PATTERNS OF CARBONATE DUST DEPOSITION: IMPLICATIONS FOR FOUR FEDERALLY ENDANGERED PLANT SPECIES

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Abstract

The calcareous soils in the San Bernardino National Forest host a group of endemic plant species, including five listed as federally endangered. The parent material for these soils is a very pure deposit of magnesium and calcium carbonate that is being actively mined. The mining operations produce copious quantities of dust. This study evaluated the quantity of dust moving across the landscape and depositing to the ecosystems, and the effect of carbonate dust on physiological parameters of a plant species acting as a surrogate for the endangered species. Most of the dust was found to deposit within one kilometer of the mining operations. Plants growing within the deposition zone had lower photosynthetic activity and less vigorous growth patterns. Several mitigation measures are recommended.

Key Words: calcareous soils, carbonate dust, dust deposition, passive monitoring.

Dust is the most common air quality problem in arid and semi-arid ecosystems. The effects of anthropogenic dust on native vegetation do not receive as much research attention as does the effects of gaseous pollutants. In part, it is because "dust" is a site-specific parameter dependent on the events or mechanisms of generation and the geologic source (Reheis et al.1995). The effects of dust deposition on plant biology and ecological function are also site specific (Farmer 1992). Both of these effects are dependent on weather and climate conditions, and characteristics of the plant community. Furthermore, damage caused by dust can vary from physical effects such as abrasion and surface coating, to chemical effects such as alkalinity due to limestone deposition or heavy metal toxicity due to road and fly ash deposition. Unlike gaseous air pollutants, which usually cause one or two symptoms related to the chemical behavior of the gas, deposition of particulate dust causes multiple responses controlled by a wide array of variables, such as wind speed, chemical composition, and particulate size.

The four common sources of dust are urban secondary aerosols, road dust (both from paved and unpaved surfaced), dust created by cement manufacturing, and open pit or strip mining – particularly limestone mining (Bačić et al. 1999; Ashbaugh et al. 2003). In this study, we evaluated the distribution of particulates and the effects of limestone mining and crushing activities on an endemic calcareous plant community in the San Bernardino Mountains of Southern California.

The Sentinel Crusher site is on the San Bernardino National Forest and leased to the OMYA Inc., an international company with North American headquarters in Proctor VT. It is located in Holcomb Valley on the north slope of the San Bernardino Mountains in southern California. OMYA Inc. actively mines dolomite deposits from open strip mines. Dolomite is a sedimentary rock containing both calcium carbonate and magnesium carbonate (collectively referred to as "carbonates"). It is a common treatment for neutralizing acid soils in agricultural systems, and as is the case for dolomite mined at the Sentinel site, it is commonly used in medical products and medicines. Dolomite mining activities such as blasting, excavating, processing, and vehicle movement to transport rock and tailings, produce large amounts of fugitive dust (Farmer 1992).

Calcareous soils developed from limestone or dolomitic parent materials provide unique habi-

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tat for many endemic plant species globally (Krunkeberg 2002). Ten rare plants in the San Bernardino Mountains occur only in localized pockets of carbonate substrates (USFWS 1997). Of those species, *Acanthoscyphus parishii* (Parry) Small var. *goodmaniana* (Ertter) Reveal (i.e., *Oxytheca parishii* Parry var. *goodmaniana* Ertter; Cushenbury oxytheca; Polygonaceae) and *Eriogonum ovalifolium* Nutt. var. *vineum* (Small) A. Nelson (Cushenbury buckwheat; Polygonaceae) are federally endangered with populations in the Holcomb Valley. Protection of these species is addressed in a U.S. Fish and Wildlife Service recovery plan (USFWS 1997b), and habitats of both are threatened by future expansion plans at the Sentinel Crusher site.

Our first objective was to measure and describe the distribution and deposition of carbonate dust in the complex terrain around the mining operation. The distribution of carbonate dust depends greatly on wind speed, wind direction, and particle size, with smaller particulates (<20 μm) able to enter long-term suspension and travel great distances. In addition, as with most limestone mines, the site managed by OMYA Corporation, is located in mountainous terrain making *a priori* estimates of direction and concentration of limestone dust generated by the mining activities difficult. The interactions of precipitation, temperature, geologic substrate, and wind speed on aerlization and subsequent deposition of dust are complicated (Reheis et al.1995; Reheis and Kihl 1995). Because it was critical to understand detailed deposition patterns, we developed a passive sampler that enabled us to monitor deposition of $Mg/CaCO_3$ at 30 locations along seven transects radiating in ordinal directions from a central point at the limestone crusher. We also deployed two real time electronic particulate monitors to provide information on atmospheric loads adjacent to the crusher and 600 m away.

Our second objective was to assess the effects of deposition on plant productivity. Because experimental manipulation of protected plant species is prohibited, we selected a surrogate species, *Eriogonum microthecum* Nutt. var. *corymbosoides* Reveal (Polygonaceae) to measure physiological characteristics and phenology.

The most obvious effect of dust deposition on plant biology is surface coating, which reduces light availability and therefore CO_2 assimilation. Gale and Easton (1979) investigated loading of leaf surfaces due to limestone mining in Israel and found that leaves reached a maximum surface loading of 15.2 mg cm^{-2} (152 g m^{-2}) and that the gradient in deposition declined to near background concentrations (1.4 mg cm^{-2} [14 g m^{-2}]) at 1.1 km. In their study, they detected little deleterious effects of dust. Several other studies have, however, shown significant reduction in CO_2 assimilation with increased dust accumulations (Farmer 1992). Some studies have suggested that since many dust particles are an ideal size to lodge in open stomata, perhaps reduction in water use efficiency and increased drought susceptibly may result from dusty environments (Eveling 1986; Manning 1971). Subsequent studies have shown both increases and decreases in transpiration (Farmer 1992) suggesting that the physiological parameters of photosynthesis, respiration, and transpiration are so closely linked that establishment of a single response is impossible.

Since the greater concern is usually productivity of agricultural or native vegetation, phenological methods have been used to establish direct links between dust deposition and productivity. In the arid Mojave, road dust caused early senescence of leaves and reduced photosynthesis (Sharifi et al. 1997). In the Appalachian Mountains, a mesic mixed hardwood forest impacted by limestone mining had smaller leaf areas in deciduous tree species and reduced apical growth in hemlocks (Brandt and Rhoades 1972). The Appalachian study also suggested that the ultimate ecological response was a shift in species composition. This, of course, is a major concern of land managers for endemic species and in developing habitat protection plans for threatened and endangered plant species in unique habitat.

