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Degradation of sandy arid shrubland environments: observations, process modelling, and management implications

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Field remote sensing, and modelling observations from a degraded Mojave Desert shrubland were used to develop a model of the progressive degradation of areas adjacent to sites of direct anthropogenic disturbance. Aeolian removal and transport and dust, sand, and litter are the primary mechanisms of degradation, killing plants by burial and abrasion, interrupting natural processes of nutrient accumulation, and allowing the loss of soil resources by abiotic transport. It is concluded that any arid shrubland with wind-erodible soils is susceptible to degradation, and where possible development of these lands should be avoided.

Keywords: desertification; wind erosion; Mojave Desert; shrublands; paleolakes; agriculture

Introduction

The Manix Basin in the Mojave Desert of south-eastern California is the site of ancient Lake Manix (Buwalda, 1914; Meek, 1989, 1990; Dohrenwend *et al.*, 1991). Far from being a unique geological setting, the fine-grained lacustrine sediments in the Basin are part of the Pleistocene legacy shared by depressions throughout the entire Basin and Range and Mojave provinces (Smith & Street-Perrott, 1983). Morrison (1991*a*, 1991*b*) has reported that 'nearly all closed or formerly closed basins in the Great Basin have ancient strandlines marked by lacustrine bars, spits, embankments, terraces, deltas, and wave-cut cliffs at elevations well above the playas or permanent lakes of today'. The lacustrine sediments of Pleistocene age that form the floors of these basins share qualities that make them amenable for agriculture and other human activities: very low slopes, little or no relief, subsurface water resources, and fine-grained sediments suitable for farming or other activities. The intersection of the human uses of Pleistocene paleolakes with their geological history creates opportunities for land degradation much greater than typically recognized.

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Wind erosion in the Mojave Desert is the principal mechanism of land degradation. Agriculture, urban development, military maneuvers, pipeline, road and powerline construction, and recreational vehicles all destroy vegetation cover and expose the soil to wind erosion (Sharifi *et al.*, 1999). These activities can result in increased dust emission, blowing sand, and damage of native vegetation.

Although the processes of arid land degradation have been well-established elsewhere in the south-western U.S. (see for example, Schlesinger *et al.*, 1990), no published process model exists for shrubland degradation in the Mojave Desert or other shrublands. In this paper, we report on the importance of human-induced wind erosion in initiating and propagating land degradation in the Manix Basin of the Mojave Desert. Based on these observations, we develop a model of wind-driven desertification in sandy arid shrublands.

Arid land degradation has received significant attention in the technical and popular media over the past several decades. Much of this interest has been practical in nature because: (1) desertification is widespread throughout the south-western United States and globally (Mabbutt & Floret, 1980; Walker, 1982; Warren & Hutchinson, 1984; Verstraete & Schwartz, 1991; Khalaf & Al-Ajmi, 1993; Dregne, 1995); (2) it has severe financial and societal consequences including property damage, increased health and safety hazards, and decreased agricultural productivity (Clements *et al.*, 1963; Bowden *et al.*, 1974; Fryrear, 1981; Hyers & Marcus, 1981; Leathers, 1981; Leys & McTainsh, 1994; Bach, 1998); and (3) some forms of desertification are irremediable on human timescales at reasonable cost (Whitford, 1992; Dregne, 1995). The increasing use of desert shrublands by humans for habitation, agriculture, industry, and recreation increases the amount of arid land directly impacted (Verstraete & Schwartz, 1991). Thus, it is important to understand the processes of arid land degradation in these environments. Improved process understanding will allow improved identification of areas at heightened risk of desertification before serious damage has occurred.

History and features of the Manix Basin, California

Our observations are drawn from the Manix Basin in the Mojave Desert, about 25 miles ENE of Barstow in south-eastern California (centred around 34°56·5′N;116°41·5′ W at an elevation of about 540 m). The basin has an area of 40,700 ha and was the site of ancient Lake Manix which existed during the peak pluvial episode of the last glaciation and drained through Afton Canyon to the east (Smith & Street-Perrott, 1983; Meek, 1989). Much of the basin is filled with lacustrine, fluvial, and deltaic sediments capped by weak armoring (Meek, 1990). There is clear evidence of pre-modern wind erosion, indicating that wind erosion, transport, and deposition has long been a dominant geological process in the area (Evans, 1992).

The modern climate of the Manix Basin is arid with an average annual precipitation of 100 mm, falling mostly in the winter, although there can be significant summer precipitation in some years (Table 1). The average annual temperature is 19·6°C, the average

Table 1. *Average precipitation (cm) by season at Daggett Airport*

	Jan–Mar	Apr–Jun	Jul–Sept	Oct–Dec	Annual
1944–1997	3·7	0·9	2·9	2·4	10·0
1980–1989	4·5	1·1	3·1	3·1	12·7
1990–1997	6·0	0·3	2·8	2·0	11·1

Source: National Climate Data Center, U.S. Precipitation by State, California: http://www.ncdc.noaa.gov/ol/climate/online/coop-precip.html (1997).

winter temperature of 9·1°C, and the average summer temperature is 31·4°C (Meek, 1990). The average wind speed at the airport in Daggett is 5·5 m s^{-1} at a height of 6·1 m and is typically from the west (National Climate Data Center, 1993).

The vegetation in undisturbed areas of the basin is dominated by an association of *Larrea tridentata* and *Ambrosia dumosa*, with minor occurrence of *Atriplex polycarpa, Atriplex hymenelytra, Atriplex canescens, Ephedra californica,* and *Opuntia* spp. *Prosopis glandulosa* occurs in some areas of the basin. Areas that have been disturbed directly by human activity are dominated by *A. polycarpa* with total cover often greater than that in undisturbed desert. *Schismus*, an exotic annual grass, in ubiquitous, but grass cover varies significantly with yearly precipitation.

There has been extensive human activity in the Manix Basin with several phases of agriculture utilizing ground-water recharged by the Mojave River. The basin was used for dryland farming in the 1800s (Tugel & Woodruff, 1978). Limited irrigated farming started in the basin in 1902 with the acreage of irrigated land increasing sharply after World War II (Tugel & Woodruff, 1978). Today alfalfa hay is the major agricultural product. In the Coyote Dry Lake sub-basin, square flood-irrigated fields and abandoned flood irrigation equipment are seen in early Landsat images. After the mid-1970s, central-pivot agriculture became the dominant form of land use in the area, but many fields have since been abandoned throughout the northern part of the basin due to increasing costs of ground-water pumping (Ray, 1995).

Methods

The Landsat Multispectral Scanner (MSS) and Airborne Visible Infrared Imaging Spectrometer (AVIRIS) images indicate clearly the growth of sand blow-outs downwind of abandoned agricultural fields in the Manix Basin (Fig. 1). AVIRIS measures the total upwelling spectral radiance in 224 bands from 400 to 2500 nm in 20-m ground pixels from a NASA ER-2 aircraft flying at 20-km altitude. Landsat MSS measures upwelling radiation in four visible-near infrared broad multispectral bands in 80-m ground pixels. Geographical information about the extent and locations of blowing sand were the object of the remote sensing analysis. Simple spatial information is readily available from uncalibrated remote sensing images. Therefore, no attempt was made to calibrate the images or correct for atmospheric scattering. The images were incorporated into a geographical information system.

