Vegetation and sand mobility in the Australian dunefield

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Vegetation and sand mobility in the Australian desert dunefield

by

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with 7 figures and 2 tables

Zusammenfassung. Die australischen Wüstendünen kommen unter einer Reihe unterschiedlicher Klimate vor, die günstig genug sind, eine beträchtliche Vegetation aufkommen zu lassen. Es ist angenommen worden, daß die Pflanzendecke diese „reliktischen" Dünen stabilisiere. Mit Ausnahme der südlichen Winterregenzone ist der größte Teil des Dünenfeldes nur wenigen Winden oberhalb der Schwelle für Sandbewegung ausgesetzt. Eine Analyse aerodynamischer Modelle der Interaktion von Wind, Vegetation und Topographie zeigt, daß die meisten Dünen mobilisiert würden, wenn die Windhäufigkeit zunähme. Die Integration von Abbremsung und Beschleunigung im Bereich von Vegetation und Sandhaufen liefert neue Informationen über die kritische Vegetationsbedeckung, die notwendig ist, um Sandbewegung auf Dünen zu stoppen. Für den Fall, daß die Windgeschwindigkeit die Flanken von Querdünen hinauf zunimmt, ist das Verhältnis der Geschwindigkeitszunahme bei mobilen zu nichtmobilen Dünen genommen worden, um die Windhäufigkeitszunahme abzuschätzen, die für die Remobilisierung von Längsdünen in Wüsten notwendig ist. Offensichtlich ist eine Zunahme der Windhäufigkeit von 20–30% notwendig. Ein Ausdruck für Sandmobilität (M) ist abgeleitet worden: $M \simeq 3.8 \times 10^{-4}\ (\bar{U})^4/(Ea/Ep)$. U ist die mittlere Windgeschwindigkeit in 10 m Höhe, und Ea/Ep ist das Verhältnis von tatsächlicher zu potentieller Evapotranspiration. Vorzeitliche Änderungen der Vegetationsstruktur als Folge von Klimaänderungen können die Einsetzbarkeit der Gleichungen für Paläoenvironment-Studien einschränken, aber die Korrelationen zwischen Klima, Vegetation und Mobilität gelten auch für die Vergangenheit.

Summary. The desert dunes of Australia lie in a wide range of climates, which are sufficiently benign to promote considerable vegetation. This cover of plants has been assumed to stabilise these "relict" dunes. However, most of the dunefield experiences few winds above the threshold for sand movement, with the exception of the southern winter rainfall zone. An analysis of aerodynamic models of wind/vegetation/topography interaction indicates that if windiness were to increase then most dunes would be mobilised. The integration of deceleration and acceleration around vegetation and sand mounds provides new information about the critical vegetation cover necessary to stop sand movement on dunes. Where wind is accelerated up transverse dune flanks the speed-up ratio for mobile and non-mobile dunes has been used to timate the increase in windiness necessary to re-mobilise the longitudinal desert dunes. Apparently an increase in windiness of at least 20–30% is necessary. An expression for sand mobility (M) has been derived, $M \simeq 3.8 \times 10^{-4}(\bar{U})^4/(Ea/Ep)$ where $\bar{U}$ is mean wind speed at 10 metres and Ea/Ep is the ratio of actual to potential evapotranspiration. Past changes in vegetation structure induced by climatic change may limit the

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palaeoenvironmental use of the equations, but the correlations between aspects of climate, vegetation and mobility are applicable to the past.

Résumé. Les dunes désertiques de l'australie existent sous une gamme des climats suffisament bénins pour qu'une végétation considérable s'y développe. On a supposé que le couvert végétal stabilise ces dunes «relictuelles». Cependant la plupart des secteurs dunaires sont exposés à des vents au dessous du seuil de vitesse nécessaire à l'entraînement du sable, à l'exception de la zone orientale à pluies d'hiver. Une analyse de modèles aérodynamiques comportant l'interaction vent/végétation/relief indique que la plupart des dunes seraient mobilisées par de l'accroissement de la fréquence du vent. L'intégration de la décélération et de l'accélération autour de la végétation et des petites collines de sable donne de nouvelles informations sur la densité du couvert végétal nécessaire pour empêcher le mouvement du sable sur les dunes. Dans les cas de vent accéléré en remontant le flanc d'une dune transversale, la relation entre l'accélération sur dunes mobiles et immobiles est utilisée à l'évaluation de l'accroissement de la fréquence du vent nécessaire à rémobiliser des dunes longitudinales désertiques. Il semble qu'un acroissement de 20 à 30% soit nécessaire. Une expression de la mobilité du sable (M) a été tirée, $M \simeq 3.8 \times 10^{-4} (\bar{U})^4/(Ea/Ep)$. U signifie la vitesse moyenne du vent à 10 m; Ea/Ep est la relation entre l'évapotranspiration réelle et potentielle. Des changements historiques de la structure de la végétation dûs au changement climatique vont limiter l'application de ces équations aux paléoenvironnements, mais les corrélations entre les aspects du climat, de la végétation et de la mobilité restent applicables au passé.

The desert dunefields of the world are covered by varying amounts of vegetation, so that a gradient of vegetation cover occurs between the driest and wettest parts. Dunes which are so completely covered by vegetation, even during prolonged drought, that there is no sign of sand movement, are usually considered to be relict or 'inactive'. The hyper-arid parts of dunefields are almost free of vegetation, good examples being large areas of the Sahara, the Namib and the Atacama. It is only in the most arid and overgrazed regions that vegetation is not limiting sand movement under prevailing climatic conditions.

Australian desert dunes are almost all vegetated to varying degrees, and so any consideration of the present-day behaviour of the dunes must consider the structure, cover and age of the vegetation. This paper is a first attempt to examine the interrelationships between sand mobility, windiness and vegetation characteristics down a climatic gradient from the semi-arid zone to the driest part of the Australian dunefield. Various aerodynamic models will be discussed with the aim of establishing the threshold conditions for dune mobility. The palaeoclimatic implications of these conditions are then explored.

The Australian Dunefield

The dunefield has an area of 1,311,000 km², about 20% of the continent's area – a significant landform type. (fig. 1). The dunes extend from the winter rainfall zone in the south, through the uniformly distributed rainfall zone of the south-centre to the summer rainfall belt in the north. The major part of the dunefield lies within the 250 mm annual average isohyet, but, in the southeast, dunes extend into areas presently receiving up to about 400 mm per annum, and in the northwest up to 625 mm. Most dunes are in areas which receive between 125 and 250 mm average annual rainfall, while the core of the arid zone north and east of Lake Eyre (in the Simpson and Strzelecki Dunefields) receives < 125 mm per annum.