This report describes the atmospheric dispersion pattern of limestone dust, provides details of a passive deposition monitoring method, and examines the effects of dolomitic limestone deposition on plant physiology and phenology.

MATERIALS AND METHODS

Study site. The Sentinel mine and crusher are located on the northeast side of the San Bernardino Mountains in the rain shadow of coastal storms (Fig. 1). The vegetation is characteristic of the San Bernardino Mountains in the Transverse Ranges subregion of the Southwestern California region of the California Floristic Province, but also carries some elements of the Desert Mountains subregion of the Mojave Desert region of the Desert Province (Hickman 1993). The area is home to a community of endemic calcareous plant species.

Most of the open strip mines and the rock crushing operation are on an east-facing slope. The terrain is rugged and steep to the north, and although flatter to the south, the landscape contains patches of dense standing vegetation, and dense patches of down and dead trees and shrubs. Mining has been active in the area for many years so there are many remnants of past activities scattered throughout the area including open pits, slag piles, and tailings.

Legend:
- ● Monitoring Sites
- ▨ Mining Disturbance
- ▨ Astragalus albens
- ▨ Erigeron parishii
- ▨ Eriogonum ovalifolium var. vineum
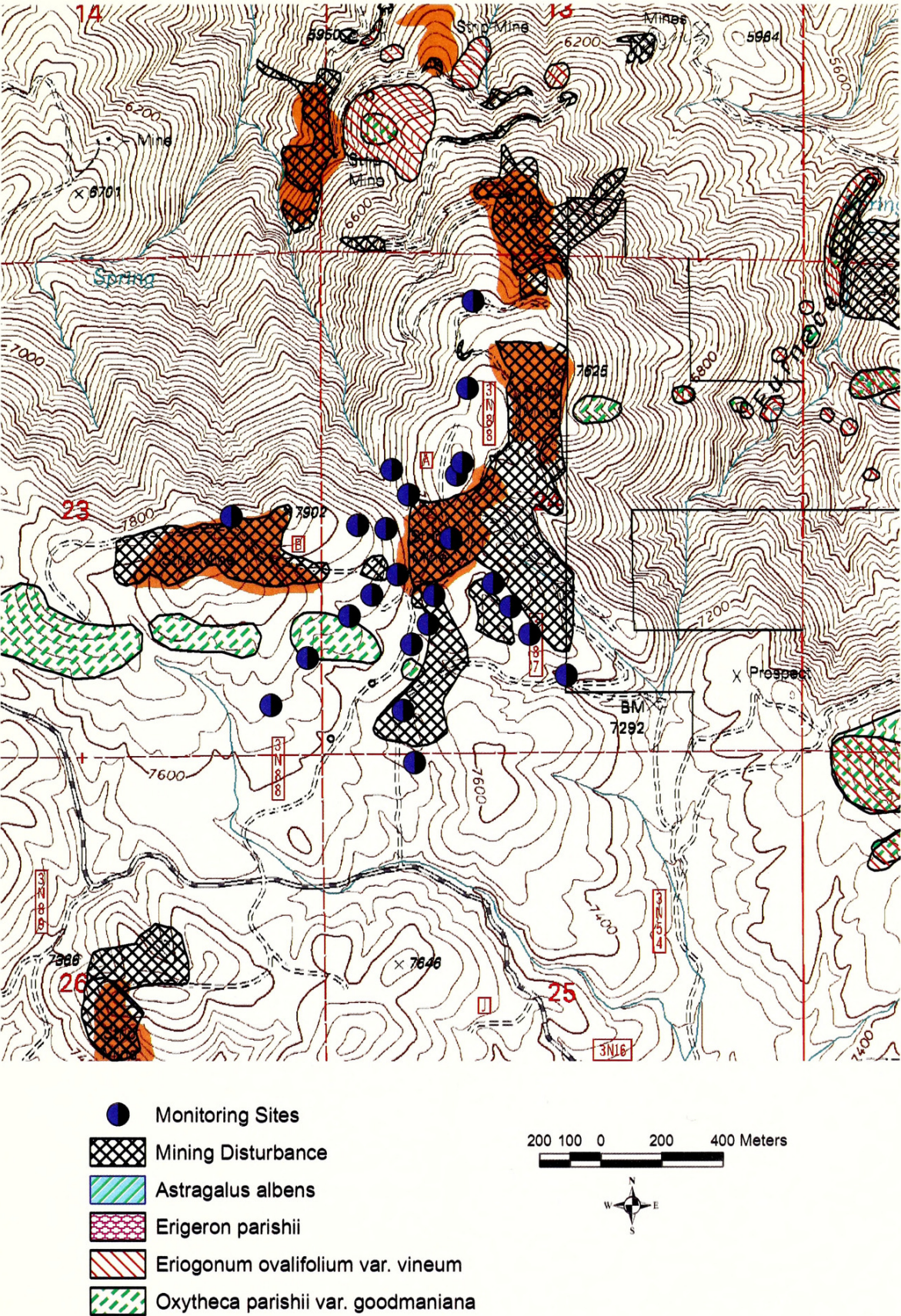- ▨ Oxytheca parishii var. goodmaniana

200 100 0 200 400 Meters

Fig. 1. Local topography and location of mining activities, plant populations and sampling sites. This map was produced with cooperation of the San Bernardino National Forest.

Preliminary survey. Deposition patterns on foliage, estimates of dust size, and evaluation of dust particles lodging in stomata was conducted in a preliminary survey. Leaf samples were collected from individuals adjacent to mining activities and at 1 km away from activities. Leaf specimens were examined with an XL30-FEG SEM (Philips, New York, NY) that uses a field

emission electron gun with a Schottky emission cathode. Samples were affixed to aluminum mounts with double stick carbon tape (Ted Pella, Inc., Redding, CA) and sputter coated with gold and palladium using an Emscope Sputter Coater 500A (Quorum Technologies, East Sussex, UK). Samples were placed approximately 40 mm from the target material (cathode) and coated at a deposition rate of 15–18 mA for 105 sec. Images were captured digitally.