A series of field trips between 1996 and 1999 were undertaken to the Manix Basin in order to verify remote-based observations of sand blow-outs. In 1998 and 1999, perennial vegetation cover was estimated at several sites in the Manix Basin by measuring individual plant diameters in circular plots with 5-m radii (12 replicates each) and assuming full, circular shrub canopies.

Finally, a quantitative assessment of observed wind erosion and deposition rates was undertaken in order to link observed phenomena with physical and mathematical wind erosion models.

Results and discussion

Remote observation from the Manix Basin

The Landsat MSS and AVIRIS images taken in Fig. 1 clearly indicate the growth of sand blow-outs downwind of abandoned agricultural fields in the Manix Basin. Deposition of sand downwind of the fields is a progressive process, with sand plumes lengthening in each successive image. No regrowth of perennial vegetation was observed in these

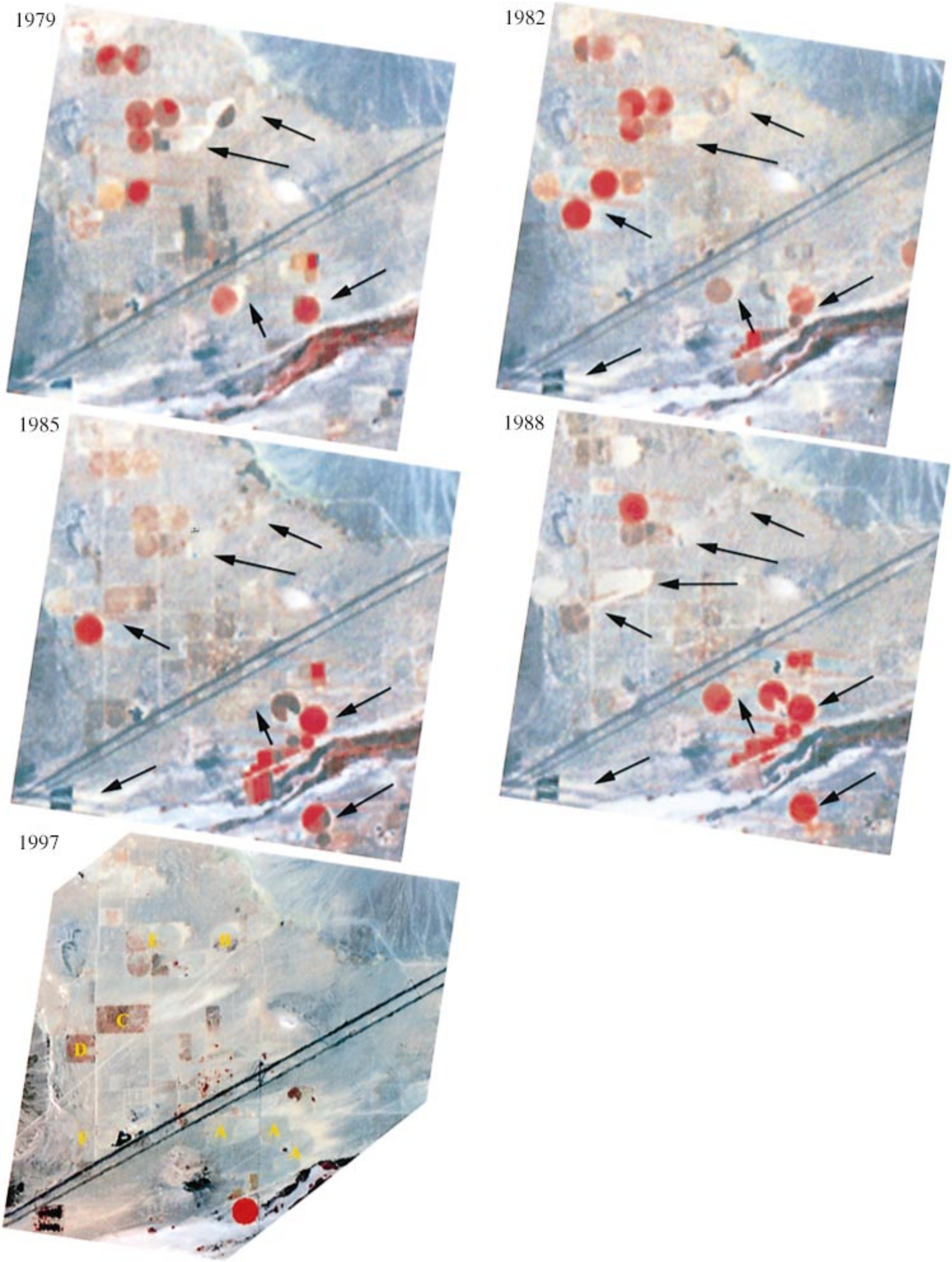

Figure 1. 1979–1988: Landsat Multispectral Scanner (MSS) images of the Manix Basin. Red is MSS band 4 (800–1100 nm), green is MSS band 2 (600–700 nm), and blue is MSS band 1 (500–600 nm). Interstate 15 goes diagonally through the centre of the images. North is up and active fields appear bright red in these images. The wind blows from west to east across the basin causing sand blowouts to appear as bright areas east of the fields. Arrows indicate the progressive appearance of sand mobilized from agricultural fields. 1997: an Airborne Visible Infrared Imaging Spectrometer (AVIRIS) image of the same area taken in 1997, and processed to display colours in the same way as in the MSS images. The relative sharpness of this image is due to the higher spatial resolution of the AVIRIS instrument. The dark-red area C consists of two fields covered with *A. polycarpa* while area A is an abandoned field with very little shrub cover. Both areas exhibit dramatic sand blowouts downwind.

Table 2. *Direct and indirect disturbance for some selected fields in the Manix Basin*

Location (see Fig. 1)	Total time cultivated (years)	Time since abandonment (years)	Soil texture	Area subject to direct disturbance (ha)	Area subject to indirect disturbance (ha)	Indirect/direct (area ratio)
A	> 7	< 10	Sand/loamy sand	185	518	2·8
B	1	26	Sand/loamy sand	62	109	1·8
C	5	15, 17	Sand	182	241	1·3
D	6	11	Loamy sand	79	91	1·2
E	6 to 8	10, 14	Loamy sand	124	33	0·3

sand plumes. Thus, the occasional darkening of the sand blow-outs is inferred to be due to annual vegetation related to winter rainfall. Annual cover can be relatively high in wet years, but seldom lasts through the spring and summer months.