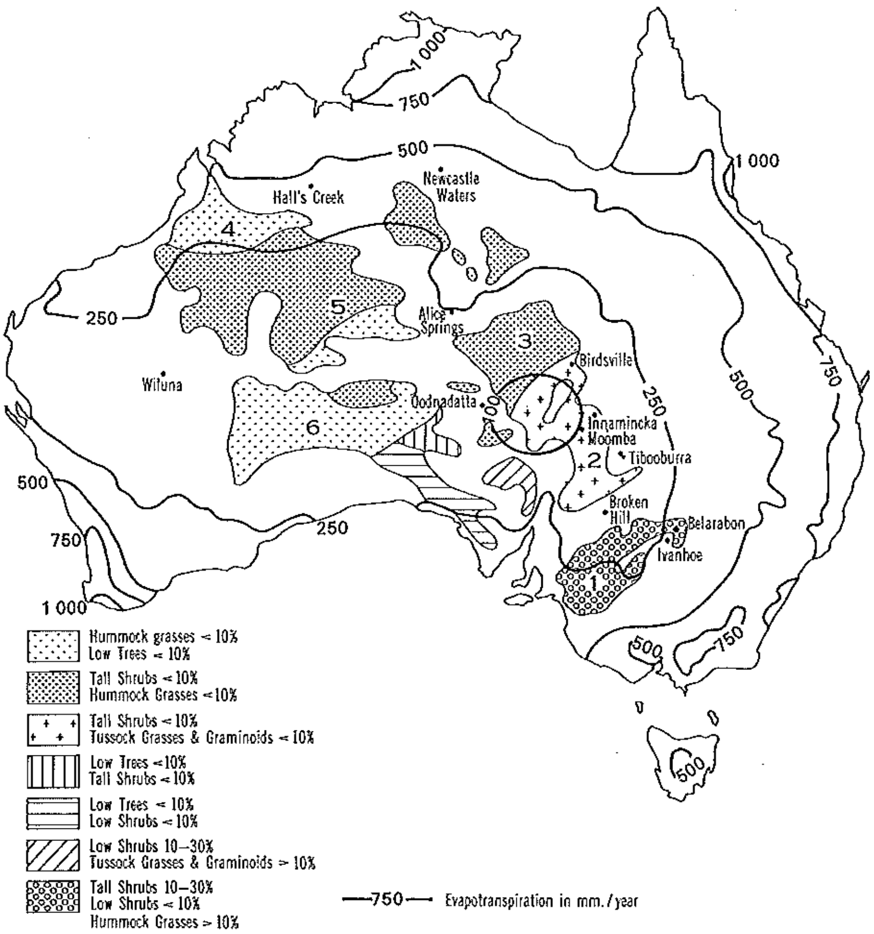

Fig. 1. Dunefield vegetation structure with evapotranspiration isopleths. Dunefields: 1, Mallee: 2, Strzelecki: 3, Simpson: 4, Great Sandy: 5, Gibson: 6, Great Victoria. Low trees are < 10 m high, tall shrubs > 2 m, low shrubs < 2 m.

The dunefield extends over a wide range of climatic types and its vegetation reflects this range. For the purposes of this paper, it is sufficient to describe the structure and cover of the perennial vegetation, but floristics becomes important when the details of dune vegetation are considered. Figure 1 shows the principal vegetation types, as adapted from CARNAHAN (1976). The main differences from north to south are in the form of the grasses (hummock grasses of the genera Triodia and Plectracne in the north, and tussock grasses, some hummock grasses and graminoids in the south). Average projective foliage cover for both trees and grasses is less than 10% for almost all of the dunefield, but, in the cool winter rainfall zone of the south, the cover of tall shrubs and trees reaches

10–30% with grass cover more than 10%. These well covered areas are dominated by mallee; low multistemmed *Eucalyptus* spp. with a grass and shrub understorey.

Not only do the desert dunes of Australia occur in very different climatic zones, but they also support vegetation which has both a wide range of life-forms and responses to stresses such as drought, fire, frost and grazing. There is no simple correlation between rainfall and dune mobility, modulated by vegetation cover, which applies to the entire dunefield.

The dunes are mostly longitudinal, that is, they are generally long, straight to slightly sinuous ridges of sand that are approximately parallel to the resultant of sand shifting winds (BROOKFIELD 1970) and apparently formed in a bi-directional wind regime (FRYBERGER 1979). There is some evidence that the modern wind regime is not exactly the same as that which built the dunes, for in a number of places the average direction of modern large-scale sand movement diverges from the trend of the longitudinal dunes.

Meteorological Patterns in Relation to the Dunefield

It has been noted already that desert dunes occur under widely differing climatic conditions, as measured by annual average totals, and seasonality, of rainfall. Climatic conditions become harsher all over the dunefield as the driest areas are reached. Cloud cover is low so radiation is high and, because of the aridity, sensible heat flux greatly exceeds latent heat flux. Surface temperatures are very high during the day and the heating causes great instability in the atmosphere. At night surfaces cool rapidly and frosts occur in winter over much of the dunefield.

Wind is difficult to characterise in a geomorphically satisfactory way. For present purposes it is sufficient to use a measure of the frequency of sand movement. The percentage of days with wind speeds greater than 8m/sec. at 3 pm(P) is plotted in fig. 2. This velocity falls between the fluid threshold for sand movement (4.6 m/sec.) and the velocity considered to produce large-scale sand movement (10 m/sec.) (BROOKFIELD 1970), as measured 10 m above the ground. This measure P does not provide information about the direction of sand shifting winds, and therefore tells us nothing about the potential for dune construction in a preferred direction.

P is approximately proportional to the mean wind speed ($\bar{U}$) in the form $P = 0.76 (\bar{U})^2$, an empirical equation based on records of the Australian Bureau of Meteorology. The values so calculated are too low in areas of highly seasonal climate, but it is a useful equation for comparing wind frequency and speed. In coastal tropical regions (10–20° S.) cyclones occasionally generate very high wind speeds which have a disproportionate significance.

Mean wind speed and windiness increase to the south with values exceeding 7 m/sec. and 40% P respectively in southwestern Australia and Tasmania. The windiness in the south inland is related to the strength of the winter westerlies and the passage of cold fronts. The zone of maximum frontal activity affects the Mallee, and the southernmost edge of the Great Victoria dunefield, where P exceeds 20%.