Study design. This study was conducted during the late summer and fall of 2003 and from spring (April) through fall of 2004. Dust distribution data are from the full growing season of 2004, as are the plant productivity data. Meteorological data and data from the DataRam particulate monitors from the fall 2003 season, as is the photosynthesis information.

The study was conducted in a 1 km radius area around the crusher. Passive monitoring sites were established along transects in ordinal directions from a center point creating concentric circles around the center point (34°19′47.85″N, 116°56′21.35″W). The center point was as close to the main point source of dust, a rock crusher, as we could safely locate it (Fig. 1). Individual sampling sites along each transect were located 200, 300, 400, 600, 800, and 1000 m from center in the ordinal directions of N, NW, W, SW, S, and SE. Sites are described throughout this paper by direction and distance from center (e.g., N200 is located 200 m north of the center point). A few monitoring sites deviated from their planned location or were eliminated because of roads, obstructions, or impassible terrain. No sites were set up to the northeast due to inaccessibility and steep terrain and only a single site at 1000 m was established east of the crusher.

Portable weather stations (Onset Computer Corp, Pocasset, MA) were set up at N200 and SW600. Wind speed and direction, temperature, and relative humidity were recorded every 10 min by a HOBO weather station data logger. The data loggers were downloaded using BoxCar® Pro 4.3 at 3- to 4- week intervals. At both weather stations, Portable Particle Sizing Aerosol Monitor/Data loggers (model DR-4000, TermoAnderson, Smyrna, GA) were installed. The DR-4000s are continuous, real-time monitors, which determine particle size (μm) and mass concentration levels ($\mu g\ m^{-3}$), reporting the data to internal dataloggers at user-determined intervals. The sampling flow rate was 1.0 L min^{-1}, readings were automatically averaged every 10 sec with a resolution of 0.0001 mg m^{-3}; and means of the averages were then recorded every 10 min. The DR-4000 aerosol monitors were gravimetrically calibrated to dolomite particles collected from the crusher site, following the ThermoAnderson® protocol, prior to placement in the field.

The passive collectors were constructed from plastic jars, 55 mm deep with a 65 mm diam. opening. To keep deposited particles trapped in the jars, each cup contained a 20 mm thick loosely-spun fiberglass filter. The passive collectors were fastened to a rebar stake at 1.0 m above the ground at each sampling site. Passive collectors were transported to and from field sites sealed and exchanged every 3–4 wks from August 25, 2003 to October 22, 2003, and from April 2004 to October 2004. Both unopened field blanks and lab blanks were used to evaluate background and potential contamination from transport.

The amount of carbonate deposited in each cup was determined by chemical analysis (Goh et al. 1993). Twenty mL of 0.4 M acetic acid was added to each collector. The jars were sealed, shaken for 30 sec, and allowed to react for 30 min, after which the pH of the solution was measured. The analysis was based on the neutralization reaction of 0.4 M acetic acid with Mg/CaCO$_3$. Milligrams of CaCO$_3$ in each collector were calculated from a standard curve with a range of 2 to 500 mg CaCO$_3$.

In addition to passive collectors, direct deposition to plant leaves was measured at 11 of the passive sites where the appropriate surrogate species was present. Five leafy stems of one individual per site were washed on August 25, 2003 with 5% acetic acid and then rinsed with nanopure water. The method was developed in a series of controlled laboratory experiments prior to use in the field. Tests were conducted using stereoscopes to determine the optimum washing method with a minimum of physical damage to the plants. One leafy stem from each plant was collected every 3–4 wk when passive cups were exchanged, making readings cumulative. Chemical analysis for CaCO$_3$ was performed in the same manner as for the passive collectors above. The leaf area for each sample was measured using a LI-3100 leaf meter (LiCor Inc., Lincoln NE) and deposition of carbonate dust on the photosynthetic tissue (both stems and leaves) was recorded as mg cm^{-2}.

A LI-COR® LI-6200 portable photosynthesis system was used to determine net photosynthesis (A), stomatal conductance (g$_s$), and transpiration (E) under ambient conditions. One small, leafy stem was sealed in a 250 ml leaf chamber for gas measurements and a flow rate of 200 μmol sec^{-1} was established. Ten plants were measured at each active monitoring site (N200 and SW600) on October 22 and 23, 2003 between 09:30 and 11:30, when photosynthetic rates for this species were maximal. Leaf area was measured using a LI-3100 leaf meter and entered into the LI-COR® LI-6200 prior to computing gas measurements. Photosynthetic measurements were repeated in 2004.
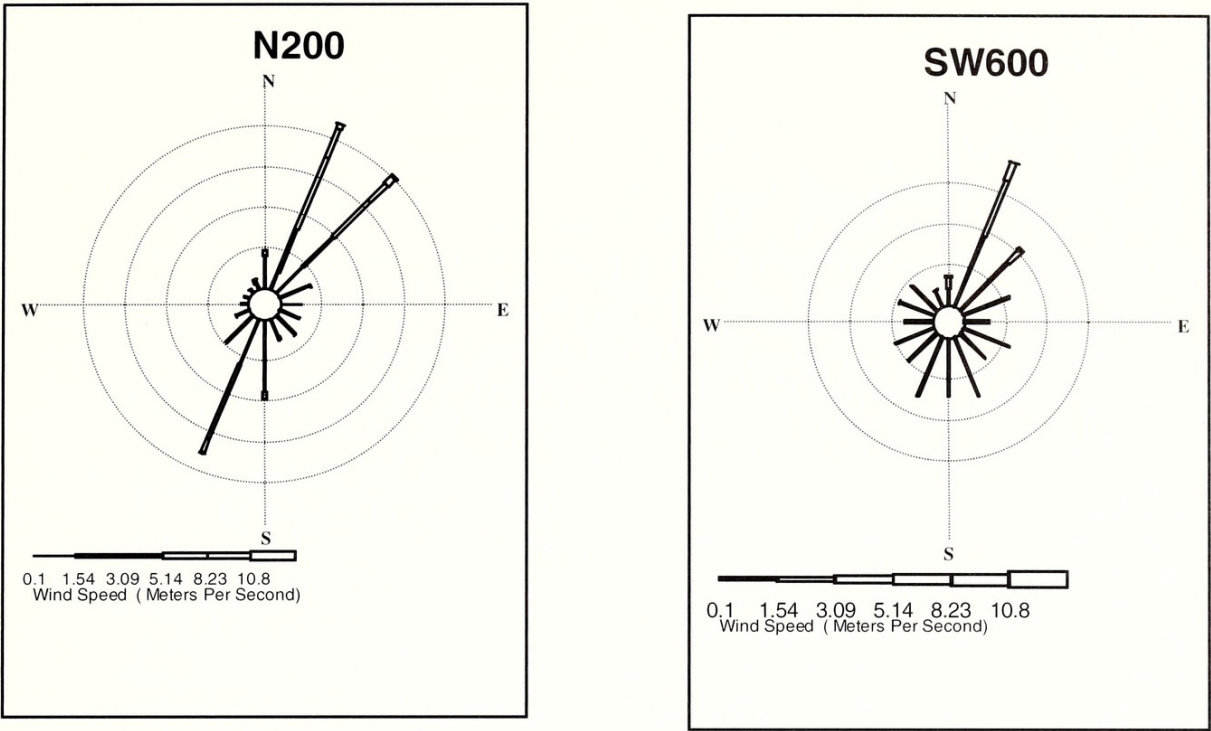
Fig. 2. Wind roses for August through October, 2003 at the N200 location adjacent to mining activities, and at SW600, partially shielded by juniper forest vegetation. Wind speeds and wind directions are the sums of 3 month exposures.