Anthropogenic disturbance in the Manix Basin may be separated into two types: direct and indirect. Direct anthropogenic disturbance refers to human activities and the consequence of those activities in the area in which they were performed. This includes the actual fields, roads, pastures, corrals, trails, and so on that are affected by land use practices. Indirect disturbance refers to the consequences of direct disturbance in areas not directly disturbed. Our observations demonstrate that both direct and indirect disturbance are extensive in the Manix Basin, and that they are coupled by wind erosion and redeposition of wind-blown sediment.

Ray (1995) reported that in 1985 agriculture in the Manix Basin reached its greatest extent with 37 active central-pivot irrigated fields accounting for 3062 ha of land in cultivation. Agricultural activity in the basin has decreased in the last decade. Thus, at least 3000 ha of land have been directly disturbed in the Manix Basin. In an areal analysis of 1998 AVIRIS data, the relative areas of direct and indirect disturbance were identified in the form of sand blow-outs, for some of the fields in the Manix Basin (Table 2). No clear relationship was found between time of abandonment nor of cultivation with the magnitude of indirect disturbance. All fields were located in soils with sandy or loamy sand soils, the dominant soil textures in the basin (Tugel & Woodruff, 1978).

Sand may be blown several kilometres beyond the downwind boundary of a field and therefore the area of indirect disturbance can exceed the directly disturbed area by several-fold. With 3000 ha of land directly disturbed in the basin, 3000–9000 ha of land may be expected to be indirectly disturbed by agriculture. This sums to 6000–12,000 ha total disturbance or 15–30% of the total basin floor area, and approximately 23–45% of the non-playa area of the basin. Other disturbances, such as housing developments and roads are also present in the basin, while large areas of the basin are taken up by the Coyote and Troy playas. Anthropogenic degradation appears to have a major impact on land quality and status in the Manix Basin.

Field observations in the Manix Basin

Direct disturbance

Before the fields of the Manix Basin could be cultivated they were cleared of vegetation. Vegetation cover shelters the soil from the erosive force of the wind by: (1) reducing the force of the wind near the ground; (2) extracting momentum above the surface (Wolfe & Nickling, 1993); and (3) trapping soil particles in transport (Lancaster & Baas, 1998). Tillage destroys fragile surface armours, thereby reducing the threshold shear velocity (Gillette *et al.*, 1980; Gillette, 1988; Tegen & Fung, 1955; López, 1998). Vegetation removal and soil cultivation, therefore, have the combined effect of dramatically increasing soil erodibility in the Manix Basin (as seen in Fig. 1). Mechanical agriculture itself visibly mobilizes dust and sand on windy days and ensures that the soil surface is exposed for at least part of the year. Active fields, therefore, become sustained sources of material for aeolian transport immediately upon clearing.

The magnitude of deflation associated with wind erosion of agricultural fields in the Manix Basin is difficult to quantify. However, in one agricultural field abandoned about 30 years ago (Fig. 1, area F), wind erosion has led to an average deflation rate of more than 1·5 cm per year, as evidence by wind excavation of buried irrigation pipes. These pipes provide a rare field constraint on deflation, as the vertical feeder sections were once flush with the ground.

Areas that have been cleared of vegetation and then abandoned follow one of two principal trajectories with respect to their vegetative cover. Areas may be recolonized

Table 3. *Percent cover by species in undisturbed desert compared with areas on abandoned central-pivot agriculture fields*

	Undisturbed	On-field (low-cover)	On-field (high cover)
Larrea tridentata	4·8%	0·8%	0·0%
Ambrosia dumosa	1·1%	0·4%	0·0%
Atriplex polycarpa	0·8%	8·3%	32·5%
Total fractional cover	6·7%	9·5%	32·5%

Plant counts were carried out in February 1998 and April 1999 in 5-m radius circles.
The 'Undisturbed' plant cover data represent three sites with 12, 4, and 12 replicates, respectively.
The 'On-field (low cover)' data represent two sites with 12 replicates each. The 'On-field (high cover)' data represent one site with 8 replicates.

principally by *A. polycarpa*, a perennial shrub, and annual exotic grasses such as *Schismus*. Perennial vegetation cover estimates from various sites in the Manix Basin are shown in Table 3. We found 8–30% cover of a *A. polycarpa* on abandoned fields, compared to 5–7% cover on undisturbed areas dominated by *L. tridentata*. In some cases, only the upwind portions of abandoned fields support a low cover of *A. polycarpa*, even after a decade or more of disuse. Fetch, and therefore, mass transport rate of the wind, is lowest here, minimizing plant abrasion and seed removal. These fields have only been abandoned for at most 30 years, and are nowhere near the 65 years that Carpenter *et al.* (1986) estimate for a creosote bush scrub community to approach climax conditions nor the several hundred years estimated by Vasek *et al.* (1975). Stylinski & Allen (1999) have suggested that in arid shrublands, altered stable states can occur if a community is pushed beyond its threshold of resilience by anthropogenic disturbance. The dramatic differences between abandoned agricultural fields and undisturbed desert in the Manix Basin after several decades certainly argue for centuries for recovery, if it occurs at all.

Some of the abandoned fields in the Manix Basin do not support any native perennial vegetation, even after a decade or more of disuse. This may be explained by: (1) transport of sand by wind over the exposed soil surface killing young seedlings; and/or (2) absence of climatic or soil conditions suitable for plant germination (Lovich & Bainbridge, 1999). In an experiment aimed at restoring Mojave Desert farmland by seeding native plants in order to reduce dust emissions, Grantz *et al.* (1998) found *A. canescens* could be established in areas without deep sand. However, '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'. Thus, natural germination of native perennial vegetation on abandoned fields may be rare, explaining the lack of cover on some abandoned fields in the Manix Basin. The importance of germination conditions highlights the dramatic role of interannual climate variability and long-term regional climatic conditions on the response of these ecosystems to human disturbance. Bare fields in the Manix Basin may be expected to take much longer than the vegetated fields to approach climax conditions, if they recover at all.

Once fields are abandoned, they serve as sources of wind-borne sediment at least until a deflationary soil pavement is re-established or the soil is crusted (López, 1998). Landsat MSS and AVIRIS images in Fig. 1 depict the mobilization of sand from abandoned agricultural fields in the Manix Basin. Area C, which appears as dark red in the 1997 AVIRIS image, is a set of two fields abandoned in the early 1980s according to Landsat images of the basin from 1973 to 1992; area A was abandoned in 1988 (Ray,

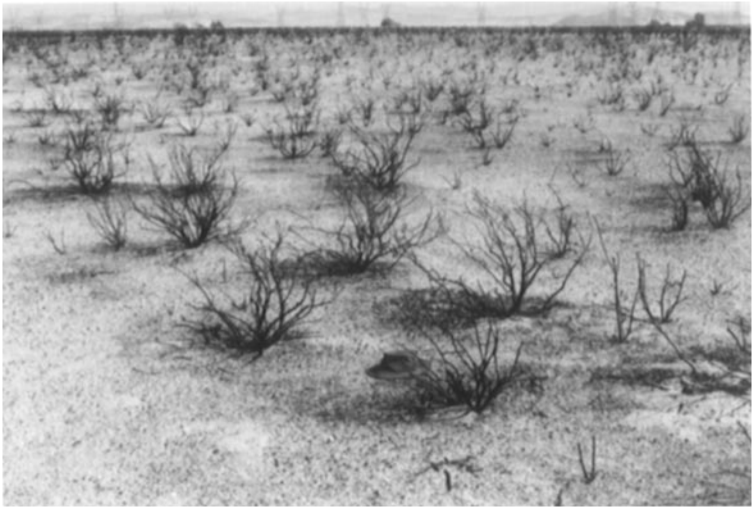

Figure 2. Photograph taken in an abandoned field in the Manix Basin after a fire in the summer of 1998 showing the response of highly disturbed areas to fire. Prior to the fire, this abandoned field had been covered with approximately 30% cover of *A. polycarpa*. Most individuals in the path of the fire in the area of high *A. polycarpa* cover were killed as shown here. Nearby, in adjacent undisturbed desert, only the annual grasses burned and perennial plant mortality was low.