The major part of the dunefield lies in areas of low windiness, generally between 5 and 20%. Most of the Great Sandy Desert lies in an area of $P < 5\%$, a very calm region on average. The only inland dunes which experience $P > 20\%$ occur in the southern Mallee of

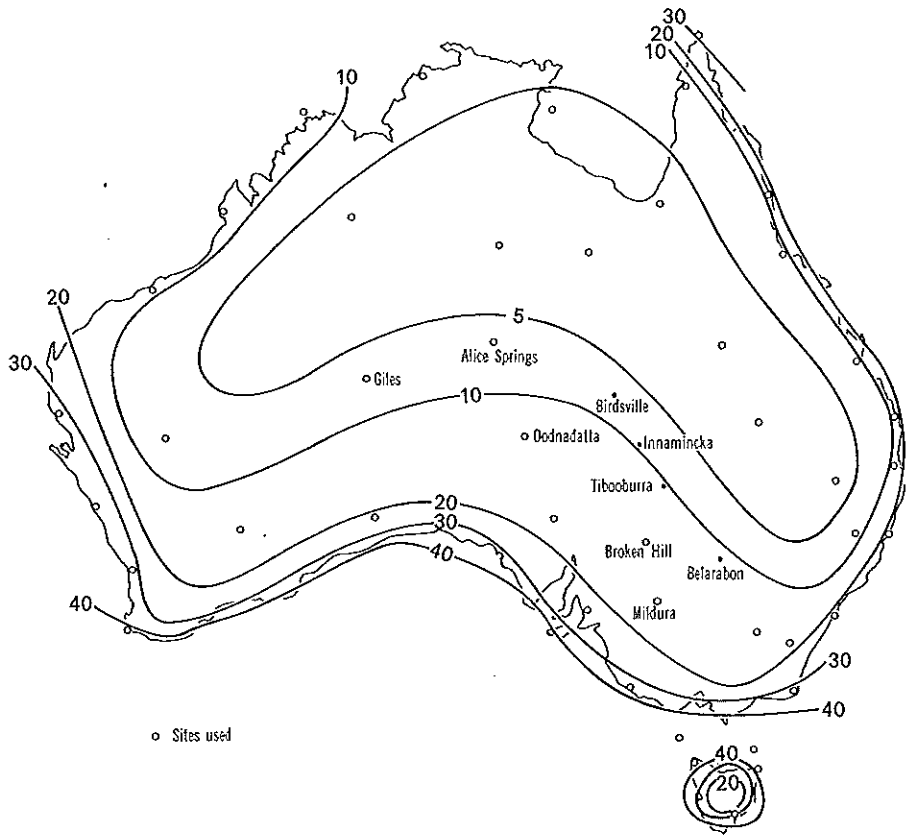

Fig. 2. Percentage of 3 pm measurements of wind speeds > 8 m/sec (P). Derived from Climatic Atlas of Australia, Bureau of Meteorology 1979.

Victoria and South Australia. The coastal dunes, on the other hand, experience the highest values of P in the continent.

Around the coast onshore winds are increased by the sea breeze which is proportional to the land-sea temperature gradient. The steepest monthly mean gradient (9 °C) occurs on the arid west coast of Western Australia and the smallest gradient occurs on the humid south and east coast of the continent.

FRYBERGER (1979) used LETTAU's modified version of BAGNOLD's equation to calculate sand drift. The equation considers wind velocity but does not allow for moist or wet sand, or for the effects of vegetation. The equation indicates potential sand movement but it does not apply to vegetated dunes. After a world-wide survey, the two Australian stations of Giles and Oodnadatta (fig. 2) were classified by FRYBERGER as low energy and intermediate wind energy environments respectively. The highest wind energy occurs in Saudi Arabia and Libya, two hyperarid locations.

According to FRYBERGER's analysis, most of the Australian dunefield should be in a low to intermediate wind energy environment. However, BROOKFIELD's (1970) derivation of sand drift potential (relative sand movement in her terminology), using almost the same method as FRYBERGER, shows considerable variability in central Australia. According to BROOKFIELD, the highest potential sand movement occurs at Finke on the north-western side of the Simpson Desert, between low potentials at Oodnadatta and Alice Springs. Furthermore, high potentials also occur at Tennant Creek and near Mt. Isa. This variability is partly related to site conditions so we have used the general pattern of P as a guide to windiness. Irrespective of the index of wind which is used it is clear that the sand moving ability of the inland winds is not very great, though they are everywhere sufficient to move sand on unvegetated dunes on a few days each year.

Dunefield Vegetation

Within each dunefield it is useful to distinguish two topographic zones and associated vegetation – the dune and the swale. Dunes mostly comprise quartz sand which has a low fertility and low water retaining capacity, especially near the crest (BUCKLEY 1979). These dunes support ephemeral herbs which grow after heavy rainfall and perennials whose survival depends on the availability of water stored within the dune. Dune perennials typically possess deep and spreading root systems to acquire water and nutrients, and sclerophyll or malacophyll leaf characteristics including a relatively smooth dense canopy which reduces evapotranspiration. On dunes which receive 250–350 mm annual rainfall there are trees of *Callitris, Eucalyptus* (often in mallee form), *Casuarina,* and *Acacia.* The larger trees reach heights of 15 m and live for periods of 100–200 years or more. Severe drought will kill these trees but fire seems to be a more frequent cause of death. Mallee, and to some extent casuarinas, produce new shoots after fire damage but *Callitris* and *Acacia* rely upon seed for regeneration. Seedlings, like ephemerals, require rainfall to maintain wet soil, and have high mortalities during drought.

In drier areas the rainfall is not only lower but also less regular so the probability of a drought is greatly increased. When water is readily available growth is rapid but these periods are relatively short so overall growth is slow and trees only reach heights of a few metres. In this environment short lived shrubs (e.g. *Eremophila, Acacia, Cassia*) are common. In Western Australia (the Western Desert) trees occur in drier areas than in the eastern dunefields. With the low biomass and vegetation cover in desert areas, there is low fire frequency and drought becomes a more common cause of death. Some shrubs may survive many decades. The upper part of dunes is drier and as the rainfall declines from 250 to 125 mm trees and shrubs are gradually restricted to the wetter zone of the lower dune flanks. In place of the shrubs and trees the dune crests and upper flanks support perennial grasses. The grasses form clumps of independent rhizomatous shoots so they have population characteristics with clump survival exceeding shoot survival. The grasses are also more efficient in their use of water.

Mobile sand occurs on dune crests in the drier areas but there is little evidence of abrasion damage to plants. Where sand is removed the roots are exposed, reducing the mechanical support for the plant, damaging the roots and possibly lowering the water table. Where sand accumulates the plant is buried so shoot and leaf functions are impaired. Root or shoot growth may alleviate these problems but this requires suitable temperatures and water. As the rate of sand movement increases the chance of plant survival or establishment declines. Grasses such as *Zygochloa paradoxa* are particularly well adapted to this environment.

Lichens and algae form crusts on dune surfaces in the semi-arid region, thereby reducing water and wind erosion. Crusts are sparse in the arid zone where they are restricted to wetter parts of dune flanks.