Phenological characteristics were measured three times during the growing season, in April, June, and September 2004. Ten plants at each of 3 locations (N200, SW600, and SE1000) were selected, and five shoots on each plant were marked for repeated measurements. The following parameters were determined: number of stems per plant, total shoot length, foliated shoot length, length of new growth on shoot, number of new branches on shoot, and number of flowers per stem.

Data analysis. The weather and aerosol data including wind speed (m s^{-1}), particle size (μm), and mass concentration levels (μg m^{-3}) were analyzed using a Mann-Whitney Rank Sum Test for non-parametric data and treatments were considered significantly different when P < 0.05. The passive cup sampling data passed both normality and equal variance tests once transformed to the negative log of the original dataset. The transformed data were then analyzed using a two-way ANOVA and reported as mean ± 1 standard error (SE) of the original data set. A (all-pairwise) multiple comparison test (Holm-Sidak method) was then used to determine significant difference (i.e., P < 0.05) among sites based on direction and distance, respectively. The data were analyzed and represented using the sum of three consecutive sampling periods between April and October 22, 2004. Statistical analysis was not performed on the plant washing data due to lack of replication.

However, the data are presented for each sampling period and site.

The gas exchange data met requirements for both normality and equality of variances once transformed to square (photosynthesis) and square roots (conductance and transpiration) of the original dataset. The transformed data were then analyzed using two-way ANOVA and were presented as mean ± 1 SE in untransformed units. Data were analyzed using Sigma Stat version 3.0 (SPSS Inc, Chicago, IL).

RESULTS

Wind speed was significantly different (P < 0.001) between the two active stations (N200 and SW600) with the N200 site (nearest the crusher) experiencing a greater median wind speed of 2.04 m s^{-1} compared to 0.93 m s^{-1} at the SW600 site (Fig. 2). The average daily dose, calculated from the three months of particulate monitoring, was consistently higher for the N200 site than for the SW600 site (Table 1). However, particle size was significantly larger (P < 0.001) at the further SW600 site than at N200 (0.34 and 0.31 μm, respectively) (Fig. 3).

At both weather stations, winds were mostly from the southwest. And, most of the stronger winds were from the southwest (Fig. 2), although the N200 monitoring station recorded periodic strong winds from the northeast. Both the fall season and the direction of the winds were consistent with Santa Ana winds—the strong
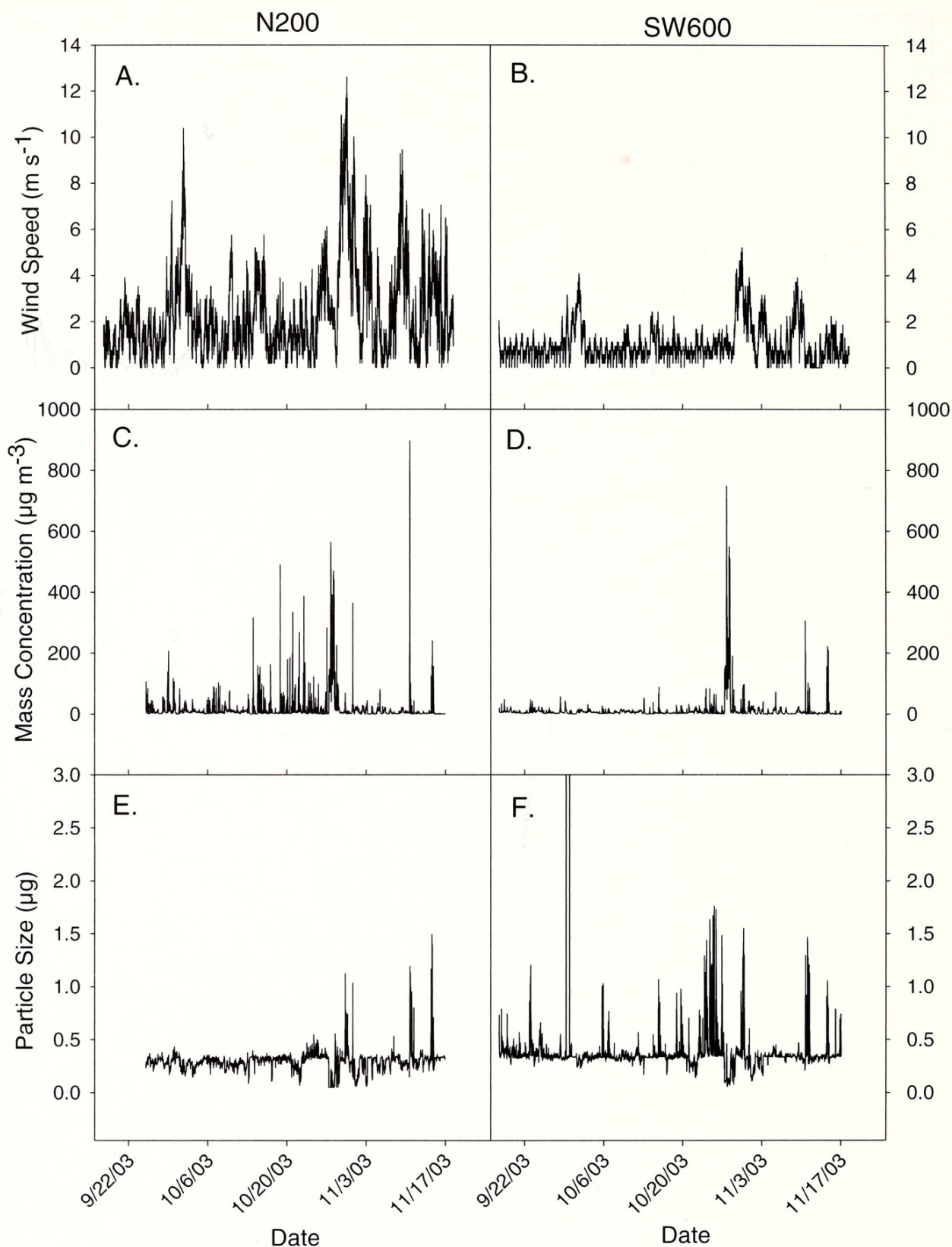
FIG. 3. Comparison of wind speed (panels A and B), atmospheric particulate loads less than 10 μm (panels C and D) and average particle size (panel E and F) between a sampling site adjacent to mining activities and a site partially shielded by juniper forest vegetation.

