

## Effects of Vegetation on the Transport of Dune Sand

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**Abstract :** The movement of wind blown sand on partially vegetated surfaces, and its consequences for the morphodynamics of sand dunes and the rehabilitation of eroded areas, is still significantly less studied than transport processes on bare sand. Currently, there are a number of parallel lines of research which do not always overlap or mesh. These are : theoretical calculations; improved instrumentation for field and wind-tunnel use, including reptation traps; fixed wind-tunnels, largely for testing new theoretical development; portable wind tunnels, largely for measuring erosion potential; sediment transport in agricultural crops and fallow areas; macro-scale erosional processes over large areas; stabilization and destabilization; analyses of patterns, trends and causative factors for current dune morphology, planforms and migration; historical and palaeontological analyses of past dunefields; coastal dune studies; dust mobilization and transport studies; and analyses of dunefield vegetation dynamics. For sparsely vegetated sand dunes, the Buckley modification of Bagnold's bare-sand transport equation, derived from wind tunnel experiments a decade ago, does not appear to have been either superseded or adequately tested in the field. Many alternative formulations have been proposed for different scales and circumstances, but none applies generally.

**Key words :** Vegetation, dune sand, transport, reptation, instrumentation, Buckley model.

The influence of vegetation on aeolian sand transport has long been recognized (Boucart, 1928; Melton, 1940; Hack, 1941), the area of vegetated dunes worldwide is far greater than the area of bare dunes, and the significance of dune vegetation in erosion and stabilization has major practical consequences for human population in many countries. Despite this, the transport of windblown sand on vegetated dunes has received far less attention, in depth and detail as well as effort and volume, than transport of sand on bare surfaces. Except for specific types of dunes whose function is clearly attributable to the presence of vegetation, most research on the morphology and dynamics of sand dunes has treated vegetation as irrelevant, or at best a second-order concern.

For the great arid sand seas of the world this approach may well be entirely justifiable; and equally, it is rational to study sand transport processes on bare surfaces before introducing the complication of vegetation. The body of literature on bare sand transport and dune morphology, however, is now so extensive and detailed that greater attention to vegetated surfaces is surely long overdue (Tsoar and Moller, 1986; Thomas, 1988, 1992; Thomas and Tsoar, 1990; Thornes, 1990; Wolfe and Nickling, 1993).

Here, therefore, I attempt to summarise recent and current research relevant to the transport of windblown sand on partially vegetated surfaces, and identify some critical issues and future directions. The topic has previously been reviewed, with a more

theoretical emphasis, by Wolfe and Nickling (1993).

Broadly, results and research are reviewed in order of increasing scale, starting with theoretical calculations and wind-tunnel experiments and finishing with large-scale field measurements and historical and palaeontological approaches. Agricultural lands and coastal foredunes represent special sets of conditions which have been studied intensively and are therefore considered separately.

### Theoretical Approaches

For vegetated surfaces, the principal recent advances through a theoretical approach are the models of Raupach (1991, 1994), who derived simplified expressions for vegetation roughness length and zero-plane displacement of vegetated surfaces, as functions of canopy height and area index. These models provide a good fit to a wide range of field and wind-tunnel data, albeit largely agricultural in origin.

Also relevant, though concerned with bare rather than vegetated sand surfaces, are the wind erosion models of Kruse (1994) and Li and Martz (1994), the particle-dispersion model of Shao (1995) and the suspension-saltation model of Scott *et al.* (1995). Models which deduce macro-scale sediment transport rate for micro-scale behaviour of particles and air, however, are unlikely to be feasible for vegetated surfaces because of the complexities of airflow and particle trajectories through and around live plants. Accurate and reliable predictive models of sediment transport across vegetated surface generally combine theoretical with empirical approaches, as in the sand drift model of Shao *et al.* (1996). Though the model was derived for agricultural areas, the approach used would be equally valuable in sparsely vegetated dunefields.