The swales comprise a great variety of substrates, including exposed bedrock, colluvium, alluvium, lacustrine sediments or aeolian deposits. The swale may be more or less suitable for plant growth than the adjacent dune. Substrates of bedrock and colluvium are more likely to support shrubs and trees while the lacustrine deposits may be saline and clay rich so they have a low and scattered flora of saltbush, lignum (*Muehlenbeckia sp.*) or samphires. The more arid and saline swales are devoid of vegetation.

Vegetation patterns are dynamic with local fluctuations in population size and migrations. The population of Acacia shrubs and trees in the arid zone increased by several orders of magnitude after the wet years of the early to mid-1970's but it will decline again if there is a prolonged dry period. In the Belarabon region some dunes date from the late-Holocene (WASSON 1976) and on these there is apparently increasing mallee abundance. Several introduced ephemerals have become abundant within the last century and there has been a great change in the fauna of the dunefields, with the introduction of rabbits, cattle, sheep, goats, horses, camels, cats and dogs. The grazing animals have reduced the abundance and growth rates of palatable plants but less palatable species are favoured. The trampling by these hooved animals destroys soil crusts and churns the soil surface. The smaller native herbivores have probably declined in abundance as a result of competiton from the introduced herbivores and predation by cats (BUCKLEY, in press).

The introduced herbivores require drinking water so their impact is localised around watering points. In the arid zone watering points are sparse so the effects of grazing are localised; for example, within a few kilometres of Strzelecki Creek in the Strzelecki Dunefield. In the semi-arid zone watering points are frequent so virtually all the vegetation has been modified by grazing. The frequency of fires has probably changed over the last 200 years. Overall there seems to have been a reduction in plant cover, especially of palatable grasses, forbs and fire sensitive trees, but shrub cover has probably increased (BOOTH & BAKER 1981).

Gradient of Dune Mobility

Dune mobility was examined along a transect from semi-arid New South Wales, beginning at Belarabon (WASSON 1976), to the driest part of the dunefield in the western Strzelecki Desert. Dunes were examined at Belarabon, Lake Frome, Fort Grey (ca. 100 km northwest of Tibooburra), Moomba area, and west of Birdsville (figs. 1 and 2). Along this transect the mean annual rainfall falls from about 300 mm at Belarabon to about 125 mm at Moomba, and windiness (P) drops from about 15% to 10%.

Mobility of sand is indicated by bare rippled sand between mounds of sand within shrubs and grasses and large mounds of sand up to 30 m long with active slip faces on the downwind end and to either side.

In general the projected cover and biomass of vegetation decrease on dunes and in swales from Belarabon to Birdsville. This is accompanied by an increase in obviously

Table 1. Vegetation cover and major taxa in part of the Australian Dunefields.

	Simpson Desert			Strzelecki Desert				Belarabon	
Lat. South	25° 30′	25° 30′	25° 30′	29° 0′	29° 0′	29° 0′	29° 0′	32° 0′	32° 0′
Long. East	137° 0′	137° 30′	138° 30′	140° 0′	140° 30′	141° 0′	141° 30′	145° 0′	145° 0′
Crest, % Mobile Lobes	0	2	1	7	1	1	0	0	0
% Mobile Sand	5	40	5	10	10	5	1	0	0
% Grass	10–20	5–30	10–30	0–10	0–10	0–15	20–30	5–30	0–5
% Shrubbs	0–1	0–1	0–1	0–1	0–8	0–2	7–15	0–20	0–10
% Trees	0	0	0	0	0–1	0–1	0–4	0–60	30–40
Flank, % Mobile Sand (Upper)	0	3	0	5	0–1	0–2	0	0	0
% Grass	15–30	10–30	10–30	7–15	5–15	10–20	20–30	5–40	0–5
% Shrubs	3–7	1–3	0–5	0–2	3–15	5–25	7–15	0–20	0–10
% Trees	0	0	0	0	0–1	0–1	0–2	0–60	30–50
Flank, % Mobile Sand (Lower)	0	0	0	0	0	0	0	0	0
% Grass	15–30	10–20	10–30	10–20	10–20	10–30	20–30	5–40	0–5
% Shrubs	5–15	5–15	0–5	0–4	3–15	5–15	4–8	0–20	0–10
% Trees	0	0	0	0	0–1	0–1	0–1	0–60	40–70
Swale, % Mobile Sand	0	0	0	1	0	0	0	0	0
% Grass	20–30	10–30	5–30	10–20	0–30	15–30	10–20	10–40	0–40
% Shrubs	8–15	5–15	2–10	0–5	0–10	0–1	0–1	0–10	0–15
% Trees	0	0	0	0	0–1	0–1	0–1	0–40	5–20
Major Taxa	*Acacia, Triodia*			*Acacia, Zygochloa*				*Callitris Eucalyptus*	

Figures are average percentages for individual aerial photographs of ca. 200 km^2.

mobile sand. On single aerial photographs (area about 200 km^2) the area of mobile sand and vegetation cover has been estimated along the transect (table 1). Only dune crests are persistently mobile under present conditions, and these only in the arid areas. At Belarabon mobile sand is not visible on aerial photographs and there is little evidence on the ground where a tree cover is significant. Algal/lichen crusts on dune sand form effective barriers to deflation. On the eastern margin of the Strzelecki Dunefield the tree element is $<4\%$ and mobile sand on dune crests is first noticed. Mounding of sand around shrubs and some trees occurs, with adjacent shallow (<1 m), vegetated deflation hollows which are activated during droughts. In this landscape the scene is dominated by shrubs and trees, and bare mobile sand is not easily visible on the ground.

Further along the transect towards Strzelecki Creek and Lake Frome the percentage of mobile sand increases (table 1), trees become unimportant and mounding around chenopods in swales, and *Zygochloa paradoxa* and *Nitraria schoberi* on dunes is marked. In the eastern to central Simpson Dunefield, shrubs (e.g. *Acacia*) occur in the swales. Up to 30% cover of grass (generally *Triodia* sp.) is the most important element of the vegetation on dune flanks, with *Zygochloa paradoxa* on sand mounds on dune crests. The mobile sand occupies between 5 and 40% of the crests.

Grazing destroys the more palatable plants and leaves so the combined effect of grazing and drought is an increase in the area of bare ground but little reduction in the frequency of trees, shrubs, and the rigid stemmed grasses. If leaves are not shed then a dead plant may retain the mechanical and aerodynamic properties of a live plant. Severe drought and grazing in the late 1960's did not reactivate the semi-arid dunes of the Belarabon area (WASSON 1976).

Fire has a more severe effect than grazing because it may completely destroy vegetation cover and thereby remove the inhibiting effect of vegetation on dune mobility. Mobile sand has been observed in severely burned areas of mallee near Lake Albacutya though dunes are immobile in vegetated areas of The Mallee (B. WELLINGTON, pers. comm.).