dry winds that occur in the fall in Southern California. The SW600 monitoring station recorded gentle breezes in all directions. The differences in wind patterns recorded at the two monitoring stations are likely due to topography (see Fig. 1). The SW600 site was located in a relatively open, flat area, whereas the N200 station was installed on an east-facing slope.

Data collected by the DR-4000 particulate monitors at the two locations indicated that wind direction and speed were important for deposition (Fig. 3). Average concentrations of particu-

lates were consistently higher at the N200 station reflecting both proximity to the crusher and prevailing wind directions (Fig. 3A, B), but periodic spikes over 400 µg m^{-3} occurred throughout the fall of 2003. Particulate sizes tended to be small, roughly 0.5 µm diam., but windier conditions increased the average diameters to 1.0 µm (Fig. 3E). The average concentrations at the SW600 location were indicative of lower wind speeds overall (Fig. 3B). Spikes in atmospheric concentration coincided with increased wind speed, and changes in wind direction (Fig. 2). Particle sizes were significantly larger at the SW600 site during these higher wind events.

The amounts of carbonate dust collected in the passive samplers were consistent with the measurements of all aerosols recorded by the DataRam 4000 active monitors. In Fig. 4, the largest concentration of carbonate dust was collected from the N, W, and SW. The data from NW transect were incomplete and not shown. At 200 m these three sampling sites were similar to each other, but significantly greater than the S or SE locations (P < 0.001). Consistent with the prevailing wind direction, the N transect collected significantly more CaCO$_3$ at all distances (P < 0.001). For all other transects, carbonate dust concentrations were essentially zero by 600 m from the crusher.

Direct deposition to foliage was measured in 2003 (Fig. 5). Foliage collected from the N200 site had significantly (P < 0.001) greater CaCO$_3$ at all three sampling periods than any of the other locations. Carbonates measured on foliage collected from N600 and SW400 on Oct 23, 2003 were significantly greater than the deposition measured at the other locations (P < 0.05).

Figure 6 shows the wide range of particle sizes collected on foliar surfaces. All four panels are of *Eriogonum microthecum*. Panel B shows the lower surface at 67× magnification. Dust particles are roughly spherical and appear to be trapped in the tread-like trichomes. At higher magnification (1098×), dust particles collecting on the upper surface (panel D) range from less than 1 µm to clumps of material greater than 20 µm. There appear to be at least two types of particles: very angular particles typical of clays and less structured particles typical of calcium carbonates. Both panels C and D capture examples of particles lodged in stomata, at least partially blocking the openings. Note that many of the particles are much larger than the 0.5 µm to 1.0 µm average size determined by the DataRam aerosol monitors.

Deposition of carbonate containing dust had a significant effect on photosynthesis and gas exchange in plants growing under high (N200) and low (SW600) deposition (Table 2). In September 2003, photosynthesis was reduced by 15% and transpiration was reduced by 27% (Table 2).

Reduction in physiological function was reflected in phenology. Total shoot length, foliated length, and length of the new growth were all significantly reduced in plants sampled at the N200 location (Table 3). However, number of stems per plant, number of new branches initiated, and number of flowers per branch did not different across the three locations.

DISCUSSION

Atmospheric deposition. Topography and wind patterns were the primary factors controlling deposition loads at each of the monitoring stations. Secondarily, and much more difficult to capture in this sampling scheme, was the effect of filtering by vegetation. Trees and shrubs are very effective at capturing mining and manufacturing particulates (Zubareva et al. 1999). The four north sampling locations (see Fig. 1) were along a ridge with relatively unobstructed fetches from both the active mine and crusher, as well as unused (but exposed) strip-mines. In contrast, the south and southeast transects were screened by large, old juniper trees, scrub oaks and other native vegetation. This, in part, explains why deposition to the south and southwest transects was lower than one might expect given the wind patterns shown in Fig. 2B.

The passive sampling method only captured material moving vertically; thus, it likely underestimated total deposition to a foliar canopy. Because foliage is an effective screen and because surface roughness tends to enhance deposition, landscape accumulation of dust may have been several times higher than the values estimated from the passive collector cups. Moreover, only carbonates were measured. Therefore, it is likely that the total movement of dust due to the mining operation was considerably greater.

In an extensive study of dust movement in Nevada and Southern California, U.S. Geological Survey scientists determined deposition using an analogous vertical capture system. Fluxes of "total dust" ranged from 5.7 g m^{-2} yr^{-1} to 38.7 g m^{-2} yr^{-1} across 60 arid and semi-arid wildland areas (Reheis and Kihl 1995). Four of their sampling sites were on the western slopes of the San Bernardino Mountains at roughly 1000 m elevation. These sites tended to be in the higher deposition range at 13.7, 17.0, 23.3, and 38.7 g m^{-2} yr^{-1}; much of the source was attributed to Santa Ana winds. The authors also quantified carbonate content, which accounted for 10–15% of total load. Total carbonate deposition in our study was measured for six months and was substantially higher than the

TABLE 1. AVERAGE DAILY DOSE OF TOTAL ATMOSPHERIC PARTICLES MEASURED AT TWO LOCATIONS. N200 was adjacent to the rock crusher and SW600 was partially shielded by juniper forest vegetation.