1995). Areas downwind of both fields show significant sand encroachment even though area A has almost no cover and C has relatively high (~30%) *A. polycarpa* cover. Thus, even after regrowth of *A. polycarpa*, abandoned fields remain sources of aeolian sand. High *A. polycarpa* cover may increase roughness length and decrease boundary layer velocity, but once the soil crust was removed, these soils clearly remained vulnerable to wind erosion.

A notable consequence of the trajectory that areas of direct disturbance follow is their potential response to fire. Lovich & Bainbridge (1999) have reported a 10-year average of 175 fires per year in the Mojave and Colorado deserts of California that affected an average of 10,927 ha annually. Besides this, there are no published definitive studies of fire-return intervals or typical areas burned in individual fires in the Mojave Desert. Nonetheless, it is clear that fire has only recently become a factor in shaping the structure and dynamics of plant communities in the Mojave Desert. In prehistoric times, limited biomass, large intershrub spacing, low combustibility of some native plants and sparse ground cover to support and propagate combustion are thought to have led to very low fire frequencies. The recent proliferation of exotic annual plants has increased the fuel load and fire frequencies in many ecosystems around the world have increased in recent years (Lovich & Bainbridge, 1999).

A fire in the Manix Basin that occurred in June 1998 showed that areas of high *A. polycarpa* cover have different fire responses than undisturbed areas or abandoned areas of direct disturbance with little or no vegetation regrowth. After the 1998 Manix Basin fire, the mortality of nearly all shrubs on the *A. polycarpa*-covered abandoned field was observed. The same fire burnt a nearby undisturbed area dominated by *L. tridentata* and *A. dumosa*. Here, the fire killed few shrubs and was only sustained as a ground fire in areas with a dense cover of exotic annual grasses. A fire in an abandoned field covered with *A. polycarpa*, therefore, re-exposed the soil surface to wind erosion while a fire in an undisturbed area has little effect on the landscape (Fig. 2). Disturbed areas that are subsequently burned therefore are likely to have much longer recovery times than their unburned neighbours, both due to fire mortality and the enhanced vulnerability of burnt landscapes to wind erosion.

Figure 3. Photograph taken downwind of an abandoned field in the Manix Basin in the spring of 1988 displaying evidence of active sand movement (sand ripples) and plant mortality. The plants in the foreground are *L. tridentata* and *A. dumosa* individuals that have been buried, abraded and ultimately killed by the encroaching sands.

Indirect disturbance

Indirect disturbance in the Manix Basin primarily takes the form of redeposition of wind-borne sediments onto previously undisturbed adjacent lands. Three types of material are removed from abandoned agricultural fields by wind erosion: saltation-sized particles, suspension-size particles, and organic litter. The removal of all three contributes to indirect disturbance. Saltation of large particles results in their redeposition wherever wind velocities drop, typically in adjacent, downwind vegetated areas or in the lee of plants growing on the field itself.

The encroachment of blowing sand into adjacent shrublands has dramatic consequences for the landscape. Field observations indicate that blowing sand abrades plants, resulting in leaf stripping and damage to the cambium and therefore to the plant's ability to distribute and use water. Young plants are especially vulnerable to the effect of blowing sand because they lack woody tissue. This results in the suppression of revegetation in bare areas and the loss of vegetation on adjacent lands. Nitrogen-fixing microbial communities and cryptobiotic crusts are buried by sand, reducing inputs of nitrogen to the soil (Belnap *et al.*, 1993; Evans & Belnap, 1999).

Blowing sand creates dunes in the wind-shadows of plants. Inspection reveals that these dunes typically have a coarser texture than the material from which they were derived, a result of the progressive removal of fines in a continual process of winnowing (Gibbens *et al.*, 1983; Hennessy *et al.*, 1986; Lyles & Tatarko, 1986). Dunes can grow and coalesce resulting in: (1) burial of large plants not able to grow fast enough to keep up with dune growth; (2) burial of all vegetation including very young shrubs in inter-shrub spaces; and (3) complete blanketing of the soil surface by sand. The persistence of branches and twigs from buried or abraded vegetation decreases the erodibility of the surface, but with time these disintegrate (Fig. 3). Since new vegetation growth is inhibited by blowing sand, the ability of vegetation in stem erosion is limited.

Anthropogenic additions

Chemical fertilizers or other soil amendments are often added to agricultural fields to increase productivity or soil workability. Inorganic salts also may be added inadvertently to the soil as irrigation water evaporates. Wind erosion of soil from an area of direct disturbance may be accompanied by the dispersal of these soil additives across the landscape. The dispersal of salts by wind onto adjacent undisturbed areas may contribute to the decreased plant growth on these areas by increasing osmolyte concentrations in soil solutions. Okin *et al.* (in press) have reported that Cl^-, SO_4^{-2}, and Na^+ are significantly elevated on an abandoned field in the Manix Basin relative to the upwind area. On the field, Cl^-, SO_4^{-2}, and Na^+ accumulated at average rates of approximately 9·9, 30, 29% per year, respectively over 7 years. This represents a dramatic addition of ions to the soil which may limit the use of these areas for extended agriculture or influence the recovery of agricultural fields after abandonment.

Soil additives (including nitrate and phosphate) act as chemical tracers of mass flux, which helps determine the relative effects of physical abrasion and nutrient loss in propagating desertification in arid shrublands. Okin *et al.* (in press) have reported significantly elevated concentrations of plant-available N and P on and downwind of an abandoned field in the Manix Basin. Fertilizer has been broadcast across the landscape as the soil from the field has been transported by wind. Despite elevated nutrient concentrations on the abandoned agricultural field at Manix, the absence of shrubs on this field indicates that recolonization of fields by native shrubs after their abandonment is not simply related to nutrient content of the soils, but is dependant more on germination conditions as suggested by Grantz *et al.* (1998). The area immediately downwind of the fertilized field has seen an increase in plant mortality and not a bloom in response to increased nutrient concentrations. This indicates that abrasion and burial of vegetation may dictate a landscape's response to wind erosion, especially in years without favourable germination conditions.

