 0.5) mm for conventional tillage and 4 (SE = 0.2) and 11 (SE = 0.6) mm for undercutter tillage. The greater  $z_o$  that was apparent after sowing wheat is likely due to an increase in ridge roughness in both treatments as a result of the sowing operation. Ridge roughness, defined according to Zingg and Woodruff (1951), was 0 mm prior to sowing and 89 and 108 mm after sowing in subsequent years. Enhanced random roughness did not contribute to the greater  $z_o$  after sowing because random roughness appeared to change very little as a result of the sowing operation (Table 2). After sowing in 2005,  $z_o$  declined with time; for example, the slope of the relationship between  $z_o$  and day of year was  $-0.14 \text{ mm d}^{-1}$  for conventional tillage and  $-0.25 \text{ mm d}^{-1}$  for undercutter tillage. Although these relationships were significant ( $P < 0.05$ ), the high  $z_o$  observed on 9 September (day 252) influenced this trend. Opposite trends were

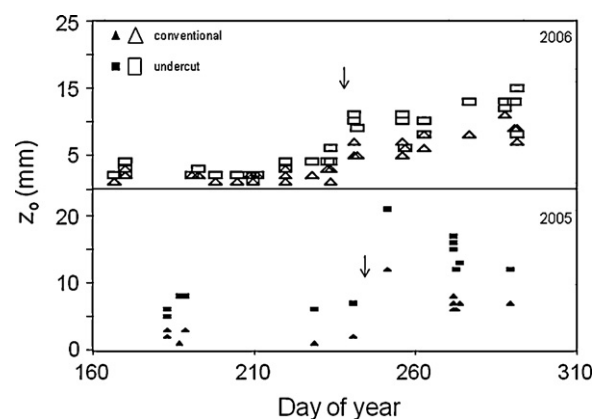


Fig. 3. Aerodynamic roughness ( $z_o$ ) of conventional and undercutter tillage during high wind events in 2005 and 2006. The arrows indicate dates of sowing both years.

observed in 2006 as  $z_o$  increased with time after sowing. In fact, after sowing in 2006, the slope of the relationship between  $z_o$  and day of year was  $0.08 \text{ mm d}^{-1}$  ( $P < 0.01$ ) for conventional tillage and  $0.06 \text{ mm d}^{-1}$  ( $P = 0.07$ ) for undercutter tillage. The increase in  $z_o$  with time after sowing in 2006 was likely due to development of winter wheat.

Aerodynamic roughness was higher for undercutter tillage than for conventional tillage during high wind events in 2005 and 2006 (Fig. 5). The slope of the relationship between  $z_o$  of tillage treatments was significantly ( $P < 0.05$ ) greater than unity both years while the intercept of the relationship was only significant in 2005. A paired  $t$ -test indicated that differences in  $z_o$  between tillage treatments were significant ( $P < 0.01$ ) both years. The greater  $z_o$  of undercutter tillage was likely due to enhanced roughness of the soil surface created by the undercutter tillage implement. Indeed, silhouette are index was consistently greater for undercutter tillage than for conventional tillage both years (Table 2). Although  $z_o$  was estimated from mean wind velocities during a high wind event, the variability or standard error in  $z_o$  during singular high wind events was examined by computing  $z_o$  for each 1 min period and sorting by wind velocity categories (6–7, 8–9, and 10–11  $\text{m s}^{-1}$  at a height of 6 m) during an event. Standard error in  $z_o$  was about 0.5 mm and varied little between tillage treatments, wind velocity categories, and years.