	Days monitored	Average daily load (mg m^{-3} d^{-1})	
		N200	SW600
Sept	6	12.53	5.46
Oct	31	18.57	13.80
Nov	16	9.04	7.25

Reheis and Kihl data. If we consider the total deposition data published by Reheis and Kihl, as "background" deposition, most of our sampling sites within 400 m of the crusher were well above background, while the sites outside of 400 m (with the exception of the north transect) were at or below background levels. Although sites close to the crusher were clearly affected by mining and transportation activities, some of the more distant sites also appeared to be affected by dust from waste piles and inactive mine areas.

The active monitors measured total suspended particles, regardless of the mineralogy or where they ultimately deposited. The EPA criteria for unhealthful conditions for human exposure is a 65.4 µg m^{-3} average over 24 hr. There is no criterion standard for adverse effects on ecosystems. There were several health criterion exceedances at the N200 location, and one or two at the SW600 location. When the atmospheric concentration data are calculated as an average daily load (Table 1), the difference between the two sites is relatively small. Suspended particle loads at the SW600 location were 45% to 80% of that measured at the N200 site. However, when the measured deposition to each of these sites is compared, a much larger difference is evident (Fig. 4).

Plants. For the most part, deposition to foliage proved to be an inconsistent monitoring method, although measured quantities did correspond to CaCO$_3$ trapped in the passive samplers, in that the sites with higher deposition as determined by the passive samplers also had higher accumulations on leaf surfaces. One of the reasons for inconsistencies in measurements is the hygroscopic nature of CaCO$_3$. The boundary layer of all living leaves contains a shallow layer against the leaf surface that is saturated with water. Dewfall also partially solublizes carbonate particles causing them to clump, dissolve, blow off, and otherwise affect deposition characteristics of plant surfaces.

Decreases in plant physiological function and growth corresponded to increased deposition rates. This study confirmed the observations reported for *Larrea tridentata* and *Atriplex*
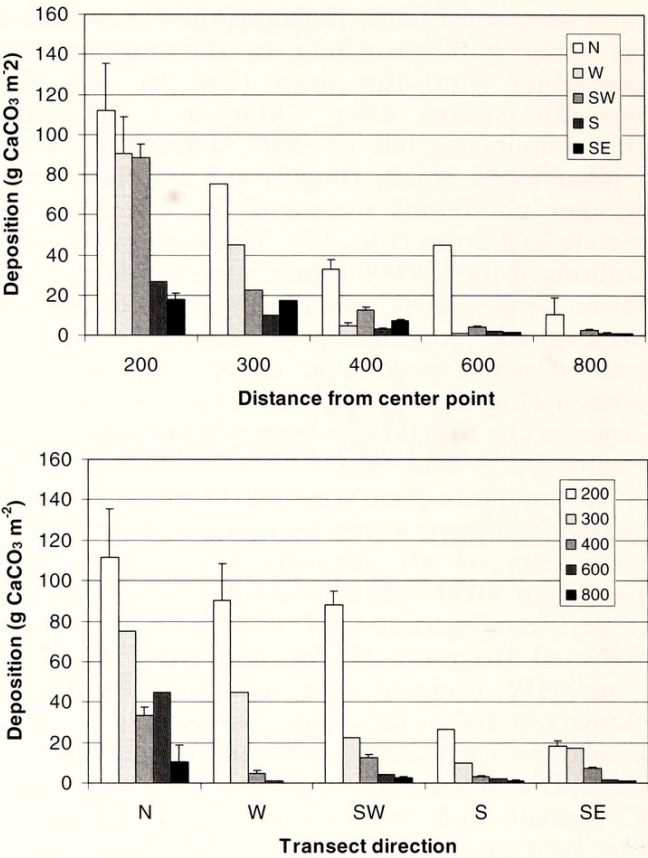

FIG. 4. Sums of carbonate deposition collected by passive samplers during the growing season, April through October, 2004. Samplers were placed along ordinal directions radiating from a center point close to the rock crusher. Samplers were replicated 3 times at the 200, 400 and 600 m distances. The NW transect data was incomplete and is not shown. The E1000 and SW1000 sites are also not displayed.

canescens in the Mojave Desert (Sharifi et al. 2003), for *Quercus coccifera* in Greece (Vardaka et al. 1995) and for mixed hardwoods in Virginia (Manning 1971). In the study presented by Sharifi et al. (1997), road dust was the source of deposition and estimated surface accumulation
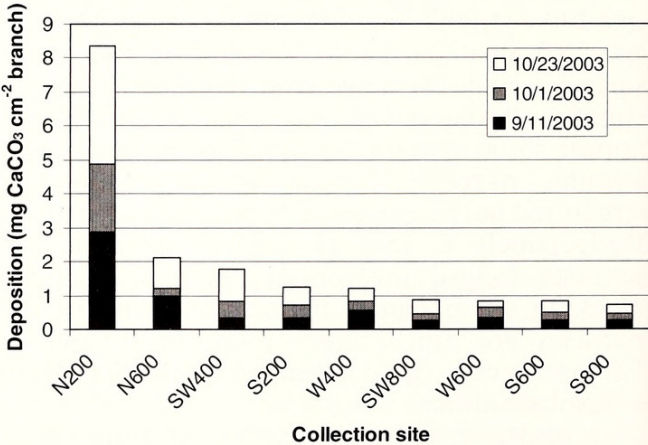