Quantitative assessment

Are the observed rates of deflation and burial of adjacent lands that are suggested quantitatively plausible in the Manix Basin? Using published threshold shear velocities and equations for the flux of wind-borne sediments, we conclude that observed deflation rates at the Manix basin are reasonable in light of literature values and theoretical considerations. Our quantitative assessment thus provides insight into the magnitude of deflation, redeposition of saltation-sized particles, and emission of nutrient-laden dust.

Wind erosion and transport processes have been reviewed many times in the literature (see for example Greeley & Iversen, 1985, table 3·5). Here, the analysis of Bagnold (1941) will be followed because it is still prevalent in the modern literature of aeolian transport and because it provides a simple method for determining the magnitude of sand transport. From momentum considerations and simplifying assumptions about the path of saltating grains, Bagnold derived a relationship for the horizontal mass flux of saltating grains integrated over all heights:

$$q = C\sqrt{\frac{d}{D}}\,\frac{\rho_a}{g}\,U_*^3, \tag{1}$$

where q is the horizontal mass flux in g cm^{-1} s^{-1}, U_* is the shear velocity, d is the grain diameter of the sand in question, D is the grain diameter of a standard 0·25-mm sand,

ρ_a is density of air, g is the acceleration due to gravity, and C is 1·8 for a naturally graded sand. Assuming that $d = D$, Bagnold's equation simplifies to

$$q = 1{\cdot}5 \times 10^{-9}\,(U - U_t)^3, \tag{2}$$

where U is the wind velocity and U_t is the threshold wind velocity measured at 1 m height. U and U_t are related to shear velocity, U_*, and threshold shear velocity, U_{*t}, respectively, by Bagnold's formula:

$$U_z = \frac{U_*}{k}\ln\left(\frac{z}{z_0}\right), \tag{3}$$

where U_z is wind speed at height z, k is von Karmann's constant taken to be 0·4, and z_0 is the roughness length (Bagnold, 1941).

Shao & Raupach (1993) have shown from energetic considerations that vertical dust flux due to suspension, F, in mass per area per unit time is linearly related to q. Based on this, Gillette *et al.* (1997) have obtained a value for F/q of $5{\cdot}4 \times 10^{-4}\,\mathrm{m}^{-1}$ from wind tunnel experiments, which is of the order of that for sandier soils (Gillette, 1977; Shao & Raupach, 1993; Gillette *et al.*, 1997) and is therefore applicable here.

For a field with cross-wind diameter, x, and area, A:

$$\Delta\tau_{saltation} = \frac{q}{\rho_B}\frac{x}{A}, \tag{4}$$

where ρ_B is the bulk density of the soil and rate of deflation due to saltation, $\Delta\tau_{saltation}$, is expressed as cm year^{-1}. ρ_B is taken to be $1{\cdot}25\,\mathrm{Mg\,m^{-3}}$ for a dry, medium-texture mineral soil (Brady & Weil, 1999), x is taken to be 750 m, and $A = \frac{\pi}{4}x^2$ for a circular field. A/x is a equivalent to erosive fetch. The total average mass rate of erosion is:

$$F_{Total} = q\left(\frac{x}{A}\right) + F \approx q\left(\frac{x}{A}\right), \tag{5}$$

and the total deflation rate (in cm year^{-1}) is given approximately by:

$$\Delta\tau_{total} = \Delta\tau_{saltation} + \Delta\tau_{suspension} = \frac{q}{\rho_B}\left(\frac{x}{A} + \frac{F}{q}\right), \tag{6}$$

where the mass flux due to saltation, q, depends on a detailed wind record, z_0, and U_{*_t} by equations (2) and (3).

The threshold shear velocity required to account theoretically for $\Delta\tau_{Total} = 1{\cdot}5$ cm year^{-1} in the Manix Basin was found iteratively using Eqn (6), Gillette *et al.*'s (1997) value for $F/q = 5{\cdot}4 \times 10^{-4}\,\mathrm{m}^{-1}$, $z_0 = 0{\cdot}04$ cm (an average of values reported by Gillette *et al.* (1980) for non-playa, uncrusted soil), and the wind conditions at Daggett Airport in the Manix Basin where wind speed has been collected hourly since 1961. U_{*t} was found to be 103 cm s^{-1}, well within the bounds of reported values for arid agricultural soils of 20–132 cm s^{-1} (Gillette, 1988). These results indicate that empirically-understood processes can account for observations in the Manix Basin and, therefore, that it is reasonable to invoke these processes to drive indirect disturbance in the conceptual model developed here.

The value $q = 8{\cdot}56\,\mathrm{Mg\,m^{-1}\,year^{-1}}$ calculated from $U_{*t} = 103\,\mathrm{cm\,s^{-1}}$ by Eqn (2) implies that the equivalent of 10^8–10^9 sand grains saltate through each metre of width per year. In fact, considering that the majority of wind erosion occurs during storms of a few days in duration, this constitutes an extremely concentrated attack on vegetation which is capable of overwhelming plants' self-healing capabilities.

The effect of abrasion acts in tandem with redeposition and dune formation to compromise vegetation in adjacent downwind areas. The total volume, V in m^3 $year^{-1}$, of soil moved by saltation from an abandoned agricultural field is given by:

$$V = \frac{qx}{\rho_B} T, \tag{7}$$

where T is the time in years before the re-establishment of an armoured surface. If the density of the soil is approximately the same after redeposition downwind, volume is conserved and the average depth of burial is given by V/A_b, where A_b is the area buried by the mobilized sand, which can be estimated from remote sensing imagery. Area C in the Manix Basin (Fig. 1, Table 2) has been abandoned for 16 years and has a 241-ha sand plume downwind. Using the value of q calculated above, we estimate that the average depth of this sand plume is 6·8 cm. However, mobilized sand usually accumulates in the wake of plants, leading to dunes larger than the average depth of burial. In the Manix Basins we have observed dunes greater than 1 m in height. There is currently no theory for determining dune height based on flux measurements or calculations.

Using Gillette *et al.*'s (1997) value for F/q, and reasonable values for x/A, $q(x/A)$ should always be greater than F, indicating that sand mobilization is more important as a wind erosion process than dust emission is terms of mass loss. However, dust emission represents the permanent removal of material from the regional ecosystem due to its potential for long-range transport. Nutrients, especially P, are often concentrated on small particles in soils (Avnimelech & McHenry, 1984; Leys & McTainsh, 1994). Assuming constant suspension flux, the removal of nutrient i from the bulk soil at time t may be written as:

$$F_i^d(t) = C_i^d(t)\,F, \tag{8}$$

where $C_i^d(t)$ is the concentration of soil nutrient i on the emitted dust and has units of mass of nutrient per mass dust. $F_i^d(t)$, therefore, is in units of mass of nutrient i lost per unit area per unit time. The mass per unit area of soil in a layer of depth, D, is:

$$M^D = \rho_B D, \tag{9}$$

and therefore, the reservoir of nutrients in this layer is $C_i^s(t)\,M^D$, where $C_i^s(t)$ is the concentration of nutrient i in the soil.