On the gradient from semiarid to arid conditions it is apparent that sand is mobile if the vegetation cover is removed by fire, severe grazing, drought or mechanical disturbance but in regions with intact vegetation cover the dunes are only active in the more arid regions, and then only on the crests and lee slipfaces. There is not a sharp boundary between active and inactive dunes but rather a dynamic gradient (cf. WILSON 1973; GOUDIE 1977).

It seems that sand mobility is inversely proportional to vegetation cover so we attempted to define this relationship more precisely.

Vegetation, Aerodynamic Roughness and Sand Movement

Vegetation affects sand mobility by protecting the surface, binding sand with roots, and by modifying wind flow. The protective process is proportional to vegetation and litter cover and is most effective in wetter areas and less important in arid areas where cover is often only 5–10%. Roots do not seem to have much significance for they are readily exposed if sand is mobile, but they do promote restabilisation if there is a tendency to deposition again.

Vegetation directly affects sand mobility by changing wind flow, and it is the larger perennial plants which are most significant. MARSHALL (1970) examined the effect that extensive arrays of objects and shrubs, on a level alluvial plain, had upon wind shear and aeolian erosion. He derived a simple relationship to determine the threshold of mobility in terms of % vegetation cover (C) and object diameter (D) and height (H),

$$C = 2.8\ D/H$$

This equation predicts that aeolian erosion will cease with 3–6% cover of typical dune vegetation on areas of the order of 10^2 m^2. In a later paper, MARSHALL (1973) concluded that wind erosion increases rapidly once vegetation cover is less than 15%.

Our observations of dunes indicate that sand mobility occurs with up to 30% vegetation cover, a figure which is higher than the absolute threshold given by MARSHALL (1973). MARSHALL's results derive from nearly horizontal and evenly vegetated surfaces, whereas our observations come from dunes in which topography is rarely flat and only a narrow band of vegetation is involved.

Vegetation limits sand movement through its influence on surface wind speed, indicated by Z_0 the aerodynamic roughness length. Z_0 is determined by the size, and spacing of roughness elements, in this case plants. To measure Z_0 accurately it is necessary to know at least two points on the vertical velocity profile, but a simpler method has been derived by LETTAU (1969) for arrays of objects

$$Z_0 = 0.5\ h\ a/S$$

where h is the average vertical height (cm) of the roughness elements, a is the silhouette area (cm^2) of the average obstacle, and S is given by the ratio of the total area (cm^2) to the total number of roughness elements. The values of Z_0 so determined agree with those from wind profile analysis within ±25%. To mobilise sand the value of Z_0 should be less than 1 mm.

To test the validity of LETTAU's equation for predicting the roughness threshold of sand movement we compared the observed and calculated values of Z_0 for uniform stands of *Zygochloa paradoxa* (R.Br.) S.T. Blake, *Triodia* spp., *Casuarina cristata* Miq., *Acacia ligulata* Aa. Cunn., and *Nitraria schoberi* L.

In many localities these species were separated by rippled sand, thereby demonstrating mobility. In each case Z_0 is much greater than 1 mm (table 2). High wind speed may

Table 2.

Species	h (cm)	a (cm^2)	S	Z_0 (cm) [1]
Zygochloa paradoxa	150	45,000	400,000	8.4 ± 2.1
Casuarina cristata	200	60,000	100,000	6 ± 1.5
Nitraria schoberi	100	10,–40,000	750,000	1.3 ± 0.3 to 5.3 ± 1.3
Triodia irritans	70	7,000	30,– 40,000	6.1 ± 1.5 to 8.1 ± 2
Acacia ligulata [2]	200	40,000	100,–200,000	40 to 20

1 Errors on Z_0 taken to be ± 25% (Lettau, 1969).
2 Measurements derived from an area of only 400 m^2.

reduce Z_0 for flexible vegetation (cf. DEACON 1949), but Z_0 is substantially independent of mean wind velocity for roughness elements which are not flexible (SUTTON 1953), and none of the species considered is very flexible.

GARRATT (1977) summarised the relationship between element density λ (defined as the element silhouette area normal to the wind per unit surface area occupied by each element) and Z_0/h. Z_0/h increases to a peak of about 0.2 at a value for λ of 0.4 and then declines. For objects where diameter equals height this peak in Z_0/h corresponds to a cover of 40%. Sand movement between plants was observed with Z_0/h values of 0.013 to 0.2 (table 2). It seems that sand mobility on dunes ceases nearer to the maximum value of $Z_0/h = 0.2$ rather than the threshold value of $Z_0/h = 0.015-0.03$ derived from MARSHALL's equation for objects with similar shapes.

The effect of vegetation on sand movement is illustrated in fig. 3 a which shows the approximate windflow pattern around an equidimensional dense shrub on a reasonably flat sandy surface. The form lines indicate the degree of acceleration around the sides of the shrub, and mound, as measured by a sensitive hand-held cup anemometer. In the cavity behind the mound, windspeed drops to 20% of its value upwind of the mound. Figure 3 b is the inferred windflow in section, as suggested both by observation in the field and from

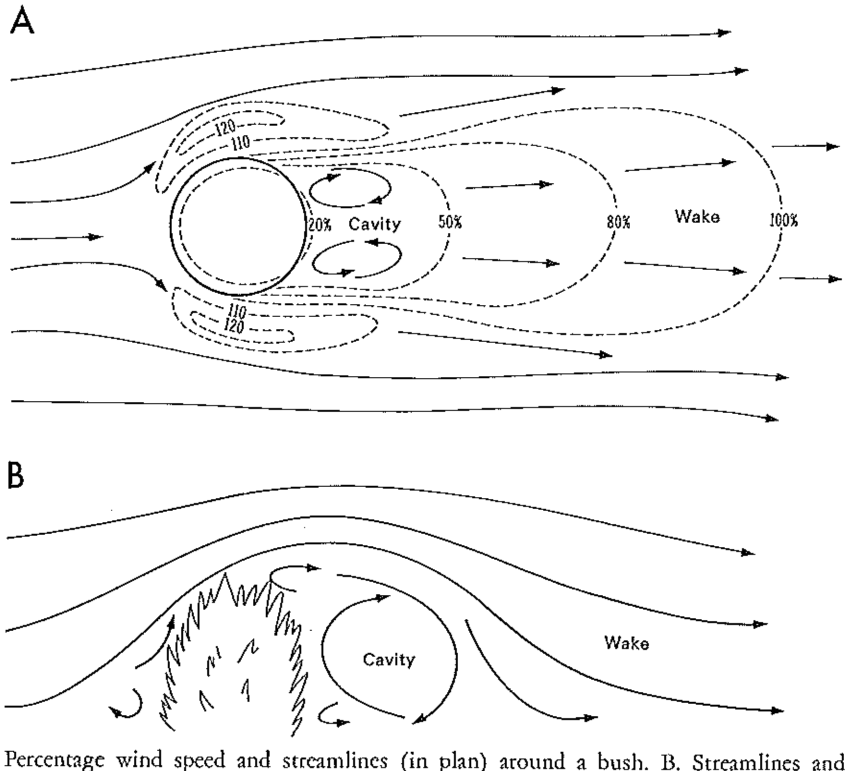

Fig. 3. A. Percentage wind speed and streamlines (in plan) around a bush. B. Streamlines and separation (in section) around a bush.