### Instrumentation

Most models of sand transport are based on or calibrated with empirical measurements, whether made in the field or a wind tunnel. These are heavily dependent on instrumentation to determine wind velocities, dust transport, saltation profiles and reptation. Some instruments are equally useful in either field or wind tunnel; others are specialised. Field measurements of airflow, for example, typically use rotating-cup hot-wire anemometers, whereas wind tunnel measurements generally use pitot tubes. There have been two particularly important advances in instrumentation recently, both of which are as relevant for vegetated surfaces as bare. The first is that the efficiencies of samplers such as the Bagnold, Fryrear and Leach traps (White, 1982; White and Mounla, 1991; Shao and Raupach, 1992; Rasmussen and Mikkelsen, 1992) have been determined by wind tunnel calibration against active isokinetic samplers (Shao *et al.*, 1993). Not only did this work determine mean sampling efficiencies, ranging from 1.02 for Bagnold traps to 0.85 for Leach traps, it also determined variability, expressed as standard errors of approximately 0.05 for Bagnold, Fryrear and Leach traps alike. The efficiency of Leach traps varies with wind speed, from 0.83 at  $9 \text{ m s}^{-1}$  to 0.90 at  $12 \text{ m s}^{-1}$ ; and for a small wind-speed range, the standard errors of these are  $\leq 0.02$ . These calibrations allow large arrays of relatively robust and inexpensive passive samplers to be used in the field, and results adjusted to isokinetic conditions with a known error.

An alternative instrument, proposed by Buckley (1989), uses a set of horizontal laser beams which are partially interrupted by saltating grains, and photodiodes to determine proportional interruption as a measure of sediment flux rate. Such an instrument was constructed, calibrated and field tested during

1990-1994 (Buckley, unpublished). It fulfilled its primary purpose of detecting fluctuations in the saltation load at millisecond time scales, but difficulties in calibration rendered it unreliable for quantitative determination of mass transport rate.

### Reptation

For sparsely vegetated sands in field conditions, the reptation load generally constitutes a large proportion of total transport, and accurate estimation of creep is therefore essential. The main technical difficulty is that creep takes place through the migration of ripples, so that at any one point, the elevation of the sand surface changes through time, and the precise vertical placement of any sampling device is hence critical. Three main approaches have been used. The first is to use vertically integrating traps with an orifice extending down to the low point of the ripple bedform, collecting reptation and saltation loads simultaneously. These traps, however, have relatively low sampling efficiencies. Even lower efficiencies, only 15-20%, were obtained by a new omnidirectional trap used in coastal foredune experiments by Arens and Vanderlee (1995).

A more sophisticated technique to measure reptation load specifically is the trap developed by Butterfield (1991), which funnels sand grains on to an electronic balance in a sealed container under the surface. Typically, this is below the floor of a wind tunnel, but it could feasibly be in a buried container for field experiments, analogous to an agricultural lysimeter. If cumulative mass in the balance pan is plotted against time, the mean reptation flux can be determined as long as the orifice of the sampling funnel extends vertically across the entire amplitude of the ripple bedform.

A third approach, more labour-intensive but more easily replicated, is simply to set

out vertical arrays of Leach traps, with the lowest one of each set precisely at base level of the ripple bedform and its collector opening positioned horizontally at the lowest point of the bedform; and sample for precisely the time required for one or more entire ripples to pass the collector opening. This is only feasible if traps can be supervised throughout experimental measurements, but it does allow extensive replication since Leach arrays are relatively inexpensive and easily moved.

For beach sands, a large-scale experiment in California, USA (Greeley *et al.*, 1996) recently tested the sampling efficiencies of various saltation traps by the conceptually straightforward method of trapping the entire sand load crossing an 0.5 m deep trench, 3 m long measured parallel to the wind, and 10 m transverse to it. This approach could also be used for vegetated surfaces.

### Wind Tunnels

Most experimental measurements of aeolian sand transport are made in wind tunnels, where wind velocity can be held constant. Most such work, however, has focussed either on transport processes for bare sand, in fixed tunnels; or on erosion of agricultural soils, often using portable tunnels. The models of Li and Martz (1994), Shao (1995) and Scott *et al.* (1995), for example, all use wind-tunnel data. One of the few direct comparisons between field and wind-tunnel data was conducted by Sullivan and Greeley *et al.* (1996) in relation to non-erodible roughness elements.

Recent wind-tunnel research not specifically concerned with, but still relevant to, vegetated sand surfaces may be considered in four categories. Iversen and Rasmussen (1994) and Selah and Fryrear (1995) examined the influence of surface slope and soil moisture, respectively, on threshold wind velocities for saltation. Both these are highly relevant

to field measurements on sparsely vegetated dunes.

Neuman (1994) and Spies *et al.* (1995) examined wind velocity profiles and windfields in wind tunnels, and their accurate measurement. Again, these approaches and issues are also relevant for wind-tunnel experiments using vegetated surfaces.