Conservation of mass gives:

$$M_i^{s,D}(t + \mathrm{d}t) - M_i^{s,D}(t) = C_i^d(t)\,F\mathrm{d}t, \tag{10}$$

where $M_i^{s,D}(t)$ is the mass of nutrient i at time t in a layer of soil of depth, D. Under the approximation that M^D is constant with time, we can divide equation (9) by M^D yielding:

$$C_i^{s,D}(t + \mathrm{d}t) - C_i^{s,D}(t) \approx C_i^d(t)\,\frac{F}{M^D}\,\mathrm{d}t, \tag{11}$$

where $C_i^{s,D}(t)$ is the concentration of nutrient i at time t in a layer of soil of depth, D. The ratio of $C_i^d(t)$ to $C_i^{s,D}(t)$ is assumed to be a constant, k_i, that is analogous to a chemical fractionation factor for nutrient i between dust and the bulk soil.

Rearranging equation (10) yields:

$$\frac{\mathrm{d}C_i^s}{\mathrm{d}t} \approx -k_i \frac{F}{\rho_B D} C_i^s. \tag{12}$$

Therefore, the time for the concentration of nutrient i in a layer of soil of depth D to drop by $1/e$ times its original value is given by t_i^D:

$$t_i^D = \frac{\rho_B D}{k_i F} = \frac{t^D}{k_i}, \tag{13}$$

where t^D is the time it takes to completely excavate a layer of depth D with a mass flux rate equal to F. For $D = 0{\cdot}05$ m (a typical sampling depth), $F = 4{\cdot}62$ kg m^{-2} year^{-1} (at $U_{*_t} = 103$ cm s^{-1}) and with a bulk density of 1·25 Mg m^{-3}, t^D is approximately 14 years. Reported values of nitrogen enrichment (k_N) in Australian arid zone soils are in the order of 10 (Leys & McTainsh, 1994; Carter *et al.*, 1999), although Larney *et al.* (1998) have reported values as low as 1·1. Thus, t_i^D may be as low as a few years.

Available N and P concentrations at a site in the Jornada Basin measured by Okin *et al.* (in press) indicate approximately an 80% net loss of available N and a 70% net loss of plant-available P in the 8 years since the establishment of the site. Thus, the *e*-folding times of N and P, t_N^D and t_P^D, in this surface soil undergoing active deflation and aerosol emission are inferred to be approximately 5–10 years. Wind erosion, therefore, impacts soil fertility in areas of both direct and indirect disturbance on short timescales. This has dramatic implications for nutrient availability in disturbed areas, especially for seed germination in surface soils where the degree of nutrient depletion will be greatest.

Conclusions

Anthropogenic desertification of arid shrublands

Extensive remote sensing, field, and quantitative assessment of arid land degradation in the Manix Basin leads us to conclude that in arid shrublands direct anthropogenic disturbance resulting in the destruction of soil crusts and vegetation cover can cause indirect disturbance of adjacent areas by initiating the disintegration of islands of fertility. Figure 4 illustrates a proposed model for the degradation of arid shrublands based on these observations. The inferred sequence can be visualized as:

(1) Transport of sand from disturbances resulting in deflation of the disturbed surface.
(2) Mobilization of dust and plant litter by wind, depleting the soils of nutrients in areas of direct disturbance.
(3) Damage to and burial of plants by saltating sand in adjacent downwind areas.
(4) Reduction of vegetation cover downwind, leading to an expanding area in which wind removes dust and litter material, depleting the soils of nutrients.

A feedback threshold may be reached when these mechanisms act to dramatically reduce shrub cover in previously undisturbed areas. The accessibility of this threshold is related to allogenic changes in regional climate and interannual variability. Reduced precipitation or increased temperature may exacerbate landscape vulnerability and cooler, wetter conditions may aid amelioration.

Nutrient relations and soil resources

Shrubs are the loci of nutrient accumulation and represent islands of fertility in shrubland ecosystems (Schlesinger *et al.,* 1990; 1996). How then does wind erosion affect soil resources in degraded shrublands?

Nutrient removal from islands of fertility has three main mechanisms: (1) physical removal of litter and organic matter by the wind; (2) wind suspension of dust particles

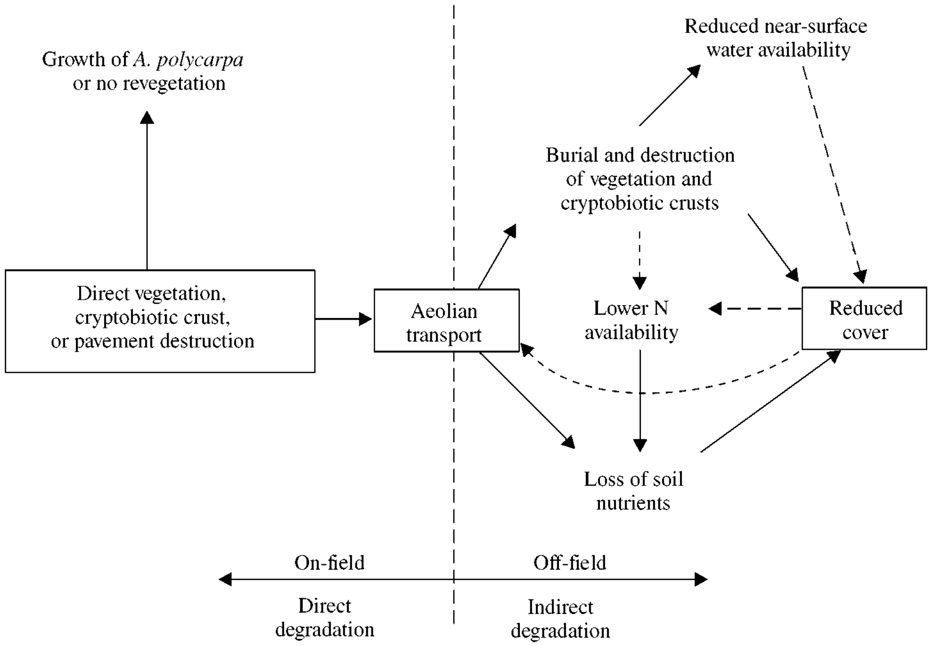

Figure 4. Process model for shrubland degradation developed from observations at the Manix Basin, California. Direct disturbance through vegetation, crust, or pavement destruction drives aeolian transport which leads to indirect degradation in the form of reduced cover in adjacent areas.

with a high concentrations of plant nutrients (Leys & McTainsh, 1994); and (3) retarded accumulation of organic N due to increased surface and air temperatures (Post *et al.*, 1985). In areas of indirect disturbance, the mantle of winnowed dune sand may lead to decreased fertility of the surface soil, which is vital for seedling establishment. Areas of direct disturbance which are the sources for dune sand will also become less fertile through preferential removal of fines by wind. Removal of litter beneath shrubs limits the future availability of organic N and C to plants (Lyles & Tatarko, 1986; Schlesinger & Pilmanis, 1998).