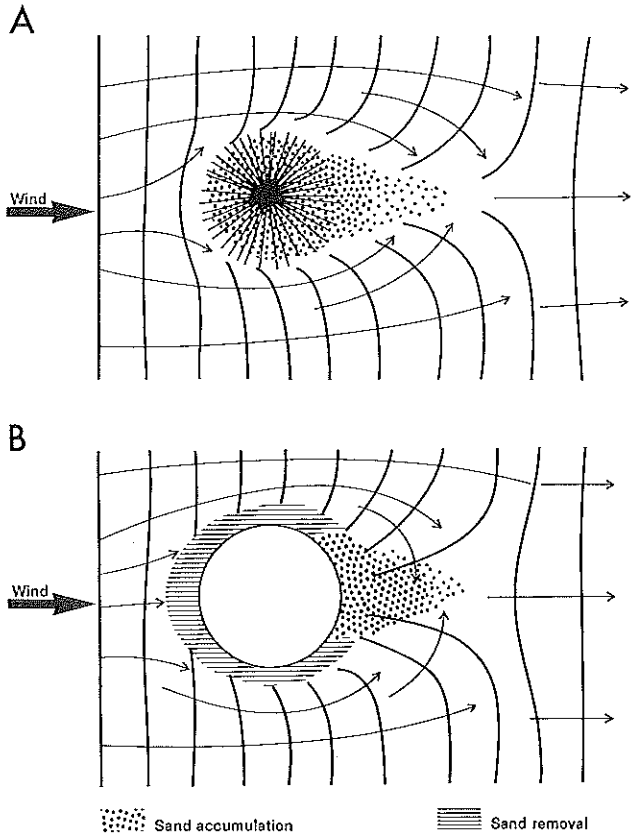

Fig. 4. A. Ripples and inferred streamlines around a plant, in plan.
Fig. 4. B. Ripples and inferred streamlines around a mound with a plant on it; in plan.

the general behaviour of turbulent flow over an object. Some shrubs and trees lose their lower leaves and branches leaving bare stems which scarcely reduce surface wind speeds.

Airflow at ground level can be judged from ripples and the "lee tail" of sand which accumulates downwind of the shrub (fig. 4). On flat ground the wind blows at right-angles to the ripple crests, and so the cavity (fig. 3) is reflected in the bent ripples. If the shrub is on a mound, then acceleration around the mound (figs. 3a and 4) is likely to erode a moat. There may be some eddying along the upwind edge of the mound, although this is likely to be small.

The length of the cavity is controlled by the shrub height (h) and diameter (d). Measured d/h ratios increase from about 0.3–0.5 in *Callitris* to 1–2 in the semi-arid shrubs to 1–3 in *Zygochloa*. The sand ripple patterns around hemispherical tussocks of *Triodia* and residuals of hard sand were recorded. For the *Triodia* tussocks, with d/h of 1–2, the length of cavity downwind of the bush is about 2.5 h but, for the residuals which vary greatly in shape, the cavity length is about 4 h for $d/h > 5$ and lh for $d/h < 0.8$. The hard residuals of more than 30 cm height have a scoured moat on their upwind side.

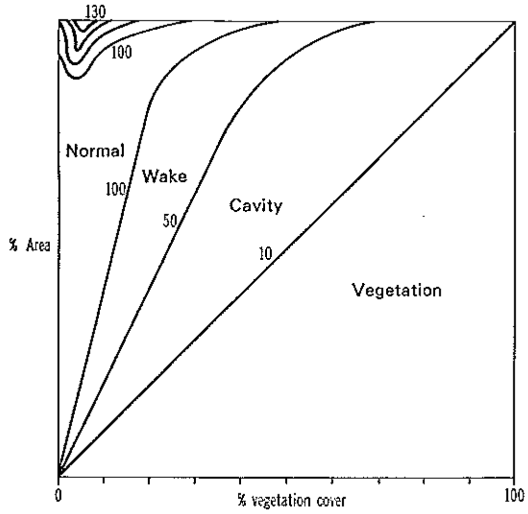

Fig. 5. Empirical relationship between percent projected vegetation cover, percent area occupied by different kinds of air flow and average relative wind speed at ground level (numbers within the figure). The values of 100–130% relative wind speed refer to acceleration around vegetation (see Fig. 3 A). The vegetation consists of plants in which diameter is approximately equal to height.

Each shrub has an associated area of accelerated and dècelerated wind (wake, cavity, and within the plant, fig. 5) and the effect of increasing cover is illustrated in fig. 6, where q is defined below. Because the dune crest populations are only a few individuals wide, and topography is sloping, no attempt was made to examine the interaction between shrubs. For a particular wind speed it is possible to calculate sand movement using BAGNOLD's (1941) relationship

$$q = 5.2 \times 10^{-4} (v - v_t)^3$$

where v is velocity at 1 m height, v_t is the threshold velocity of dry sand (4 m/sec), and q is tonnes of sand/metre width/hour.

By calculating the planimetric ground surface areas experiencing different wind speeds (by acceleration and deceleration) at different shrub covers it is possible to calculate q for

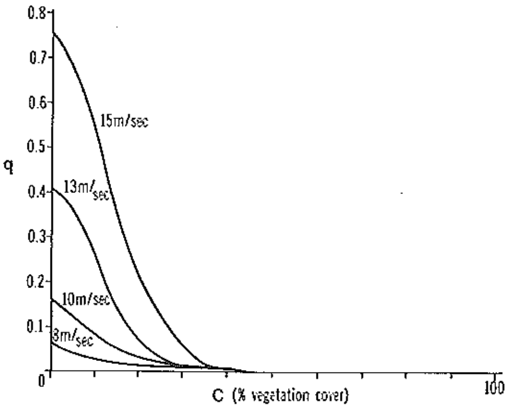

Fig. 6. Relationship between q and % cover for different wind speeds.

varing shrub cover (fig. 6). Significant sand movement occurs with up to 35% plant cover. This result is in agreement with our observations on the Strzelecki Desert dunes and lunettes of the Willandra Creek area and Lower Darling River (southwestern New South Wales).

Although the Z_0/h ratio and this simple model are useful, they present problems where dune surfaces are irregular and the vegetation dynamic.