FIG. 5. Dust deposition to *Eriogonum microthecum* foliage during the fall of 2003. Branches were rinsed at the beginning of the experiment and then collected at 3 wk intervals.
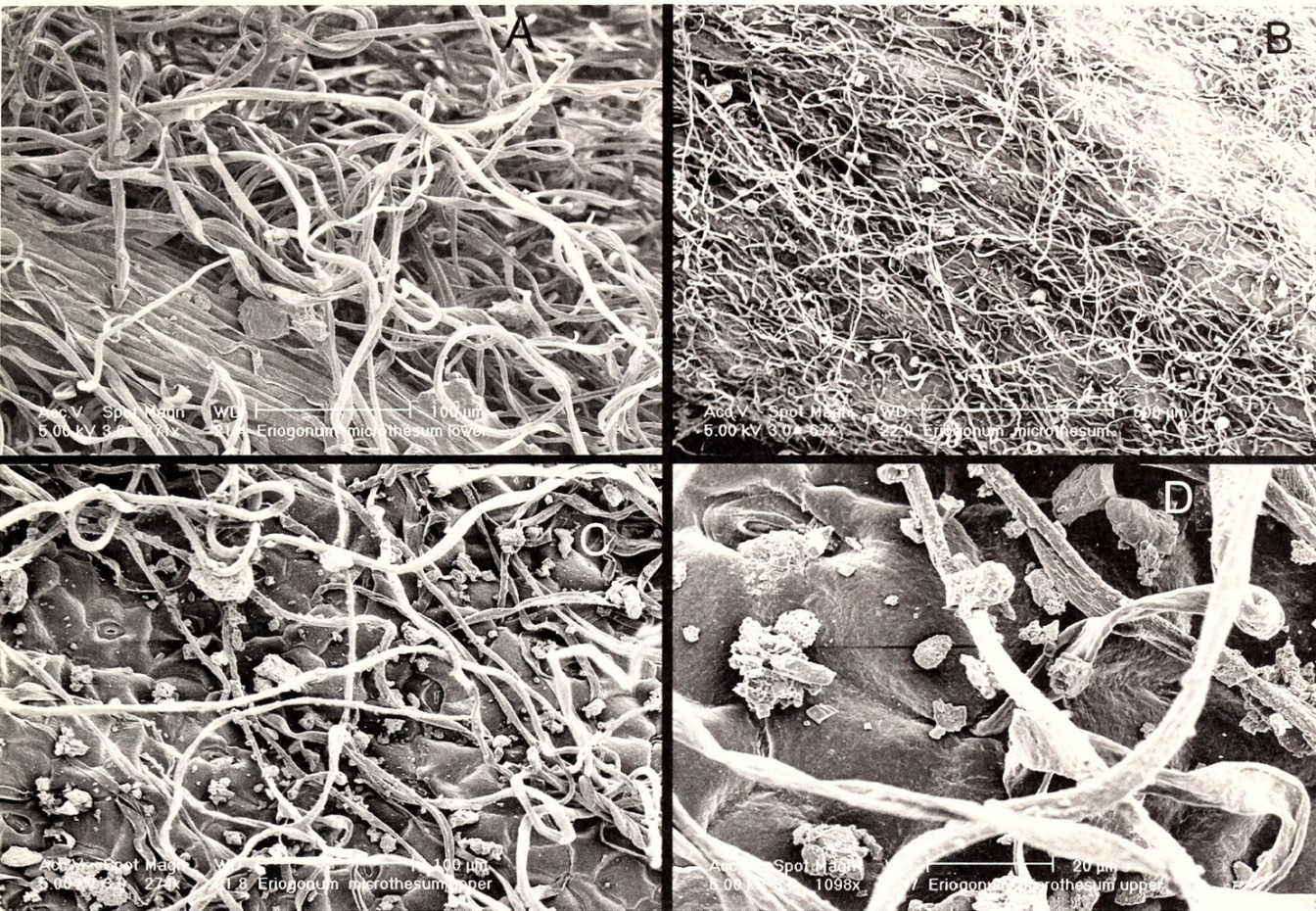
FIG. 6. Scanning electron micrographs of *Eriogonum microthecum* collected from locations near the mining operations. Panel A: 274× magnification, lower surface. Panel B: 67× magnification, lower surface. Panel C: 271× magnification, upper surface. Panel D: 1098× magnification, upper surface. Note stomata on the upper surface.

was 16 g m^{-2} for *Larrea* and 40 g m^{-2} for *Atriplex*, which is similar to the 10 to 20 g m^{-2} of $CaCO_3$ we estimated for *E. microthecum*. Depression in photosynthesis was also quite similar between the two studies. In *Larrea*, CO_2 assimilation rates were 13.2 µmol m^{-2} s^{-1} at the clean sites and 2.3 µmol m^{-2} s^{-1} for the dusty sites. *Atriplex* assimilation rates went from 19.9 µmol m^{-2} s^{-1} (clean) to 12.9 µmol m^{-2} s^{-1} under heavy loads of road dust. The differences in assimilation rates of *E. microthecum* exposed to carbonate dust were smaller than in the desert study, but statistically were significant with a difference of 8.32 µmol m^{-2} s^{-1} at the cleaner location and 7.06 µmol m^{-2} s^{-1} at the dusty location. Similar differences in photosynthetic rates were also reported for *Q. coccifera* by Vardaka et al. (1995) and others (Farmer 1993).

The differences in phenological characteristics exhibited by *E. microthecum* were also consistent with the reported literature. Older studies conducted near a limestone mine in Virginia noted reduced growth in hemlock, wild grape, and sassafras (Manning 1971). Although we did conduct preliminary evaluations of the leaf surface condition of several local plant species, they were less detailed than those by Bačić et al. (1999) who carefully described and monitored the effect of cement factory dust on the epicuticular wax of *Pinus halepensis* needles. Dry and wet deposition of limestone causes serious damage to the needle surfaces and seemed to accelerate blockage of stomatal cavities. Based on our preliminary evaluations, we suspect at our heaviest deposition sites, similar effects are occurring, but conclusive evidence will require further study.

TABLE 2. MEAN GAS EXCHANGE MEASUREMENTS FOR N200 AND SW600 SITES (±1 SE). Letters denote a significant difference between sites (P < 0.05).

	Units	N200	SW600	P	F
Photosynthesis	µmol m^{-2} s^{-1}	7.06 ± 0.49[a]	8.32 ± 0.39[b]	<0.001	41.982
Conductance	mol m^{-2} s^{-1}	0.12 ± 0.01[a]	0.16 ± 0.01[b]	<0.001	264.370
Transpiration	mmol m^{-2} s^{-1}	5.24 ± 0.22[a]	7.15 ± 0.33[b]	<0.001	606.142

TABLE 3. PHENOLOGIC MEASUREMENTS OF THREE *ERIOGONUM MICROTHESUM* POPULATIONS AT THREE DISTANCES FROM MINING ACTIVITIES. Ten plants per site were selected and three branches per plant were marked and resampled through the growing season.

