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Multi-scale controls on and consequences of aeolian processes in landscape change in arid and semi-arid environments

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Abstract

Aeolian processes are tightly linked to soil and vegetation change in arid and semi-arid systems at multiple spatial and temporal scales. Wind influences patterns of vegetation and soil within the landscape, and these patterns control wind erosion at patch to landscape scales. Aggregated at larger scales, patterns in soil and vegetation distributions influence global distributions of dust and its biogeochemical impacts. Understanding the controls on aeolian processes is therefore important not only in understanding the biogeochemistry and land cover patterns in dryland environments, but also in understanding global land cover, climate, and biogeochemistry. Although the microscopic physics that control aeolian processes are well understood, the controls on these processes in real landscapes are poorly constrained, particularly for structurally complex plant communities such as shrub-invaded grasslands. This paper reviews the controls on aeolian processes and their consequences at plant-interspace, patch-landscape, and regional–global scales. Based on this review, we define the requirements for a cross-scale model of wind erosion in structurally complex arid and semi-arid ecosystems.

Keywords: Aeolian processes; Desertification; Dust emission; Landscape change; Wind erosion

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[1]Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture.

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Nomenclature

a	ground area where wake flow intersects surface (cm^2)
A	supply limitation coefficient, $0 \leqslant A \leqslant 1$ (dimensionless)
A_B	average basal area of plants in an area, s (cm^2)
A_P	average profile area of plants in an area, s (cm^2)
b	average plant diameter (cm)
β	ratio of drag coefficient of vegetated surface to drag coefficient of unvegetated surface, $\beta \equiv C_R/C_S$ (dimensionless)
c	empirical constant with value ~0.37 (dimensionless)
C	total fractional cover (dimensionless)
C_d	drag coefficient (general notation) (dimensionless)
C_R	drag coefficient for plant (dimensionless)
C_S	drag coefficient for unvegetated soil (dimensionless)
δ	Kronecker Delta, $\delta = 1$ when $u_{*t} > u_{*tv}$ and $\delta = 0$ otherwise (dimensionless)
D	displacement height (cm)
F_a	vertical sediment (dust) flux for specified set of conditions ($g\,cm^{-2}\,s^{-1}$)
g	acceleration due to gravity (981) ($cm\,s^{-2}$)
h	average plant height (cm)
k	Von Karmann's constant (~0.4) (dimensionless)
K	the ratio of vertical flux, F, to horizontal flux, q (cm^{-1})
L	intershrub distance (cm)
L_{min}	the maximum distance that wake flow extends past the downwind edge of a plant (cm)
λ	lateral cover, $\lambda \equiv nbh/s$ (Raupach et al., 1993) (dimensionless)
n	the number of plants in an area, s (dimensionless)
N	plant number density, $N \equiv n/s$ (cm^{-2})
q_{eq}	equilibrium horizontal sediment flux for specified set of conditions ($g\,cm^{-1}\,s^{-1}$)
ρ	density of air ($g\,cm^{-3}$)
s	area on the ground with n plants (cm^2)
σ	ratio of the average plant basal area to average profile area, $\sigma \equiv A_B/A_P$ (dimensionless)
τ	surface shear stress ($g\,cm^{-1}\,s^{-2}$)
u_*	wind shear velocity ($cm\,s^{-1}$)
u_{*ts}	threshold shear velocity for an unvegetated surface ($cm\,s^{-1}$)
u_{*tv}	threshold shear velocity for an vegetated surface ($cm\,s^{-1}$)
$U(z)$	wind speed at height, z ($cm\,s^{-1}$)
z	height above the surface (cm)
z_0	roughness length (cm)

1. Introduction

The world's arid and semi-arid regions cover more than 30% of the Earth's land surface. Conversion of grasslands to shrublands is occurring at an alarming rate in these regions. Due to low and variable vegetation cover, aeolian processes (i.e. erosion and transport of particles by wind and subsequent downwind deposition of these particles) are prevalent in desert environments and wind is an important factor in redistributing sediments and dust-borne nutrients. Redistribution of material by wind occurs at multiple scales. At the plant-interspace scale, material can be scoured from interspaces and deposited underneath nearby plants (Gibbens et al., 1983). At the patch scale, wind can remove sediment from one area, deposit the coarse material in an adjacent area, and remove the fine material (dust) for long-range transport (Okin et al., 2001a, b). At the landscape scale, wind is an important geomorphic process (Greeley and Iversen, 1985). At global scales, dust emitted in one region of the globe can be important in the biogeochemistry of downwind ecosystems (Chadwick et al., 1999; Okin et al., 2004).

The two principal mechanisms for the transport of sediment by wind are saltation and suspension. In saltation, particles are removed from the surface by aerodynamic lift and travel in short, arcuate hops through the air (Bagnold, 1941). Dust particles, fine particles with Stokes' settling velocity less than the vertical component of the wind velocity during turbulent flow, are transported by suspension. The primary ecological consequence of saltation is the physical effect of saltation-sized particles on soils and vegetation.

Unlike saltating silt and sand grains, dust particles are not removed from the surface by aerodynamic forces, but instead are emitted when saltating particles sandblast the soil surface (Gillette, 1977). Horizontal mass flux (expressed in units of mass per unit distance perpendicular to the wind per unit time) is comprised mostly of saltating particles greater than 50 mm in diameter. Vertical flux (expressed in units of mass per unit area per unit time) consists of the flux of dust from the surface and available for long-range transport by wind. Because of the relative differences in transport distance for suspended and saltating particles, the saltated sediment typically has a very local influence on vegetation and soils, whereas the influence of suspended sediment can extend thousands of kilometers. The primary ecological consequences of dust emission and subsequent downwind deposition of suspended particles arise from the fact that small, saltation-sized particles are largely responsible for soil quality, generally defined. In particular, because soil nutrients are concentrated on dust particles, dust emission and redeposition have significant impacts on local and downwind soil nutrient status.

Our objective is to review the influence of aeolian processes on landscape processes and to examine the feedbacks and cross-scale interactions between vegetation cover and aeolian processes in arid lands. Emphasis is given to research and results from the Jornada Experimental Range (JER) located in the Chihuahuan Desert in southern New Mexico, USA. Special consideration is given to the controls on and consequences of aeolian processes at three scales: (1) the plant-interspace scale (cm—a few meters), (2) the patch-landscape scale (10s of m—10s of km), and (3) the regional–global scale (greater than 100s of km).