An important result to emerge from these observations is that in the more arid parts of the dunefields the present vegetation cover on dune crests and flanks is not sufficient to stop sand movement. It seems that a lack of wind is preventing greater dune mobility in the arid zone, a conclusion consistent with the analysis of windiness (P). In the semi-arid regions vegetation cover is sufficient to stop sand movement.

The Role of Topography in Sand Mobility and Estimation of Mobility Thresholds

In order to define more closely the relationship between sand mobility, vegetation and windiness we made use of natural local variations of wind speed which are related to topography.

Air moving up the foreslope or flank of a dune accelerates. For low hills like dunes, JACKSON & HUNT (1975) found that the fractional speed-up ratio $\Delta W = (\Delta U/U_0)_{Z_1}$, which compares the increase in wind speed at height Z_1 above the surface of the hill with the undisturbed speed at the same height above the upwind surface U_0 (BRADLEY 1980), is given by 2H/L where H is dune height and L is slope length at H/2 (see fig. 7).

For steep dunes the average wind speed relative to upwind level areas will increase up the flank or foreslope (JACKSON & HUNT 1975) to 280% at the crest and then decline to only 20–40% on the lee slopes. The effect is of fundamental importance in the formation and shape of dunes because it partly determines the mobility of sand. BUCKLEY (1979) measured sand movement on dunes near Andado in the north-western Simpson Desert, and showed that movement is two orders of magnitude greater on crests and upper flanks than it is on lower slopes and in swales. MABBUTT (pers.comm.) has shown by measurement that significant movement only occurs on the crests of western Simpson Desert dunes.

In this way it is possible to relate the amount of mobile sand at the crest to the height and slope length of a tranverse dune (L). However, it is difficult to estimate wind speed acceleration for wind blowing obliquely to the dunes, as in the case of longitudinal dunes. Lunettes are good topographic localities to define the wind acceleration required to mobilize sand in a particular region because they are fairly uniform, and have a level lake bed area upwind.

It was not possible to record the slope length at half height exactly so the ratio of 4H/N was used (see fig. 7 for definition of N). For lunettes of the Willandra Creek and Lower Darling River areas the relationship between mobility M (% of crest mobile), H and N is depicted in fig. 7. Mobility occurs once the ratio H/N exceeds 0.05, yielding a value of 20%–30% acceleration for the beginning of significant sand movement. The mean wind speed therefore increases from about 4.4 to 5.3 m/sec and the percentage of days with sand moving winds increases from about 16 to 22 in this area. There are historical records that these lunettes were mobile before the introduction of sheep or cattle so the results are applicable to the undisturbed natural vegetation.

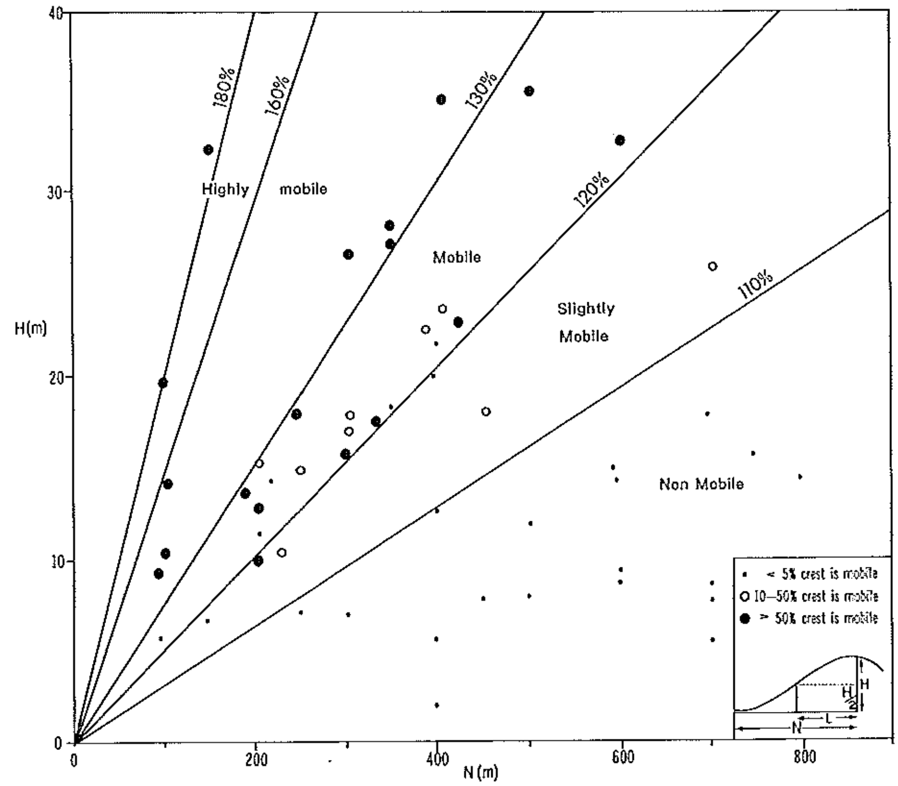

Fig. 7. Percentage acceleration on sandy lunettes of varying mobility as a function of lunette height (H) and half-length (N).

In the arid regions of the Simpson and Strzelecki Deserts the corresponding threshold wind speeds correspond to about 10% acceleration with threshold wind speeds of 3.2 m/sec and 11% of days with sand moving winds.

In humid regions there are few lunettes from which thresholds of sand mobility may be derived but there are transverse coastal dunes which are vegetated on the upwind coastal flank and have mobile sand at their crests and on lee flanks (e.g. Fraser I., Cape Flattery, Cape Leeuwin, N.E. Tasmania). These dunes have less regular shapes than lunettes but it is possible to calculate the same ratios of H/N and determine thresholds for sand mobility. In these cases the threshold for mobility is much higher with wind speeds of about 8.7 m/sec and 40% of days with sand moving winds.

The vegetation in each of these regions is principally determined by moisture availability which may be expressed in terms of the mean annual ratio of actual evapotranspiration/potential evapotranspiration (Ea/Ep). This ratio is a good index of both plant growth and vegetation cover. The ratio Ea/Ep increases from about 0.07 in the Simpson Desert to 0.25 in the Willandra Creek region, and 0.7–0.8 at the humid coastal dunes. Along this gradient, threshold wind speed increase sharply from 3.2 to 5.3 to

8.7 m/sec and the days with sand moving winds (P) increases from 10% to 22% to over 40% respectively. These observations of thresholds for sand movement may be expressed as empirical equations in terms of Ea/Ep and either P or $\bar{U}$.

In the following equations sand mobility (M) occurs when a threshold value of 1.0 is exceeded.

$$M = 5\times10^{-4}(P)^2/(Ea/Ep)$$

and

$$M \simeq 3.8\times10^{-4}(\bar{U})^4/(Ea/Ep)$$

For the range of wind speeds normally observed over the dunes, the term $(\bar{U})^4$ is almost exactly proportional to the term $(V-V_t)^3$ which was derived by Bagnold (1941) to describe sand mobility. This shows that vegetation as measured by Ea/Ep affects sand mobility in a fairly simple way.