Shao and Raupach (1992) and Neuman and Nickling (1995) used wind tunnels to examine specific aspects of sediment transport processes. The former focussed on the overshoot and equilibration of saltation and latter on the effects of non-erodible roughness elements. Finally, Nicholson (1993) and Shao and Raupach (1993) studied dust entrainment.

In addition, portable wind tunnels are now used increasingly for measuring soil erodibility *in-situ*, e.g., in agricultural areas or revegetation sites (Leys and Raupach, 1991; Shao *et al.*, 1996).

### Agricultural Soils

Wind erosion of agricultural soils is an issue of major practical concern in many parts of the world, and there are a number of complex and largely empirical models to estimate soil loss under various circumstances. Some of these are for standing crops, others for stubble and crop residues. In particular, extensive work by the US Department of Agriculture (USDA) has produced a series of such models. The most recent is named the Wind Erosion Prediction System (WEPS) (Nanney *et al.*, 1993). This incorporates crop types, soil types, tillage regime, decomposition, weather and hydrology. It has been tested in Alberta, Canada (Larney *et al.*, 1995), as well as in the USA.

There is continuing specialist research on each of these individual parameters, e.g., characterization of the wind-erodible fraction of different soil types by Fryrear *et al.* (1994). Large-scale measurements of actual erosion

rates have demonstrated the importance of even sparse plant cover in reducing soil loss. Measurements by Fryrear (1995) in areas with 356-915 mm mean annual rainfall in 5 US States, for example, found that as little as 4% cover could reduce soil loss by 15% relative to bare ground.

In Australia an analogous model, the Wind Erosion Assessment Model (WEAM) has been developed by Shao *et al.* (1996). This model incorporates soil moisture, particle size distribution and non-erodible roughness elements such as crop stubble. An earlier model was put forward by Findlater *et al.* (1990).

There have been several recent wind-tunnel studies with an agricultural focus, but most have used simulated vegetation. Bilbro and Fryrear (1994) examined the effect of simulated crop residues on soil loss; and Brunet *et al.* (1994) and Shaw *et al.* (1995) used nylon stalks to simulate waving wheat. Schwartz *et al.* (1995) tested how the porosity of simulated windbreaks affected airflow patterns. Perhaps unsurprisingly, they found that the vertical distribution of porosity also has a significant effect.

None of these researches specifically investigate the movement of windblown sand on sparsely vegetated dunes. Agricultural soils are generally wetter and less well sorted than dune sands. Most crops are much denser than most arid zone dune vegetation. Stubble and crop residues are very different in plan form, profile and flexibility from desert or even coastal dune plants. And there is no guarantee that airflow and sediment transport past small wooden dowels, bottlebrushes or nylon stalks in wind tunnels are the same as airflow and sediment transport past real plants of real sand dunes.

Agricultural soil-erosion research is relevant, however, because it has involved an extensive and integrated programme of

theoretical and empirical research at all scales, with models derived from wind-tunnel experiments being tested through large-scale measurements of actual soil loss during natural storm events. A similar intensive integrated approach is needed for the partially vegetated sand seas and dunefields of the world.

### Stabilization

Complementary to agricultural erosion research are studies of sand stabilization and destabilization. This topic has been reviewed very extensively in the past (Watson, 1985). Recent research appears to have focussed on nabkhas or nebkhas, small dunes formed within and around individual plants on mounds of vegetation, often in association with drought, desertification or over-cultivation (Nickling and Wolfe, 1994; Sadek and Eldarier, 1995; Tengberg, 1995). A large-scale experiment by Wiggs *et al.* (1994) in the Kalahari involved burning of vegetation and measuring consequent changes in wind velocity profiles.

### Large-scale Dunefield Studies

Large-scale investigations of sand transport of vegetated dunefields have been relatively few. It is now a decade and a half since Gupta *et al.* (1981) measured macro-scale erosion from sandy plains in western Rajasthan, comparing bare and partially-grassed areas. These were followed by more detailed investigations in arid central Australia (Ash and Wasson, 1983; Wasson and Nanninga, 1986). These studies were reviewed by Tsoar and Moller (1986). More recently, the influence of plant cover on albedo and spectral reflectance has received particular attention, both in regard to erosion risk and remote sensing (Coude-Gaussen *et al.*, 1993; Harazono *et al.*, 1994; Tsoar and Karnieli, 1996). Callot and Oulehri (1996) have meanwhile used aerial photo interpretation to examine migration of dunefields in the northwestern Sahara. In the southern

Kalahari Wiggs *et al.* (1994, 1995, 1996) and Bullard *et al.* (1996) have used arrays of anemometers to characterise airflow patterns over partially vegetated linear dunes. As in central Australia (Buckley, 1979) they found that whilst the dunes are largely stable under current climatic conditions, sand does move on the dune crests and upper slopes, depending on wind speed and plant cover.