2. Plant-interspace scale

2.1. Controls on aeolian processes at the plant-interspace scale

In general, aeolian processes are initiated when the *erosivity* of the wind exceeds the *erodibility* of the surface. Wind erosivity is typically quantified as the *shear velocity* of the wind. Shear velocity is directly proportional to the rate of increase of velocity with log-height for a neutral atmosphere and is defined as $u_* \equiv \sqrt{\tau/\rho}$, where τ is the surface shear stress and ρ is the density of air. The amount of drag exerted by the surface on the wind is related to the shear velocity and the wind speed by:

$$C_\mathrm{d}(z) = (u_*/U(z))^2, \tag{1}$$

where C_d is the drag coefficient and $U(z)$ is the wind speed at height, z.

The erodibility of the surface is typically related to the *threshold shear velocity*, the shear velocity below which saltation flux will not occur. The threshold shear velocity of the surface depends on the both the soil and the vegetation. Threshold shear velocity for soils is largely determined by the texture of the soil, the amount of protective coverage provided by nonerodible clasts or crusts, and soil moisture (Ravi et al., 2004). Marticorena and Bergametti (1995) provided a parameterization for the threshold shear velocity on soils based on mean particle diameter showing that particles from approximately 80–120 μm are efficient saltators with low threshold shear velocity. Gillette et al. (2001) suggested that some soils may be "supply limited", meaning that the population of saltation-sized particles is not large enough to sustain the maximum theoretical horizontal flux.

Vegetation modulates the erodibility of the surface primarily through three mechanisms (Fig. 1, Wolfe and Nickling, 1993): (1) vegetation can directly shelter the soil from the force of wind by covering a fraction of the surface and providing a lee-side wake in which average wind speed is dramatically reduced, (2) vegetation can extract momentum from the wind, thus reducing the wind erodibility, and (3) vegetation can trap windborne particles reducing total horizontal and vertical flux and providing loci for sediment deposition.

2.1.1. Sheltering by vegetation

The wind can only act on the fraction of the soil surface that is not directly sheltered by vegetation. Vegetation provides sheltering either by covering the soil surface or by creating lee-side wakes in which turbulent flow dominates and the mean velocity is either zero or, in some cases, opposite the direction of the free-stream wind direction (Wolfe and Nickling, 1993). The degree of sheltering by the wind is therefore related to both the fractional cover and the sheltering provided by wake flow. Lee and Soliman (1977) have defined three flow regimes depending on the size of the wake behind vegetation and the vegetation spacing (see Fig. 2): (1) isolated roughness flow, where there is no interaction between wakes and adjacent downwind vegetation, (2) wake interference flow, where wakes from upwind plants intercept downwind vegetation, and (3) skimming flow, where wakes completely overlap and the entire soil surface is within the protected wake region.

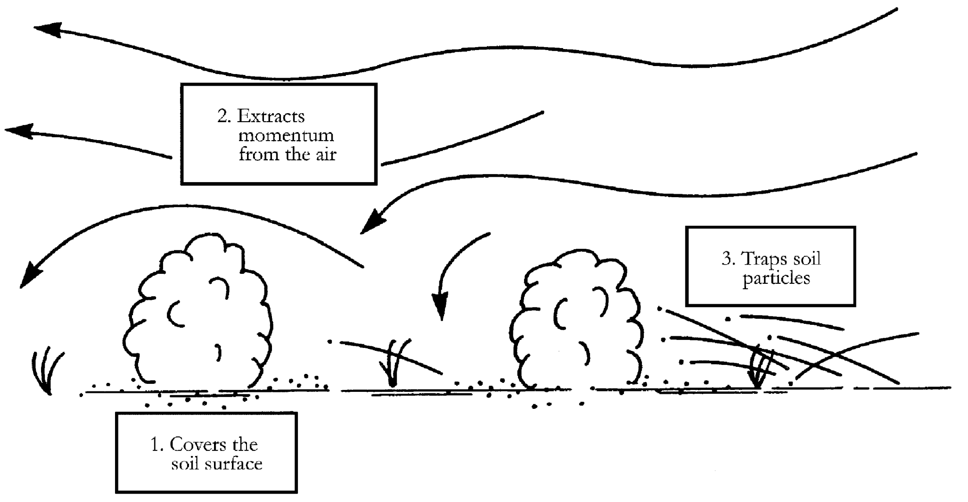

Fig. 1. The three mechanisms by which vegetation protects the soil surface from wind erosion; from Wolfe and Nickling, 1993.

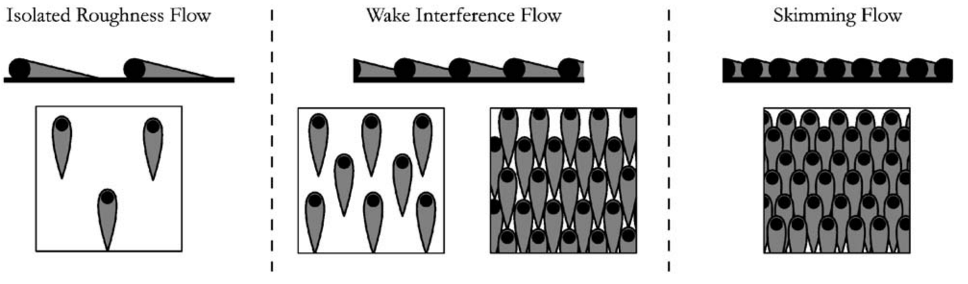

Fig. 2. Flow regimes and associated theoretical wake development. Shaded areas are wake regions; adapted from Wolfe and Nickling (1993) after Lee and Soliman (1977).

In his treatment of drag partitioning in vegetated landscapes, Raupach (1992) derived a formula to describe the area downwind of a plant (approximated to have cylindrical shape) protected from the erosive force of the wind in the wake:

$$a = cbh\frac{U(h)}{u_*}, \tag{2}$$

where a is the area where wake flow intersects with the surface, c the constant with a value of approximately 0.37, b the diameter of the plant, h the height of the plant, and $U(h)$ the wind speed at the top of the canopy (Fig. 3). If the wake is considered to be a tapering prism (Fig. 3) for plants with $b \geqslant h$, the maximum distance that the

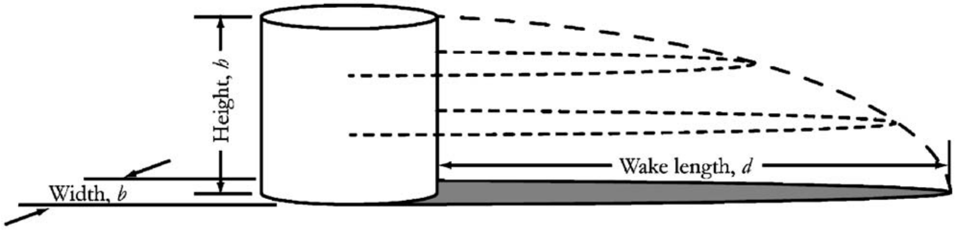

Fig. 3. Sheltering provided by a cylinder. Shaded area is the intersection of wake with ground; after Raupach (1992).