Islands of fertility associated with shrubs are normally sites for recolonization by seedlings (Schlesinger & Pilmanis, 1998). These young plants are more vulnerable to sand abrasion and burial than their mature predecessors and their establishment may be limited. In many areas adjacent to abandoned agricultural fields in the Manix Basin, shrub sites are generally not recolonized and become areas of soil nutrient removal, effectively dismantling the islands of fertility. Schlesinger & Pilmanis (1998) have reviewed field experiments in which shrubs have been removed by cutting, herbicides, or fire. These studies show variable rates of soil degradation, but in each case, 'a loss of the local biogeochemical cycle associated with shrubs has allowed physical processes to disperse soil nutrients across the landscape'. Thus, the progressive reduction in fertility acts in tandem with the mechanical action of sand to further decrease shrub cover which, in turn, increases the susceptibility of the land to wind erosion. The permanent removal of suspension-sized particles from the soil by wind erosion results in a change of the soil texture, which may also reduce soil binding properties, resulting in increased wind erodibility.

In a study aimed at determining the effect of wind erosion on nutrient availability, Okin *et al.* (in press) have measured available N and P at a disturbed site in the Jornada LTER site in south-central New Mexico. Their results indicate that surface soils upwind of the disturbance are richer in available N and P than those from downwind. Assuming that the soils from the upwind transect are considered representative of the original conditions throughout the study site, there has been an 80% net loss of available N and a 70% net loss of plant-available P from the soils blown off of the disturbed area. In addition, the site itself lost nearly 94% of its available N and nearly 79% of its plant-available P. Similar results have been reported by Leys & McTainsh (1994) in Australia.

The nutrient cycle may be further disrupted when soil microbial communities are buried or destroyed by blown sand, minimizing their ability to fix atmospheric nitrogen and add it to the nutrient reservoir of the soil. The burial of cryptobiotic crusts also reduces their ability to enhance infiltration of water leading to decreased near-surface soil moisture (Belnap *et al.*, 1993; Belnap, 1995).

It has been suggested by Gibbens *et al.* (1983), Lyles & Tatarko (1986), Hennessy *et al.* (1986), and Leys & McTainsh (1994) that permanent removal of suspension-size particles from the soil by wind erosion may reduce water-holding and cation-exchange capacities. This may result in less water in the surface soil, marginalizing the water balance of desert shrubs and increasing their susceptibility to drought and climate change. On short timescales, this may be particularly important for the establishment of annual grasses. In wet years, these grasses form a carpet that reduces the susceptibility of soils to wind erosion (Lancaster & Baas, 1998). In dry years, decreased near-surface soil moisture makes the landscape more vulnerable to wind erosion. Dust storm frequency has been correlated with reduced soil moisture, indicating that soil erosion and nutrient removal are accelerated by decreased soil moisture (Brazel & Nickling, 1987).

Lessons for land managers

Several aspects of the arid shrubland degradation observed at the Manix Basin can provide lessons for land management in these environments. Wind erosion is the principal mechanism of degradation in arid shrublands on basin floors. The main consequences of land degradation are therefore:

(1) sand blasting of vegetation and equipment;
(2) burial of vegetation and equipment;
(3) dust emissions leading to decreased nutrient availability, cation-exchange capacity, water-holding capacity, and atmospheric pollution.

For virgin lands, not already converted to human uses, we stress that if possible, arid shrublands with sandy wind-erodible soils should not be used for many activities. These are extremely fragile lands, the degradation of which could easily upset marginal economic gains from their cultivation or make recreation and habitation impossible. Furthermore, disturbance of arid shrubland landscapes may preclude successional processes, resulting in permanent landscape change. Where development is deemed necessary, planning must precede plowing. A principal consideration must be the wind erodibility of soils. In the United States, county-wide soil surveys typically provide information on soil texture. Soils of sandy or loamy sand textures, even when covered by a thin layer of protective crust (deflationary crust, desert pavement, or cryptobiotic crusts), are very vulnerable to wind erosion. Activities that break up soil crusts and destroy vegetation are best avoided. High-risk activities include agriculture, grazing, ORV recreation, and military training. Roads, when necessary, should be situated to minimize the area of wind-erodible soils affected. The location of natural wind breaks such as trees, hills, and mountains should also be used to determine the location of planned developments.

For land already under cultivation or used for recreational purposes, we suggest technological and logistical methods for minimizing the effects of wind erosion in local vegetation, crops, and infrastructure. Equipment, sheds, and other buildings should be situated upwind of fields so that they are not sandblasted or buried. Fields, likewise, should not be situated such that one is close to and downwind of another, or else sand eroded from one will be deposited on another. In the extremely sandy western lowlands of the Cape province, South Africa, Talbot (1947) has observed that uncultivated areas between fields may stem wind erosion and keep redeposition of sand from occurring in undesirable places. Other wind breaks, preferably indigenous plants which do not need to be watered after establishment, will also help stem erosion. Attempts must be made to keep vegetation on fields. In light of this, nitrogen-fixing cover crops may be planted to minimize erosion and add nitrogen when tilled back into the soil. Fallow periods, especially in the windiest time of the year should be avoided, and cover crops planted instead. Fertilizers may need to be added every few years, when significant nutrient loss is detected and when nitrogen-fixing cover crops are not sufficient to renew the soil resources. When abandoned, fields should be planted with a final, long-lived perennial indigenous cover that will help minimize wind erosion for years to come, and will allow natural succession processes to take place.

Novel techniques may provide the best opportunities for sustainable management of arid shrublands. We suggest yearly monitoring of soil nitrogen and phosphorous in order to identify times or places where dust emission has significantly depleted the soil of nutrients. Where possible, use should be made of remote sensing and precision farming technologies to ascertain soil condition and to respond appropriately. Carter *et al.* (1999) have reported success in stemming erosion and improving soil conditions by adding clays of sub-soil origin to sandy soils in Western Australia. These and other techniques could be used to dramatically improve the sustainability of agriculture in arid lands.

Past agriculture in the Manix Basin is a good example of unregulated and unmanaged human activities for short-term gain leading to long-term loss of value. As farming in the basin became less profitable, farmers, simply abandoned the land to natural degradation processes without implementing long-term remediation strategies. A principal lesson from this area, therefore, is that policy mandates and financial incentives need to be put in place that promote soil conservation initiatives during land use and require restoration of the landscape after cultivation stops. Efforts at remediation do not need to focus on restoring the environment to its pristine condition, although this is preferable. Instead, they can focus on halting or slowing soil erosion by planting long-lived, native, and perennial shrubs that will partially protect the surface. Funds for post-agriculture remediation should be earmarked before cultivation begins, and must be considered a part of the cost of business in vulnerable lands. In this way, remediation becomes the responsibility of the short-term land-user and not someone else's long-term problem.

Regional drivers and effects

In addition to the increasing intensity of human disturbance, arid lands are affected by changes in regional climate. How might climate change affect arid shrubland degradation?