	Site	April Mean (n = 30)	SEM	June Mean (n = 30)	SEM	September Mean (n = 30)	SEM
No. Stems per plant	N200	10.70	0.49	nd		5.89	1.10
	SW600	9.40	0.76	nd		6.60	0.79
	SE1000	11.20	0.45	nd		6.00	0.57
Total shoot length (base to apex, mm)	N200	129.90	3.20	113.45	5.47	117.59	5.11
	SW600	137.33	4.52	147.00	6.58	150.86	7.15
	SE1000	152.70	5.94	163.50	5.86	169.50	5.02
Foliated shoot length	N200	50.33	3.13	70.83	4.38	58.89	4.97
	SW600	68.63	4.41	95.41	5.84	79.48	6.52
	SE1000	69.07	3.17	95.00	3.47	93.07	2.70
Length of new growth	N200	2.47	0.24	52.29	4.85	43.31	4.92
	SW600	2.77	0.16	61.90	5.03	58.28	5.10
	SE1000	1.87	0.13	64.40	5.95	60.33	7.35
No. New branches per shoot	N200	6.60	0.31	4.15	0.30	2.48	0.29
	SW600	7.87	0.38	5.77	0.51	2.07	0.27
	SE1000	7.83	0.28	4.30	0.32	2.73	0.39
No. flowers per stem	N200	0.00		1.34	0.13	0.88	0.06
	SW600	0.00		0.70	0.15	0.88	0.06
	SE1000	0.00		1.40	0.16	0.93	0.05
Dust deposition g $CaCO_3$ m^{-2} (April through Sept)	N200	0.00		24.67	3.85	35.84	13.77
	SW600	0.00		4.15	0.01	2.66	0.19
	SE1000	0.00		1.17	0.08	0.44	0.19

CONCLUSIONS

The differences in growth and physiology suggest that plants growing within 400 m of disturbed limestone landscape or unprotected stockpiles are in degraded habitats. Plants further away, but in exposed areas within the prevailing winds are also in degraded habitats. Our data using a surrogate species in combination with data from the published literature indicates that deposition of dust, particularly carbonate dust, can reduce productivity of several endangered plant species. We conclude that limestone mining has detrimental effects on endemic populations of these rare species.

Our data suggest three mitigation measures that could reduce the extent of habitat degradation. First, maintain vegetation buffers around the crusher, stock and slag piles, and around the open mining operations. Natural barriers from trees and shrubs provide dust screens that may benefit sensitive species. Second, keep mining activities contiguous and contained. The greater the perimeter, the greater the extent of the disturbance and habitat degradation. Third, cover and replant spent mines, slag heaps, and areas no longer in active use.

LITERATURE CITED

ASHBAUGH, L. L., O. F. CARVACHO, M. S. BROWN, J. C. CHOW, J. G. WATSON, AND K. C. MAR-GLIANO. 2003. Soil sample collection and analysis for the fugitive dust characterization study. Atmospheric Environment 37:1136–1173.

BAČIĆ, T., A. H. LYNCH, AND D. CUTLER. 1999. Reactions to cement factory dust contamination by *Pinus halepensis* needles. Environmental and Experimental Botany 41:155–166.

BRANDT, C. J. AND R. W. RHOADES. 1972. Effects of limestone dust accumulation on composition of a forest community. Environmental Pollution 3:217–225.

——— AND ———. 1973. Effects of limestone dust accumulation on lateral growth of forest trees. Environmental Pollution 4:207–213.

EVELING, D. W. 1986. Scanning electron microscopy of damager by dust deposits to leaves and petals. Botanical Gazette 147:159–165.

FARMER, A. M. 1993. The effects of dust on vegetation—a review. Environmental Pollution 79:63–75.

GALE, J. AND J. EASTON. 1979. The effect of limestone dust on vegetation in an area with a Mediterranean climate. Environmental Pollution 19:89–101.

GOH, T. B., R. J. ARNAUD, AND A. R. MERMUT. 1993. Carbonates. Pp. 177–185 *in* M. R. Carter (ed.), Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL.

HICKMAN, J. 1993. The Jepson manual: higher plants of California. University of California Press, Berkeley, CA.

KRUCKEBERG, A. R. 2002. Geology and plant life the effects of landforms and rock types on plants. University of Washington Press, Seattle, WA.

MANNING, W. J. 1971. Effects of limestone dust on leaf condition, foliar disease incidence and leaf surface microflora of native plants. Environmental Pollution 2:69–76.

REHEIS, M. C. AND R. KIHL. 1995. Dust deposition in southern Nevada and California, 1984–1989: relations to climate, source area and source biology. Journal of Geophysical Research 100: 8893–8918.

———, J. C. GOODMACHER, J. W. HARDEN, L. D. MCFADDEN, T. K. ROCKWELL, R. R. SHROBA, J. M. SOWERS, AND E. M. TAYLOR. 1995. Quaternary soils and dust deposition in southern Nevada and California. Geological Society of America Bulletin 107:1003–1022.

RICKS, G. R. AND R. J. H. WILLIAMS. 1974. Effects of atmospheric pollution on deciduous woodland part 2: effects of particulate matter upon stomatal diffusion resistance in leaves of *Quercus petraea* (mattuschka) Leibl. Environmental Pollution 6:87–106.

SHARIFI, M. R., A. C. GIBSON, AND P. W. RUNDEL. 1997. Surface dust impacts on gas exchange in Mojave Desert shrubs. Journal of Applied Ecology 34:837–846.

USFWS (US FISH AND WILDLIFE SERVICE). 1997. San Bernardino Mountains carbonate plants draft recovery plan. Region 1, Portland, OR.

VARDAKA, E., C. M. COOK, T. LANARAS, S. P. GARDELIS, AND J. D. PANTIS. 1995. Effect of dust from a limestone quarry on the photosynthesis of *Quercus coccifera* and evergreen schlerophyllous shrub. Bulletin of Environmental Contamination Toxicology 54:414–419.

ZUBAREVA, O. N., L. N. SKRIPAL'SHCHIKOVA, AND V. D. PEREVOZNIKOVA. 1999. Dust accumulation by components of birch phytocenoses in the impact zone of limestone quarries. Russian Journal of Ecology 30:308–312.