wake extends past the downwind edge of the plant, $L_{\min}$, is:

$$L_{\min} = h\frac{U(h)}{u_*} - \frac{b}{2}. \tag{3}$$

For cases in which vegetation cover is low, such that wakes from one plant do not interact with the sheltered area of other plants (e.g. isolated roughness flow),

$$\frac{U(h)}{u_*} \approx \frac{1}{\sqrt{C_S + \lambda C_R}}, \tag{4}$$

where C_S is the drag coefficient for the soil and C_R the drag coefficient for the plant. Drag coefficients quantify how the drag force on the surface varies with wind speed. The parameter λ is *lateral cover*, the total frontal silhouette area of vegetation intercepted by wind per unit ground area (Musick and Gillette, 1990; Musick et al., 1996; Shao and Lu, 2000). Values for C_R are approximately 0.25 for cylinders (Taylor, 1988) and values for C_S have been reported to be approximately 0.0025 (Crawley and Nickling, 2003). Thus, for values of λ near 0.01, the wake region should extend downwind approximately 10 times the height of the plant. Thus, Eqs. (3) and (4) are consistent with results from wind tunnel experiments by Minvielle et al. (2003) which suggested a protective wake approximately 10 times longer than vegetation height. Drag coefficients for porous objects are likely higher than those of solid objects considered in most wind tunnel and theoretical studies (Grant and Nickling, 1998; Raupach et al., 2001). For real vegetation, therefore C_R will increase (relative to values for solid cylinders) and wake area protected by vegetation ($L_{\min}$) will decrease. For porous vegetation, therefore, the area of wake protection can be expected to be less than 10 times vegetation height.

2.1.2. Momentum extraction by vegetation

Vegetation can extract momentum from the wind, reducing its erosive force on the surface. Shear velocity is related to wind speed and vegetation structural parameters by the Law of the Wall. For a neutral atmosphere:

$$U(z) = \frac{u_*}{k}\ln\left(\frac{z-D}{z_0}\right), \tag{5}$$

where k is the Von Karmann's constant, z_0 the aerodynamic roughness length, and D is the zero-plane displacement height. z_0 and D are related to surface roughness and, in vegetated areas, are mainly determined by the amount and structure of vegetation cover. When D is not equal to zero, a wake is present and wind erosion will not occur. z_0 has been related to lateral cover by Lettau (1969) and Wooding et al. (1973) using $z_0 = h\lambda/2$, where h is equal to canopy height. This relation holds for $0 < \lambda < \sim 0.1$. For $\lambda > \sim 0.1$, z_0/h remains approximately constant. Marticorena et al. (1997) suggested a relation that incorporates the leveling-off of the linear relationship with increasing λ:

$$z_0 = \begin{cases} (0.479\lambda - 0.01)h & \text{for } \lambda \leqslant 0.11, \\ 0.05h & \text{for } \lambda > 0.11. \end{cases} \tag{6}$$

(*Note*: this formulation is slightly different from that found in Marticorena et al. (1997) due to a typographical error in that publication). These equations do not account for interspecific variability in the flexibility of the vegetation. These changes can be accounted for empirically by changing the coefficients.

2.1.3. *Trapping of windborne sediment by vegetation*

Because turbulent flow dominates in and around plant canopies, total surface shear stress within plant canopies typically approaches zero and the ability of wind to carry sediments is reduced. In addition, windborne particles can impact vegetation, losing their momentum, and be removed directly from the air stream. Thus, vegetation canopies are typically the loci of deposition in partially vegetated areas. Coarse-grained particles travel short distances and therefore are often moved from plant interspaces to adjacent regions underneath plant canopies or in plant wakes. Fine-grained particles that are suspended in the wind can also be intercepted by plant canopies and deposited within the plant canopy.

The ability of a plant canopy to trap windborne sediment depends, in part, on its porosity. Field (e.g. Grant and Nickling, 1998), wind-tunnel (e.g. Lee et al., 2002), and theoretical (e.g. Raupach et al., 2001) studies have shown that the ability of vegetation to act as a windbreak for sediment has a maximum value for an intermediate value of porosity, with porosities of approximately 20–40% showing the maximum effect.

2.2. *Consequences of aeolian processes at the plant-interspace scale*

The consequences of wind erosion at the plant-interspace scale are directly linked to the two main processes of aeolian transport: saltation and suspension (Fig. 4). Saltation flux dominates the horizontal mass flux during aeolian transport. Saltating particles are therefore responsible for the majority of deflation and subsequent downwind deposition of windborne sediments (Gibbens et al., 1983). Hennessy et al. (1986) determined that in mesquite duneland areas on the JER, saltation-sized particles are eroded from plant interspaces and redistributed to areas under plants, with little or no net loss of sand but a net loss of fine particles. On the

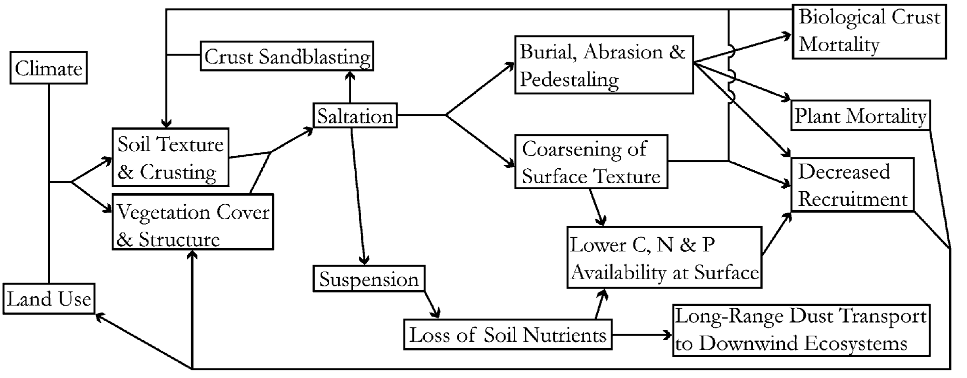

Fig. 4. Selected causes and consequences of aeolian processes.

plant-interspace scale, therefore, a landscape undergoing wind erosion exists as a fine-scale mosaic of deflational and depositional areas.

Deflation can cause "pedestaling" of plants in areas actively experiencing wind erosion. Pedestaling is a process whereby the soil surface is lowered by deflation, which exposes plant roots and can result in plant mortality. Deposition occurs when the mean wind velocity decreases, usually due to the presence of vegetation, and windborne sediments are deposited. Deposition can result in burial of vegetation, and if it occurs at a rate greater than the rate of vertical growth of a plant, can result in mortality (Okin et al., 2001a).