The 1980s and 1990s—the decades in which large areas of the Manix Basin were abandoned from agriculture and in which the greatest land degradation has been seen—were neither unusually windy nor dry. The annual average wind speed for the period 1961 to 1990 was $5{\cdot}5\ \mathrm{m\,s^{-1}}$, identical to the period of 1980–1989 (National Climate Data Center, 1993). Annual precipitation was only slightly higher between 1970 and 1990 than for the period 1941 to 1997 (Table 1). When the decadal-scale regional climate in the Manix Basin shifts to a windier or drier period, the area affected by nutrient loss and aeolian sand mobilization can be expected to increase dramatically.

There has been much discussion about the relative importance of human *vs*. indirect climate drivers of desertification. Both can have a dramatic impact on the landscape (Schlesinger *et al.*, 1990; Brown *et al.*, 1997). Climate change may either increase or decrease anthropogenic effects on a landscape. For example, during wetter than average years, the presence of annual grass cover greater than about 15% halts wind erosion, and increased soil moisture leads to higher threshold shear velocities (Brazel & Nickling, 1987; Lancaster & Baas, 1998). In drier than average years, threshold shear velocity may be lower due to decreased soil moisture, and annual cover is greatly reduced, leading to accelerated degradation. In the northern Mojave Desert, Schultz & Ostler (1993) have reported a dramatic decrease in total plant cover after only 4 years of drought. Clearly, resistance to climate-induced changes is dependent on the degree of anthropogenic disturbance and *vice versa*. Thus, regional decadal-scale climate conditions may be expected to dramatically influence the rate of arid shrubland degradation.

Extrapolation to other areas

In the process model developed from observations in the Pleistocene paleolake Manix, the primary driving mechanism is the aeolian mobilization of sand, dust, and litter material initiated by anthropogenic disturbance of the soil surface crust and vegetation cover. Any process that destroys the surface crust in an arid or semi-arid shrubland and increases the boundary layer velocity over a soil with saltation- and suspension-size particles will result in the progressive devegetation of the downwind area. Thus, our model can be extended to apply to any arid or semi-arid shrubland with a source of wind-erodible material.

Other land forms in the arid south-west

Any arid shrubland with a source of wind-erodible, fine-grained material at the surface may be susceptible to anthropogenic degradation. Our study of the Manix Basin indicates that arid shrublands on Pleistocene paleolake beds are especially susceptible to anthropogenic degradation. Pleistocene lacustrine deposits are common in basins throughout the arid south-western United States, where large, shallow pluvial lakes existed during the Last Glacial Maximum (Smith & Street-Perrott, 1983; Morrison, 1991*a*, *b*). Closed basins that were once Pleistocene lakes exist in many now-arid areas throughout the globe. The degradation observed in the Manix Basin is an example which can be applied to similar geological environments globally. Many of the areas exhibit qualities that make them amenable for many human use, such as very low slopes, little or no relief, subsurface water resources, and fine-grained sediments suitable for farming or other activities. Thus, the areas of greatest potential use are also susceptible to serious degradation.

The armoured soils of desert bajadas—defined as broad, gently inclined alluvial surfaces extending from the base of mountain ranges to inland basins—may also be susceptible to human-induced degradation. Although these soils are typically too gravelly or steep to be used for agriculture, these landforms may be wind erodible when disturbed by human activities. When present, the soil armour has been argued to develop through the 'born at the top' model of McFadden *et al.* (1987), wherein fine, wind-mobilized particles are trapped by surface cobbles that float atop the accumulation of fine-grained material. Removal of the very stable desert pavement therefore exposes a layer of extremely wind-erodable wind-derived material, sometimes metres thick. Anthropogenic disturbance in these areas is likely to have profound consequences. Certainly, 'born at the top' pavements downwind of areas of active dunes will be at high risk of degradation should the cover of protective pebbles be disturbed. Other soils of aeolian origin, including stabilized dunelands, will similarly be susceptible to anthropogenic degradation of the type discussed here.

Cryptobiotic soil crusts—communities of cyanobacteria, lichens, and mosses—are found throughout the world's deserts. These crusts bind fine soil particles by linked cyanobacterial fibres which protect the soil from wind erosion. Belnap (1995), Williams *et al.* (1995), and Marticorena *et al.* (1997) have suggested that the presence of cryptobiotic crusts dramatically decreases wind and water erosion. When disturbed, cryptobiotic crusts lose most of their protective qualities allowing mobilization of the underlying mineral soils. Shrubland areas with widespread cryptobiotic crusts are thus also vulnerable to progressive degradation should human activities disturb these fragile soil crusts.

Global implications

The problem of wind-induced land degradation is not limited to the south-western United States. Greater use of mechanized agriculture in arid regions throughout the world, as well as other land-use demands, is increasing the amount of arid and semi-arid shrublands brought into cultivation or under human influence (see, for example, Luk, 1983; Kealah, 1989; Khalaf & Al-Ajmi, 1993; Zha & Gao, 1997; Kasusya, 1998; Khresat *et al.*, 1998; Koch & El Baz, 1998; Mitchell *et al.*, 1998). This trend, linked with political/economic instability or the marginal and water-limited nature of arid land agriculture, makes sustainable arid region agriculture especially challenging.

Nations with a large proportion of their territory situated in arid environments with wind-erodible soils are particularly vulnerable to the consequences of land degradation. Great care needs to be employed in the responsible stewardship of these lands to promote sustainable agricultural, economic and social development.

Summary

Aeolian mobilization of dust, sand, and litter triggered by anthropogenic disturbance contributes to the destruction of islands of fertility by killing shrubs through burial and abrasion. This interrupts nutrient-accumulation processes and allows the loss of soil resources by abiotic transport processes. The resulting reduction of vegetation cover, in turn, increases susceptibility to wind erosion.

Land degradation processes necessarily exist in the context of regional climate and can either be bolstered or hindered by climatic conditions and changes, a fact that makes the rate of degradation ultimately climate-related. The process model developed here suggests various remediation techniques to halt shrubland degradation, but ultimately indicates that human use of landscapes susceptible to wind erosion should be avoided where possible.

In the face of largely unsustainable socioeconomic factors, the vulnerability of arid lands to degradation argues for the development of linked degradation process models and monitoring strategies in order to minimize environmental damage and to promote sustainable management of human activities in arid lands. The dramatic landscape changes that accompany arid shrubland degradation can be monitored using present and future remote sensing techniques and technologies. When informed by process models, such as the one presented here, remote monitoring tools may be used in the future to identify areas at risk of runaway degradation before large areas are adversely affected.

Globally, degradation of already-marginal arid lands represents a dramatic threat to local populations, food resources, and regional stability. Presently, the United Nations Convention to Combat Desertification is before the United States Senate for ratification.

This treaty provides for scientific and technical exchange to combat desertification. The processes of arid land degradation must be understood, effective monitoring techniques developed, and effective remediation and management techniques implemented to avoid costly and prolonged environmental crises. The model presented here represents a small step in attaining these goals.

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