These equations indicate the increase in windiness and/or increase in aridity required to mobilise sand on transverse dune flanks, and probably the flanks of longitudinal dunes as well.

Palaeoenvironmental Implications

The equations are derived from present conditions and their validity in the past is limited if there were significant changes in vegetation. These limitations include a rapidly changing climate, changes in seasonality, temperature, carbon dioxide, fires and grazing. For example, atmospheric carbon dioxide concentrations were about half their present value during the coldest part of the last glacial period (OESCHGER 1979), when Australian desert dunes were mobile (BOWLER et al. 1976), and this would have a major effect on plant growth. The growth response of plants to decreasing carbon dioxide is linear so, as a first approximation, it is reasonable to adjust the growth term (Ea/Ep) by the ratio of actual/present carbon dioxide concentration (Ca/Cp).

Despite the reduction in growth rate, final plant size is not reduced though spacing between plants may increase because more water is transpired. The composition of plant communities may change perhaps favouring C_4 plants (for C_4 plants see HATCH & SLACK 1970). It seems likely that halving CO_2 concentration reduces vegetation cover but not by as much as half.

Most geomorphological studies of dunes disregard their vegetation. It is often thought of either as a slightly important nuisance on dunes considered to be active, or it is believed to be the agent of stabilisation on dunes which are considered to be relict. The gradation between these two extremes has only been systematically examined by HACK (1941), and he highlighted the role of sand supply, wind strength and vegetation cover in determining the type of dune which will develop.

Along the transect selected in the Australian dunefield, it is very clear that there is a gradient of vegetation cover and sand mobility from the wettest fringes to the driest interior parts. No simple line can be drawn which separates "inactive" from "active" dunes. The gradient changes its slope depending upon antecedent rainfall, and prevailing windiness – the latter where Z_0 is affected by wind velocity in flexible vegetation.

Since a boundary cannot be drawn with ease, attempts to estimate climatic change from the difference between the modern "active" dune zone and the relict zone are liable to large errors (cf. GOUDIE 1977).

Our analysis of the broad pattern of windiness in Australia and the aerodynamic relationships between vegetation and sand mobility indicates that one of the reasons for low mobility of dunes in Australia is a lack of wind. This conclusion is indicated by the generally low values of P (fig. 2) over the desert dunefields, and that the vegetation cover (on average) is small enough (fig. 1) to allow considerable sand movement.

The lack of wind over the central and northern parts of the dunefield limits dune movement. But in the belt of winter westerlies in the south the vegetation cover is much higher (fig. 1) and it seems that the limit to dune mobility is vegetation, controlled by precipitation and evaporation.

Sand supply becomes important when comparing coastal and inland dunes. In the former, abundant sand is supplied from beaches, but sources of sand for inland dunes are unavailable, except beside rivers, because of vegetation and, in some cases, soil formation. Movement of sand from swales probably requires considerably higher values of the mobility index (M) than on dunes.

By implication, when the central and northern dunes were building (which appears to have last occurred between 25,000 and 14,000 years B. P., BOWLER et al. 1976) the mobility index values were greatly increased by an increase in windiness and lower evapotranspiration. The magnitude of the increase in windiness is at least 10% in the arid zone, 20% in the semi-arid zone and 30% at the humid fringe of the dunefields. The change in the gradient of mobility is unknown but it seems unlikely that the arid regions were less affected than humid areas so the minimum change is probably at least 30% in even the most arid regions. Actual increases of windiness and the decline in evapotranspiration may have been much greater than these threshold values.

The postulated increase in the frequency and intensity of winds agrees with BOWLER's (1978) conclusions derived from considerations of water balance and sedimentary facies, and SPRIGG's (1965) earlier conclusion that the Australian desert is not very windy.

Conclusions

– 1. Desert longitudinal dunes in Australia occur in widely differing climates under present conditions. As a consequence, the vegetation growing both in the swales and on the dunes differs from the north to the south and from humid to arid regions.

– 2. The percentage of sand shifting winds (P) is generally low over the central and northern dunefields, and it is high in the winter westerly belt and along the coast.

– 3. Along a transect from the southeastern semi-arid margin to the driest part of the dunefield, the area of mobile sand on dune crests and upper flanks increases and vegetation cover decreases.

– 4. Vegetation cover limits sand movement through its effect on wind flow. MARSHALL's analysis indicates that a shrub cover of 3–6% will reduce aeolian erosion to zero on level alluvial surfaces of fine texture and, more generally, aeolian erosion increases rapidly once vegetation cover is less than 15%. Our observations show that sand movement occurs with greater vegetation cover on dune crests. LETTAU's equation estimates a value of aerodynamic roughness length (Z_0) for vegetated surfaces but this is an overall value rather than the value between plants where sand movement occurs. Both of these analyses generalise the acceleration and deceleration of the wind around extensive arrays of plants. Although Z_0 does not seem to be a good index of sand mobility, Z_0/h may be more useful. When surface wind patterns are considered, and BAGNOLD's sand discharge (q) equation is used, we find that considerable quantities of sand can be moved amongst small populations of plants with cover up to 30%.

– 5. Winds are ineffective in the northern and central dunefields under present conditions, despite the low vegetation cover. Therefore, during past dune building phases there must have been increased windiness. This conclusion agrees with that reached by BOWLER and SPRIGG, using a different approach.

– 6. The fractional speed-up ratio of air moving over lunettes has been used to estimate the likely minimum increase in windiness during dune building phases. Lunettes which have been deflated indicate that an increase of at least 20–30% is required and actual values may have been much higher.

– 7. At a regional scale sand mobility (M) is indicated by the equation.

$$M = 5\times10^{-4}(P)^2/(Ea/Ep)$$
$$M \simeq 3.8\times10^{-4}(\bar{U})^4/(Ea/Ep)$$

where P is the % of days with sand moving winds, $\bar{U}$ is mean wind speed at the surface and (Ea/Ep) is the ratio of actual to potential evapotranspiration.

– 8. Dunes in the semi-arid region are too vegetated to allow sand movement. To mobilise these dunes would require considerable changes to the vegetation, either its destruction (by fire, for example) or a change to a more arid vegetation with sparser and smaller plants.

– 9. This paper has considered only the general mechanical attributes of plants and the broad correlations of vegetation with climate. This approach is justified because there are usually several species with similar life form, so if one species is eliminated another will take its place. In other words, vegetation is more stable than its component species. In detail this assumption is not valid and past changes of the environment may have significantly changed the character of the vegetation and the interaction with wind and sand mobility.

– 10. A number of the relationships derived in this paper could be improved by more detailed micrometeorological measurements both in the field and in the wind tunnel.

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