If the horizontal velocity of windborne particles in the saltation layer is equal to the average windspeed in the saltating layer, then the kinetic energy flux ($\mathrm{J\,m^{-1}\,s^{-1}}$) increases as a linear function of mass and a cubic function of particle diameter. Under these assumptions, a horizontal mass flux consisting solely of 100 μm particles has approximately 1000 times greater kinetic energy flux than the same flux consisting solely of 10 μm dust particles. When saltating sand grains strike a plant, this excess energy causes physical damage, mainly in the form of destruction of the cambium and leaf stripping (Okin et al., 2001a). If this physical damage does not directly result in plant mortality, it almost certainly results in slowed growth, which may compromise a plant's ability to overcome burial or pedestaling. Abrasion and burial by saltation-sized particles therefore act in tandem to stress vegetation. The excess kinetic energy of saltating particles can also sandblast fragile soil crusts that form in desert regions, reducing the threshold shear velocity of the affected surface and exposing it to increased wind erosion (Gillette and Pitchford, 2004).

Suspension-sized particles are winnowed from areas undergoing erosion and can either be removed for long-range transport (Gillette, 1974) or trapped by near-field vegetation (Raupach et al., 2001). Fine-grained particles account for the majority of the soil resources important to vegetation, including nutrient exchange capacity and water-holding capacity. The contribution of fine particles to soil nutrient availability results from the fact that particles in this size fraction have a high surface area and soil nutrients such as nitrate, ammonium, potassium, magnesium, and phosphate are adsorbed onto these particles, especially those with clay mineralogy.

Long-range transport of dust particles contributes to overall loss of soil resources for an area undergoing wind erosion (Okin et al., 2001b). At the plant-interspace scale, winnowing results in the depletion of fine particles from plant interspaces (Hennessy et al., 1986). Plant interspaces are therefore the sites of decreased soil resource availability (Wright and Honea, 1986; Schlesinger et al., 1996; Okin et al., 2001a, b). The interception and trapping of the suspended load can lead to increased soil resource availability within and around plant canopies (Raupach et al., 2001). A landscape undergoing wind erosion therefore exists as a fine-scale mosaic of areas of winnowing and trapping resulting, in part, in the well-documented resource island phenomenon in shrublands (Schlesinger et al., 1990; Schlesinger et al., 1996).

3. Patch-landscape scale

3.1. Controls on aeolian processes at the patch-landscape scale

Horizontal mass flux has been modeled by a large number of authors using different approaches. Bagnold (1941) approached the problem first and provided a physically reasonable solution that was later confirmed by the analysis of Owen (1964). Equations that predict saltation have been suggested by many authors and verified by wind tunnels, field experiments, and alternate theoretical derivations. Many good discussions exist in the literature of the physical and mathematical formulations for mass flux during wind erosion (e.g. Shao and Lu, 2000). One such formulation is by Shao and Raupach (1993):

$$q_{eq} = A\frac{\rho}{g}u_*(u_*^2 - u_{*tv}^2)\delta, \tag{7}$$

where q_{eq} is the horizontal mass flux ($\mathrm{g\,m^{-1}\,s^{-1}}$), ρ the density of air, g the acceleration due to gravity, u_* the wind shear velocity, and u_{*tv} the threshold shear velocity of a vegetated surface (m/s). δ is set equal to 0 for $u_{*tv} \geqslant u_*$ and 1 otherwise. The parameter A in Eq. (7) has been suggested by Gillette et al. (2001) and Gillette and Chen (2001) as a correction to account for the relative availability of sand particles for transport. In the absence of other information, A is typically assumed to be equal to 1.0. Vertical mass flux, F_a ($\mathrm{g\,m^{-2}\,s^{-1}}$), is linearly related to horizontal mass flux by a constant K that is typically on the order of 10^{-2}–$10^{-3}\,\mathrm{m^{-1}}$, but can vary by several orders of magnitude based on soil texture and other factors (Gillette, 1977; Alfaro and Gomes, 2001).

In an analysis of drag partitioning over a vegetated surface, Raupach et al. (1993) derived an equation to estimate the impact of vegetation on the threshold shear velocity, u_{*tv}:

$$u_{*tv} = u_{*ts}\sqrt{(1-\sigma\lambda)(1+\beta\lambda)}, \tag{8}$$

where u_{*ts} is the threshold shear velocity for an unvegetated surface, σ is equal to the ratio of the average basal area to average profile area (i.e. $\sigma \equiv A_B/A_P$) of the vegetation, and β is the ratio of the drag coefficient of an isolated plant to the drag coefficient of the ground surface in the absence of the plant (i.e. $\beta \equiv C_R/C_S$). Eq. (8) may be re-expressed (Okin, 2005) as:

$$u_{*tv} = u_{*ts}\sqrt{(1-C)\left(1+\beta C\frac{A_P}{A_B}\right)}. \tag{9}$$

The first terms under the radicals in Eqs. (8) and (9) (i.e. $[1-\lambda\sigma]$ and $[1-C]$) account for the degree to which the vegetation covers the surface (see Section 2.1.1), focusing the erosive force of the wind on the exposed portion of the surface. The second terms under the radicals (i.e. $[1+\beta\lambda]$ and $[1+\beta CA_P/A_B]$) account for drag that the vegetation exerts on the wind (see Section 2.1.2), reducing the ability of wind to detach and transport particles.

Aeolian sediment flux tends to increase with the distance over which the erosion occurs (*fetch distance*), an effect known as the *fetch effect* (Gillette et al., 1996). The fetch effect is caused by aerodynamic effects (the Owen effect), particle-to-particle interactions, reattachment of separated boundary layers, and changes in the soil in the path of wind erosion. In discontinuous canopies where isolated roughness flow dominates, the fetch length is determined by the spacing between plants. Okin and Gillette (2001) used high-resolution aerial photography to investigate plant spacing in mesquite-dominated areas of the JER (see also, Ludwig et al., 2002). They concluded that plant spacing can be anisotropic, and that areas of extremely long fetch distance, known as *streets*, existed and tended to be aligned with the direction of the prevailing wind. The observed streets were inferred to be the cause of extremely high dust emission in well-developed dunelands.

Gillette and Pitchford (2004) examined wind erosion in streets of mesquite dunes to determine if fetch effect is an important factor for determining horizontal flux in vegetated areas dominated by isolated roughness flow or wake interference flow. Their study showed that flux increases along streets in the windward direction, reaching a maximum at the end of the street.

Data from Li and Okin (2004) and Hartman (personal communication) also support the importance of fetch (Tables 1–3). A very strong positive correlation exists between the percent of the surface comprised of unvegetated gaps >200 cm and average horizontal flux (Table 2). The anticorrelation between percent of the surface comprised of gaps other than those >200 cm and flux is a result of the strong anticorrelation between gaps >200 cm and other gaps (Table 3). The regression line for the >200 cm gap percentage and total horizontal flux intercepts the gap percentage axis at approximately 22%, indicating there is a minimum percentage of an area covered by large gaps that will enable significant wind erosion to occur. We hypothesize that with vegetation distributions in which there are not large gaps, wake interference and skimming flow predominate and the soil surface is largely protected from erosion.