### 3.4. Impact on dust flux

The aerodynamically rougher surface of undercutter tillage should reduce sediment flux and dust emissions during high wind events as compared with conventional tillage. Indeed, Sharratt and Feng (2009) reported 15–70% less sediment flux and vertical dust

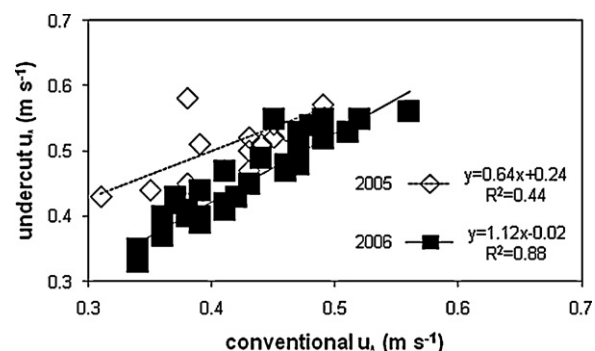


Fig. 4. Relationship between friction velocity ( $u_*$ ) of conventional and undercutter tillage across all high wind events observed in 2005 and 2006.

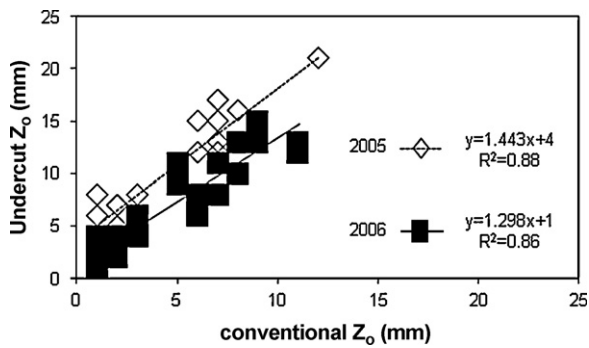


Fig. 5. Relationship between aerodynamic roughness ( $z_0$ ) of conventional and undercutter tillage across all high wind events observed in 2005 and 2006.

flux from the undercutter tillage plot than from conventional tillage plot across four high wind events in 2005 and 2006. However, differences in sediment loss and dust flux between tillage treatments were not observed when the soil surface was completely covered with a crust. Since  $u_*$  was higher for undercutter tillage than for conventional tillage, the smaller  $F$  measured from undercutter tillage can only be possible if  $u_{*t}$  was also higher for undercutter tillage than for conventional tillage. Based upon silhouette area and prostrate residue cover measured prior to sowing both years (Table 2),  $u_{*t}$  estimated from Eq. (5) was  $0.35 \text{ m s}^{-1}$  for conventional tillage and  $0.85 \text{ m s}^{-1}$  for undercutter tillage in 2005 and  $0.30 \text{ m s}^{-1}$  for conventional tillage and  $0.55 \text{ m s}^{-1}$  for undercutter tillage in 2006. For undercutter tillage, the estimated  $u_{*t}$  exceeded the observed  $u_*$  both years; therefore, the estimated  $F$  was zero prior to sowing in 2005 and 2006. Dust flux, however, was observed from undercutter tillage during one high wind event prior to sowing in 2006 (Sharratt and Feng, 2009). This disparity in estimated and observed dust flux, although for one high wind event, may be due in part to inaccurately specifying the threshold friction velocity of unconsolidated soil particles (we assumed a mean particle diameter of  $100 \mu\text{m}$ ) in estimating  $u_{*t}$ . For conventional tillage, the estimated  $u_{*t}$  was less than the observed  $u_*$  both years; thus, the estimated  $F$  was  $>0 \mu\text{g m}^{-2} \text{ s}^{-1}$  both years. Although  $\gamma$  in Eq. (3) varies between  $\sim 0.001$  and  $0.01 \text{ g s}^3 \text{ m}^{-6}$  for the Columbia Plateau (Claiborn et al., 1998),  $\gamma$  was assumed to equal  $0.001 \text{ g s}^3 \text{ m}^{-6}$  for the purpose of conservatively estimating flux in this study. According to Eq. (3), the estimated  $F$  from conventional tillage was  $0.5$  and  $4.5 \mu\text{g m}^{-2} \text{ s}^{-1}$  prior to sowing in subsequent years. Although Sharratt and Feng (2009) only observed  $F$  during one high wind event prior to sowing across both years, their observed  $F$  from conventional tillage in 2006 ( $9 \mu\text{g m}^{-2} \text{ s}^{-1}$ ) is comparable to that estimated in 2006. These findings suggest that the aerodynamically rougher surface of undercutter tillage likely increases the threshold friction velocity and thereby reduces sediment flux and vertical dust flux during high wind events as compared with conventional tillage.