### Historical

In parallel to large-scale field research on modern-day dunefields, there has been continuing investigation on dunefield history and palaeoclimate at various time scales. Wasson (1994) emphasised the importance of historical context and global change in any analysis of land degradation. Gaylord and Stetler (1994) made a detailed time-sequence analysis of 30 sand dunes in south-central Washington, USA, over a 40-year period to predict likely future volume of bare and vegetated sand. Tsoar (1995) reviewed desertification in the northern Sinai during the 17th and 18th centuries.

Neuman (1993) reviewed aeolian transport in the seasonally cold environments of northern Canada, noting the very high sediment transport which had occurred during the Pleistocene. In the Kelso dunes of the Mojave, Lancaster (1993, 1994) correlated dune activity with Quaternary palaeoclimates. Livingstone and Thomas (1993) examined the palaeoenvironmental significance of factors influencing linear dune activity in the Kalahari Desert of Southern Africa. In the sparsely-vegetated linear dunefields of the western Simpson Desert, Australia, Nanson *et al.* (1995) used thermoluminescence dating to develop a palaeochronology of aeolian and alluvial activity over the past 90,000 years.

### Coastal Dunes

Coastal dunes provide a valuable test bed for investigations of aeolian sand transport

on partially vegetated surfaces, because they have relatively similar morphology, and in many cases, similar wind regimes and vegetation patterns. Equally, however, results from coastal dunes may not be applicable generally because coastal dunes often have shallow water tables, salty sands, limited sand supply, and a wind regime unlike that of most arid zone dunes. In addition, some coastal dune sands are calcareous, rather than siliceous.

Research on the morphology and dynamics of coastal dunes was reviewed by Sherman and Bauer (1993). Since that date there have been descriptive studies of vegetation and erosion on coastal foredunes in areas such as the Netherlands (Arens and Wiersma, 1994), southern New Zealand (Drobner, 1995), southern Spain (Decastro, 1995) and Brazil (Costa *et al.*, 1996). The importance of shallow ground water was noted in several of these. The effect of vegetation in stabilising a climbing-falling coastal dune in South Africa was described by Hellstrom and Lubke (1993). Arens *et al.* (1995) described windflow over a Dutch coastal foredune in great detail, with 4000 hourly wind profiles, and Nordstrom and Jackson (1993) recorded the effects of 5 high-wind events on the foredune of a narrow beach in New Jersey, USA. Not surprisingly, they found that sand transport on the foredune was strongly dependent on wind direction and the state of the tide.

The most significant new research, however, is a large-scale experiment by Greeley *et al.* (1996) on a beach in California, USA. They measured sand transport downwind of a 100 m x 20 m sand strip by digging a 3 m x 10 m x 0.5 m trench and emplacing 168 bins to catch surface creep and saltation. Though the area concerned was unvegetated, this approach could readily be adapted to vegetated areas, at a scale which could provide

integrated average measures for different plant planform, profile and projected foliage cover.

## Conclusions

The general pattern and emphasis of recent research relevant to aeolian sand transport on vegetated surfaces is not significantly different from that in the past. The principal focus has been on more precise models for agricultural soils and coastal foredunes, supported by ever more detailed wind-tunnel studies and theoretical calculations. Large-scale field measurements in natural dunefields are still rare, and the experimental results reported by Buckley (1987) still appear to be the only direct measurements of aeolian sand transport over dry, level, well-sorted sand surfaces with various densities of live vegetation. The remarkably simple modification to Bagnold's sand transport equation yielded by those experiments has apparently yet to receive rigorous testing under field conditions. Relevant data have now been collected over the past 5 years, as weather conditions have permitted, from a site in Queensland, Australia (Buckley, unpublished), but tests in a variety of field conditions will be required before the equation can be used with confidence in practical applications. Meanwhile, it would be valuable to reanalyse recent experimental results presented in the work cited above to determine to what degree the modified Bagnold equation would fit them, and whether the detailed empirical results on agricultural soil erosion could be expressed in the form of plant cover multiplier in that equation.

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