Table 1
Gap percent, fractional cover, and horizontal flux for five vegetation plots on the JER[a]

Treatment	Percent of 50-m transect comprised of gaps of size:					Fractional cover (%)	Horizontal flux ($g\,m^{-1}\,s^{-1}$)
	25–50 cm	51–100 cm	101–200 cm	> 200 cm	> 500 cm		
T4	1.58	4.35	7.19	70.71	82.25	15.3	266.1
T3	6.01	15.49	21.09	35.54	72.12	19.3	80.0
T2	4.35	9.01	29.89	40.69	79.59	14.7	52.6
T1	8.31	19.48	29.19	21.21	69.88	17.4	29.8
Control	8.56	17.37	30.23	24.85	72.45	15.6	18.9

[a]Data are from four vegetation treatment plots (plus one control) in which vegetation was selectively removed. Aeolian flux was estimated in these plots using Big Springs Number Eight (BSNE) windborne sediment samplers and the method of Gillette and Pitchford (2004) for calculating total horizontal flux from the surface to 1 m. BSNE samples were from March to July, 2003. Fractional vegetation cover was estimated from three 50-m transects in each plot, oriented parallel to the direction of the prevailing wind. Unvegetated gaps were identified from transect data and the percent of each transect covered by gaps in five size bins (25–50 cm, 51–100 cm, 101–200 cm, > 200 cm, and > 50 cm) was calculated (see Herrick et al., 2005). Transect data were collected in August–September, 2003. Annual plant cover was ignored in these calculations because annuals are not present during the spring dust season.

Table 2
Correlation and regression statistics between gap percent or fractional cover and horizontal flux

	Percent of 50-m transect comprised of gaps of size:					Fractional cover (%)
	25–50 cm	51–100 cm	101–200 cm	> 200 cm	> 500 cm	
Correlation	−0.88	−0.82	−0.97	0.96	0.75	−0.22
Slope	−30.66	−13.29	−10.02	4.97	14.21	−11.93
Intercept	266.14	264.14	325.04	−102.32	−980.28	286.06
R^2	0.77	0.68	0.95	0.92	0.56	0.05

Table 3
Correlation between percent of transect comprised of gaps > 200 m and other gap sizes and fractional cover

	Percent of 50 m transect comprised of gaps of size:					Fractional cover (%)
	25–50 cm	51–100 cm	101–200 cm	> 200 cm	> 500 cm	
Correlation	−0.97	−0.95	−0.90	1.00	0.90	−0.37

The weak anticorrelation between sediment flux and vegetation fractional cover (Table 2) indicates that threshold shear velocity is not simply a function of cover, as suggested by Eq. (9). Instead, the manner in which this cover is distributed, and in particular the degree to which vegetation is distributed to create large gaps, is vital in controlling aeolian flux. These data therefore argue strongly for including fetch length in assessment and monitoring of wind erosion on vegetated landscapes (Herrick et al., 2005).

3.1.1. Landscape-scale controls on aeolian processes: Land use and land management

Land use and management impact both soils and vegetation in arid regions (Fig. 4). In the short-term, soil erodibility is usually increased by any activity that disturbs the soil surface (Bach, 1998; Belnap, 1995). Soil surface disturbance destroys physical and biological crusts and exposes more highly erodible subsurface material. Non-erodible gravel and rock fragments are often incorporated into the soil, exposing fine-textured material when physical disturbance mixes the surface layers of the soil. Short-term disturbance impacts are generally higher when the soil surface is dry. On wet soils, some types of disturbance will only deform the surface and may even reduce erodibility by contributing to the development of a physical crust or compacted layer, particularly in fine-textured soils such as loams and clays. Examples of activities that disturb the soil surface and increase aeolian flux are: military activities and maneuvers (Prose, 1985; Khalaf, 1989; Koch and El Baz, 1998) grazing (Wilshire, 1980; Khalaf, 1989; Fredrickson et al., 1998) and off-road vehicle (ORV) traffic (Nakata et al., 1976; Sheridan, 1978; Hyers and Marcus, 1981; Webb, 1982; Brown and Schoknecht, 2001).

The role that vegetation plays in modulating both the erosivity of winds and erodibility of the surface is impacted by any land use or management scheme that impacts vegetation cover. For example, fire can destroy above-ground biomass, reducing fractional and lateral cover of vegetation, thus exposing the surface to wind erosion. A striking example of this phenomenon is shown in Fig. 5. In October–November, 2003, large wildfires burned in the mountains of southern California. By the end of November, these fires had been extinguished, but the burn scars can still be seen in satellite imagery. The MODIS/Terra instrument captured strong winds on November 27, 2003 carrying ash and dust westward into the Pacific Ocean.

Agricultural activities often enhance aeolian activity in arid and semi-arid environments (Fig. 4). During the peak growing season, crops protect the soil from erosion by wind, but periods of bare ground during the beginning or end of the growing season can lead to significant erosion (Hagen, 1991; Nanney et al., 1993; Retta et al., 1996). The practice of maintaining some vegetation residue on the soil surface (i.e. *stubble*) has long been advocated as a practice to minimize wind erosion. Fallowing of fields, sometimes for long periods, can also be a significant source of windborne sediment (Larney et al., 1995). For example, in the Sandveld of the Western Cape Province of South Africa, a region of strong southerly winds and sandy soils (Talbot, 1947), seed potatoes are a principal crop. To protect from blight infestations, this crop can only be planted approximately one year in seven and fields are kept fallow during the remaining six years. As a means to control wind erosion on fields during the long fallow periods, stripes of vegetation are left in fields. These stripes are predominantly oriented east-west in order to minimize north-south fetch distance in fields and reduce erosion (Fig. 6). Similar impacts occur when rangeland is cleared and reseeded. Vegetative cover removal, intense surface disturbance, and