#### 4. Conclusions

Undercutter tillage has been promoted as a conservation tillage practice during the summer fallow phase of a winter wheat–summer fallow rotation to reduce wind erosion within the Columbia Plateau of the Pacific Northwest United States. Unknown, however, is the extent to which undercutter tillage affects soil surface characteristics that govern wind erosion. Friction velocity and  $z_0$  were greater for undercutter tillage than for conventional tillage, apparently due to enhanced roughness of the soil surface created by the undercutter tillage implement. Based upon estimates of  $u_{*t}$  from crop residue cover and silhouette area index prior to sowing both tillage treatments, vertical dust flux is expected, and was collaborated, to be lower from undercutter tillage than from conventional tillage. Undercutter tillage promotes retention of crop residue and roughness elements on the soil surface that reduces dust emissions from soils in the Columbia Plateau.

#### References

- Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Methuen, New York, NY.
- Burnham, T.J., 2007. Study finds savings in using undercutter. In: Western Farmer–Stockman, May, p. 6.
- Campbell, G.S., 1986. An Introduction to Environmental Biophysics. Springer-Verlag, Inc., New York, NY.
- Claiborn, C., Lamb, B., Miller, A., Beseda, J., Clode, B., Vaughan, J., Kang, L., Newvine, C., 1998. Regional measurements and modeling of windblown agricultural dust: the Columbia Plateau PM10 program. J. Geophys. Res. 103, 19753–19767.
- Currence, H.D., Lovely, W.G., 1970. The analysis of soil surface roughness. Trans. ASAE 13, 710–714.
- Fryrear, D.W., 1986. Wind erosion and its effect on plant growth. Ann. Arid Zone 25, 245–254.
- Gillette, D.A., Passi, R., 1988. Modeling dust emission caused by wind erosion. J. Geophys. Res. 93, 14233–14242.
- Hagen, L.J., 1996. Crop residue effects on aerodynamic processes and wind erosion. Theor. Appl. Climatol. 54, 39–46.
- Hudson, T., Cary, A., 1999. Dust storm causes deadly pileup on I-84. In: Tri-City Herald, September, A1, Kennewick, WA.
- Oke, T.R., 1987. Boundary Layer Climates. Routledge, New York, NY.
- Raupach, M.R., Gillette, D.A., Leys, J.F., 1993. The effect of roughness elements on wind erosion threshold. J. Geophys. Res. 98, 3023–3029.
- Schillinger, W.F., 2001. Minimum and delayed conservation tillage for wheat-fallow farming. Soil Sci. Soc. Am. J. 65, 1203–1209.
- Shao, Y., 2000. Physics and Modeling of Wind Erosion. Kluwer Academic Publishers, The Netherlands.
- Sharratt, B., Lauer, D., 2006. Particulate matter concentration and air quality affected by windblown dust in the Columbia Plateau. J. Environ. Qual. 35, 2011–2016.
- Sharratt, B., Feng, G., 2009. Windblown dust influenced by conventional and undercutter tillage within the Columbia Plateau, USA. Earth Surf. Proc. Land. 34, 1323–1332.
- Stull, R.B., 2000. Meteorology for Scientists and Engineers, 2nd edition. Brooks/Cole, Pacific Grove, CA, 502 pp.
- Thom, A.S., 1975. Momentum, mass and heat exchange of plant communities. In: Montheith, J.L. (Ed.), Vegetation and the Atmosphere. Academic Press, New York, NY.
- Wagner, S.W., Lindstrom, M.J., 1996. Portable virtual instrumentation for soil infiltration and roughness measurements. In: Zazueta, F.S. (Ed.), Sixth International Conference on Computers in Agriculture, St. Joseph, MI Am. Soc. Agric. Eng..
- Zingg, A.W., Woodruff, N.P., 1951. Calibration of a portable wind tunnel for the simple/determination of roughness and drag on field surfaces. Agron. J. 43, 191–193.