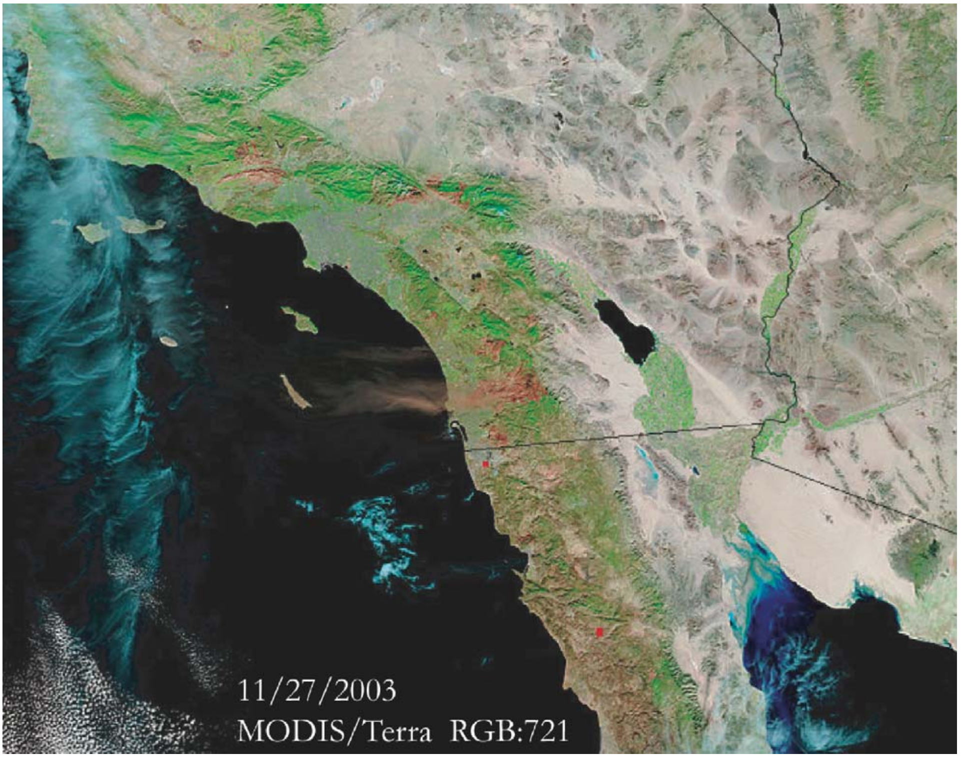

Fig. 5. False-color image of the southern California coast captured with the MODIS instrument aboard the Terra satellite on November 27, 2004. Red is MODIS band 7 (2155 nm), green is MODIS band 2 (876 nm), blue is MODIS band 1 (670 nm). Reddish areas are burn scars from fires at the end of October and beginning of November, 2003. Red dust can be seen heading westward over the Pacific from the two most southerly fire scars due to strong winds. Cyan areas over the western and southern portions of the image are clouds or sediments in the Colorado River Delta. Image courtesy of MODIS Rapid Response Project at NADA/GSFC.

typically low seedling establishment often leave soil susceptible to wind erosion for several years (Herrick et al., 1997; Breed and Reheis, 1999).

Grazing and ORV traffic tend to increase erosivity by reducing both cover and stature and by breaking physical and biological soil crusts. The effects of both types of activities tend to be highly concentrated. This leads to the creation of mosaics of areas that are relatively exposed within a pasture in which average cover is sufficient to prevent wind erosion. Off-road vehicle activity can be particularly damaging when oriented parallel to dominant winds because it has the potential to create wind erosion streets. Consequently, whereas a management activity may have a minimal effect on average cover measured within a pasture, wind erosion may increase in those small areas of the pasture in which activity is concentrated. In the long-term, both grazing and ORV activity can have persistent effects on wind erosivity by promoting changes in plant community composition, which ultimately affects both cover and structure (Fig. 4).

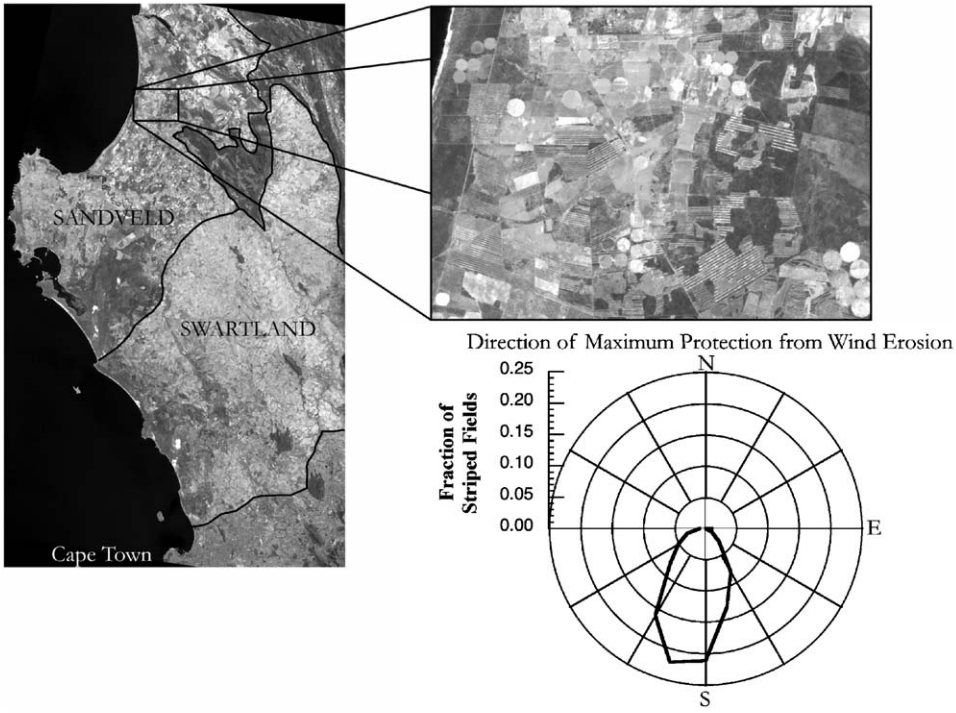

Fig. 6. Landsat ETM+ Band 8 (15-m resolution panchromatic band) images showing the southwestern coast of South Africa and a rose diagram of the directions protected from wind erosion by linear stripes of vegetation left in fields. Cape Town can be seen at the bottom of the full image. The enlarged image shows how the vegetation strips appear at full resolution in the image. The rose diagram is derived from measuring the orientation of all striped fields in the area labeled "Sandveld". Erosive winds in the region are typically from the south, the direction of maximum protection in the striped fields. Farmers in this region of South Africa are managing for wind erosion of fields during long fallow periods by maintaining short streamwise fetch lengths through the maintenance of vegetation stripes.

The timing of management activities relative to significant wind events is critical in arid and semi-arid ecosystems. While this fact is widely recognized in the case of cultivated systems, the effect of timing of grazing and ORV activity on wind erosion is rarely considered. For example, in the southwestern United States, most wind erosion occurs during the spring. Minimizing vegetation removal and soil surface disturbance during winter and spring on highly wind-erodible soils has the potential to limit long-term soil degradation. This hypothesis has not been explicitly tested at the landscape scale. Similarly, limiting road grading and maintenance activities to periods when a physical crust-producing precipitation event is likely to occur before a significant wind event should reduce sediment loss from roads and road margins.

Because of these multi-scale interactions, historic and pre-historic land uses (i.e. historic legacy, Peters and Havstad (2006)) may have long-term impacts that may or may not be readily apparent. For example, the spread of small areas of mesquite established by Native Americans (Fredrickson et al., 2006) may have been due in part to grass abrasion, burial, and reduced soil surface stability caused by aeolian sand moving from these shrub-dominated areas.

Land managers require an ability to predict management effects on wind erosion and an understanding of the likely effects of wind erosion and deposition on susceptibility to future erosion. Whereas the effects of broadly defined land use types (e.g. cultivation vs. permanent pasture) are generally understood at the patch scale, currently available models fail to account for the cascading effects of management-mediated changes in vegetation cover and structure at multiple spatial scales. Further, these essentially agronomic models do not account for the temporally variable and interacting effects of soil surface disturbance (which increases soil erodibility) and spatially variable vegetation growth and removal (which increases wind erosivity) in perennial ecosystems. Most models also fail to address linkages among landscape units, and the direct and indirect effects of both erosion and deposition on susceptibility to future erosion.

3.2. Consequences of aeolian processes at the patch-landscape scale

The two most significant consequences of aeolian processes at the patch-landscape scale are (1) the transport of saltation-sized particles from an eroding patch to an adjacent stable patch, and (2) the large-scale reduction of surface soil resources in both erosional and depositional areas (Fig. 4). The consequences of aeolian processes at the patch-landscape scale are similar to those at the plant-interspace scale, but take place over a larger area. Thus, while saltation can lead to the movement of coarse material from plant interspaces to nearby plant canopies to create dunes at the plant-interspace scale, saltation may also lead to the growth of mesquite dunelands into former grassland areas at the patch-landscape scale.

In their studies of the impacts of saltation flux and dust emission on vegetated patches downwind of areas where vegetation had been removed, Okin et al. (2001a, b) determined that saltation flux caused physical damage to shrubs in the downwind patch. They also determined that a mantle of coarse-grained particles derived from winnowing the original soil surface and depositing the remaining particles downwind had covered the original surface. The local mantling of the original surface resulted in an effective reduction of soil nutrient resources in the surface soil (top 5 cm). This, together with increased soil instability, could result in a decrease in recruitment of new vegetation when this mantle is thicker than the depth of soil needed for seedling establishment. These results are consistent with those of Larney et al. (1998a, b) and Leys and McTainsh (1994), who showed that significant changes in soil nutrient content could result from aeolian transport of soil particles. On fine-textured soils, however, sand deposition increases plant water availability by increasing infiltration. For example, on the south end of the Jornada Basin where tarbush (*Fluourensia cernua*) dominates loamy soils with high runoff rates, black grama (*Bouteloua eriopoda*) and bunchgrasses occur in patches covered by a mantle of aeolian sand. Deposition of finer-textured material may also serve as a nutrient source, particularly for microbiotic crusts, which lack the capacity to acquire nutrients from deeper soil layers (Belnap et al., 2001).

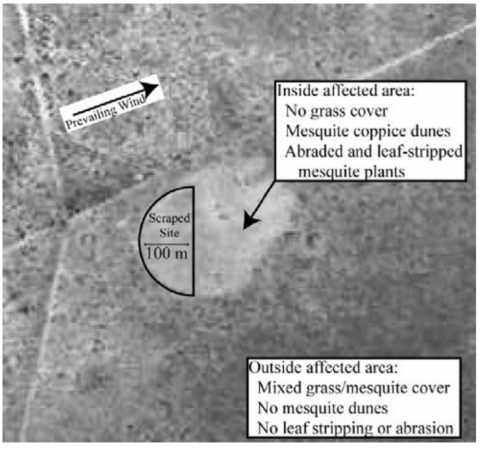

Fig. 7. The Jornada "scraped site," shown here in a 1999 low-altitude AVIRIS image with resolution of ~5 m. This site proves that wind erosion can affect ecosystem stability in this ecosystem. It has experienced an average deflation rate of 1.8 cm/yr (Gillette and Chen, 2001) and plant-available N and P have been reduced by 89% and 78%, respectively (Okin et al., 2001b). No vegetation has regrown on the scraped site itself. The vegetation community downwind of the site has changed from a grassland to a shrubland due to burial, abrasion, and leaf stripping from saltating particles off of the scraped site itself and plant-available N and P in surface soils in the downwind area have been reduced by 82% and 62%, respectively. The location of the downwind plume indicates the constancy of the wind direction at the JER.

In the decade since complete removal of vegetation at a site on the JER (the *scraped site*, Fig. 7), changes in soil texture, soil nutrients, and vegetation cover have been observed in the area downwind of the site (Okin et al., 2001b; Okin and Painter, 2004). This site has provided a dramatic example of the importance of wind erosion in understanding the relationship between adjacent vegetation patches. At a large scale on the JER, this inter-patch interaction has probably contributed to the expansion and coalescence of mesquite duneland patches. These patches, which experience the highest aeolian transport of all vegetated areas on the JER (Gillette and Pitchford, 2004), likely act as sources of coarse-grained sediment which flows into adjacent patches, burying or killing low-stature vegetation and covering the surface with a winnowed layer. This process may have also resulted in the expansion of mesquite dunes into the west side of a formerly grass-dominated playa ("Red Lake") at the north end of the JER.

4. Regional–global scale

4.1. *Controls on aeolian processes at the regional–global scale*

Although the controls on aeolian processes discussed in earlier sections are certainly general enough to be applied in arid and semi-arid regions around the globe, the most important controls on aeolian processes at the global scale are not well understood. The dust observed over North Africa, for example, certainly originates in the Sahara and Sahel regions, but current technologies do not allow unique identification of the loci in these landscapes of greatest dust emission, nor what surface processes are responsible for creating the strongest sources.

Ginoux et al. (2001) and Prospero et al. (2002) argued that the dominant sources of atmospheric desert dust are topographic lows (often paleolakes or ephemeral water bodies) with little or no impact from humans. Their studies were based on satellite and modeling studies. Although this provides a significant step forward in our understanding of the spatial characteristics of dust sources, the observation that dust emission occurs primarily in topographic lows provides very little insight about the geomorphic or anthropogenic processes responsible for creating these source areas. This theory does not explain why some topographic lows are better sources than others. Furthermore, Mahowald et al. (2002) suggested that extant atmospheric remote sensing data cannot eliminate the possibility of disturbed landscapes being important sources of desert dust to the atmosphere in North Africa because topographic lows also typically coincide with areas of human activity and disturbance of vegetation and the soil surface. By comparing atmospheric loading predicted in models and observed with satellites, Tegen and Fung (1995) argued that 50% of atmospheric dust loading could be due to "disturbed" soils: soils known to have been affected by the Saharan/Sahelian boundary shift, cultivation, deforestation, and wind erosion. The importance of spatial heterogeneity in aeolian processes also provides a significant challenge to understanding the global controls on dust emission: small sources may be responsible for the bulk of dust emission in an area, but may be too small to be resolved using global observations or models (Raupach and Lu, 2004; Okin, 2005).

4.2. Consequences of aeolian processes at regional to global scales

Saltation-sized particles are important at plant and patch scales. Over millennia, saltation can also be important at landscape scales. Aeolian movement of saltation-sized particles is believed to be trivial at regional to global scales due to low rates and obstructions that ultimately stop particle movement, with the obvious exception of periglacial loess deposits. However, dust emitted from arid and semi-arid regions can be transported globally. Airborne dust, also known as mineral aerosols in the atmospheric science community, impacts global climate through its ability to scatter and absorb light (Sokolik and Toon, 1996), to affect cloud properties (Wurzler et al., 2000), and to impact atmospheric chemistry (Dentener et al., 1996). Desert dust is thought to play a major role in ocean fertilization and CO_2 uptake (Duce and Tindale, 1991), terrestrial soil formation (Chadwick et al., 1999), and nutrient cycling (Reynolds et al., 2001; Bao and Reheis, 2003; Okin et al., 2004). Dust is also an important vector for the movement of plant nutrients (Okin et al., 2004), environmental contaminants (Travis, 1975; Breshears et al., 2003), pathogens (Leathers, 1981; Plumlee and Ziegler, 2004), and allergens (Griffin et al., 2001).

5. Toward a cross-scale model of wind erosion in structurally diverse arid and semi-arid ecosystems

Many arid and semi-arid landscapes exist as a mosaic of grass and shrub cover at the patch scale, and as a mixture between two landscape endmembers at the landscape scale: sparse arid shrubland and semi-arid grassland. Transitions between grass- and shrub-dominated communities are of particular concern to land managers in many parts of the world (Schlesinger et al., 1990; Laycock, 1991; Hoffman et al., 1995; Milton and Dean, 1995). Shrub-dominated systems commonly have higher rates of runoff and wind and water erosion. Self-reinforcing feedbacks between soil erosion and plant growth can lead to relatively irreversible thresholds (Wright and Honea, 1986; Schlesinger et al., 1990). Wind erosion models that explicitly address these dynamics are required so that managers can anticipate and prevent threshold transitions from occurring. Understanding dust emission from shrub-invaded grasslands is also important to understanding dust emission on regional to global scales, and physically based improvements of modeling efforts in mixed landscapes (e.g. encompassing grasslands, shrublands, mixed shrubland-grassland, and savannas) would allow improved global dust loading predictions (Mahowald et al., 1999; Ginoux et al., 2001; Zender et al., 2003). As a first step, we suggest the construction of a model that explicitly treats landscapes as mosaics of different life forms.

The models of Raupach et al. (1993), Marticorena and Bergametti (1995), Shao and Lu (2000), Zender et al. (2003), Okin (2005) or others could be used to model wind erosion and dust emission from shrubland or grassland endmember landscapes. In regions composed of a mosaic of grass, shrub, and bare ground, constructing a model is more difficult. Individual grass plants tend to have lower stature and smaller diameters than shrubs in these environments. At the JER, Gillette and Pitchford (2004) observed that shrublands generally experience greater aeolian mass flux than grasslands on the same soils, whereas mesquite dunelands produce the most dust. It is not clear how the diversity of life forms (i.e. grasses vs. shrubs) and covers can be included in existing models cited above. Okin (2004, 2005) suggested a stochastic method similar to that of Raupach and Lu (2004) for including variable vegetation cover in models of aeolian transport, but neither of these models accounts explicitly for vegetation structural diversity. The value of these stochastic or probability-based approaches is that surface variability can be included in existing models without rewriting these models to explicitly account for interplant dynamics. Additional information is required on the variability of vegetation cover, β-parameter, shape, height, and width as well as bare soil threshold shear velocity before this approach can be fully implemented. Significant field efforts in dust-producing regions around the world will be needed to determine the magnitude of variability of these parameters. In the absence of field data for this purpose, probability distributions in the landscape features that control wind erosion and dust emission could be used as tuning parameters in local modeling studies of dust emission.

Several elements must be included in a new wind erosion model that can account for mixed life forms in desert environments and can incorporate the range of community types observed in arid and semi-arid landscapes worldwide. Based on the considerations discussed above, we believe that such a dust emission model would have the following components:

(a) *A description of airflow between shrubs*. This component would incorporate the sheltering effect of grasses in intershrub areas but would treat grasses and shrubs separately.
(b) *An expression of the relationship between intershrub distance and sand flux*. For sites with extremely low grass cover in shrub interspaces, fetch effect can be an important determinant of the amount of wind erosion that occurs, especially in heterogeneous or anisotropic communities. This component would quantify the fetch effect in heterogeneous communities.
(c) *A threshold shear velocity for wind erosion in shrub interspaces*. We anticipate that erosion only occurs in shrub interspaces, but the threshold for particle movement can vary depending on grass cover in interspaces. Because grass cover changes seasonally and inter-annually as well as from site to site, a model which can incorporate high-frequency grass dynamics separately from low-frequency shrub change would seem to be necessary in order to incorporate differences in life forms in desert environments.
(d) *A statistical description of the dependence of intershrub distance on shrub cover and size*. Okin and Gillette (2001) found intershrub distance is dependent on both plant size and fractional cover, and that intershrub distance can be anisotropic. Thus, this component of the model would account for how shrubs are distributed on the landscape.

6. Conclusions

Aeolian processes play an important role in shaping arid and semi-arid regions worldwide. The framework proposed by Peters and Havstad (2006) to explain the heterogeneity in vegetation dynamics focuses on five key elements that connect units of variable spatial scale. Aeolian processes are related to these key elements (feedbacks, resource redistribution, transport, context, and legacy) and contribute to variable vegetation patterns and threshold behaviors at all hierarchical scales. Feedbacks exist between individual plants and wind. Saltation physically impacts downwind plants and plant cover affects transport and erosion of soil. Threshold gap sizes exist, below which erosion may not occur. Patch structure is also important given that horizontal flux increases with fetch. Mosaics of vegetation structure created by concentrated activities (e.g. grazing, ORV activity) may result in areas that are more susceptible to erosion than would be predicted based on the average cover for a pasture. Saltation processes are most important at plant and patch scales at short time-scales. At longer time-scales, saltation processes can also be important at the landscape scale. Dust emission is important at the plant and patch scales whereas dust deposition tends to be more important at the regional and global scales.

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