# INFLUENCE OF CRYPTOGAMIC CRUST DISTURBANCE TO WIND EROSION ON SAND AND LOAM RANGELAND SOILS

JOHN F. LEYS[1]* AND DAVID J. ELDRIDGE[2]

[1] *Department of Land and Water Conservation, P.O. Box 462, Gunnedah NSW 2380, Australia*
[2] *Department of Land and Water Conservation, c/o School of Geography, University of NSW, Sydney, 2052, Australia*

## ABSTRACT

A portable field wind tunnel was used to assess the sediment flux rates of loam and sand textured soils in the Mallee region of southeastern Australia. Three levels of crust disturbance (nil, moderate and severe) simulating stock trampling were investigated. The results demonstrated the importance of cryptogamic crusts in binding the soil surface and providing roughness after the soil was moderately disturbed. On the loamy soil, the crust helped maintain sediment flux rates below the erosion control target to $5 \, g \, m^{-1} \, s^{-1}$ for a $65 \, km \, h^{-1}$ wind measured at 10 m height. Once the crust was severely disturbed, sediment fluxes increased to 1·6 times the erosion target. On the sandy soil, even with no crust disturbance the sediment flux was 1·6 times the erosion control target. Disturbing the crust increased sediment fluxes to a maximum of 6·7 times the erosion control target. Removal of the crust also decreased the threshold wind velocity that resulted in an increase to the risk of erosion from <5 per cent to 20 per cent. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: wind erosion; wind tunnel; soil erodibility; sediment flux; dry aggregation; cryptogamic crust

## INTRODUCTION

Wind erosion and subsequent dust storms in rangelands in southeastern Australia have been reported for the last 200 years (Ratcliff, 1938; Brock, 1975; McTainsh and Pitblado, 1987; McTainsh and Leys, 1993; Miles and McTainsh, 1994). The extent and severity of wind erosion have increased with the introduction of domestic stock (Noble *et al.*, 1984), removal of vegetation (Leys, 1991a) and the destruction of soil crusts (Rogers, 1977; Eldridge *et al.*, 1995; Eldridge and Kinnell, 1997).

On sandy soils, Gillette *et al.* (1980, 1982) have shown that physical soil crusts reduce wind erosion rates. They suggest that clay content, salt content and calcium carbonates enhance crust formation which increases the threshold friction velocity ($u_{*t}$), that is, the amount of wind drag required to initiate erosion. The stabilizing role of soluble salts was further investigated by Nickling (1984) who found an exponential relationship between surface salt concentration and $u_{*t}$. Even simple crusts created by wetting and flooding the surface of a very fine sandy loam showed reduced soil loss (Rice *et al.*, 1995). Although Gillette *et al.* (1982) investigated organic matter as a cause of increasing crust strength, no significant relationships were found. They reported that the low levels of organic matter found in arid land soils may be a factor in this finding. They also concluded that they did not take into account the important effects of soil binding by biological components in the soil which they considered may have been important agents.

Apart from physical soil crusts, biological crusts (also known as cryptogamic, microphytic or microbiotic crusts) are common in arid and semi-arid landscapes (Eldridge and Greene, 1994; West, 1990). Biological soil crusts are formed by an intimate relationship between a rich assortment of lichens, bryophytes (mosses and liverworts), cyanobacteria (blue-green algae), green algae and fungi, and the uppermost layers of the soil. This crust is more than just a group of organisms growing on the soil. The integrity of the crust is uniquely linked with these organisms, and its survival depends on the survival of the organisms and *vice versa*. Destruction of

the crust ultimately leads to the death of the constituent organisms. These crusts are common in rangelands that are not excessively stony, sandy or burned (West, 1990). In southern Australia, lichen- and moss-dominated crusts are important components of the soil surface (Rogers, 1977; Eldridge and Tozer, 1997), and more than 120 species of lichens, mosses and liverworts are associated with these crusts (Eldridge, 1996; Eldridge and Tozer, 1996).

Cryptogamic crusts are important for many reasons. They reduce soil erodibility by binding small, erodible micro-aggregates into non-erodible macro-aggregates (>0·84 mm diameter; Chartres, 1990; Eldridge and Greene, 1994); they fix atmospheric nitrogen, making it available to developing vascular plants; they provide a niche for soil invertebrates; and they are useful indicators of environmental health (West, 1990; Belnap, 1995; Harper and Marble, 1989). Crusts are destroyed by both grazing (Eldridge and Tozer, 1997) and fire (Johansen *et al.*, 1990; Eldridge and Bradstock, 1994; Greene *et al.*, 1990), resulting in surface instability, reduced infiltration, and therefore unfavourable conditions for germination of vascular plants (Mücher *et al.*, 1988).

Although there are few empirical studies, anecdotal evidence suggests that cryptogamic crusts reduce wind erosion (Eldridge and Greene, 1994). Field-based studies in the United States demonstrated that lichen- and moss-dominated crusts reduced wind erosion, even after they had been killed with fungicide (Williams *et al.*, 1995). On sandy soils that have low levels of natural aggregation, cryptogamic crusts are often dominated by cyanobacteria such as *Microcoleus vaginatus*. Along with free-living fungi and fungal hyphae associated with lichens in the crusts, they secrete organic gels and polysaccharides that physically bind sand particles together (Belnap, 1995) providing considerable surface stability. Laboratory-based wind erosion studies on similar sandy soils have indicated that without loose lag material on the surface, crusts are stable in wind velocities up to $19 \, \mathrm{m \, s^{-1}}$ (McKenna-Neuman *et al.*, 1996). The addition of saltation material into the airstream, however, abrades the crust, physically destroying the polysaccharide bonds and destabilizing the soil surface. This abrader simulates the bombardment effect of loose, wind-erodible sand grains present on the surface, which sometimes comprise more than $91 \, \mathrm{g \, m^{-2}}$ on the surface (Potter, 1990).

This paper reports on a study using a portable field wind tunnel to investigate the relative sediment fluxes and threshold wind velocities of two soils with three levels of surface crust disturbance: nil, moderate and severe. A sheep's foot roller was used to simulate the disturbance caused by domestic stock. Hypotheses about the role of cryptogamic crusts in providing soil protection from wind erosion by binding the surface and increasing its surface roughness are explored.

## METHODS

### The Study Area

This study was undertaken at two sites in southwestern New South Wales, Australia. Site 1, referred to as the 'loamy' site, was located within Mallee Cliffs National Park (34°16′S 142°31′E). The Park has been ungrazed by domestic stock since the late 1970s, but carries variable populations of grey and red kangaroos (*Macropus robustus*, *M. rufus*), feral goats (*Caprus hircus*) and European rabbits (*Oryctolagus cuniculus*). Site 2, referred to as the 'sandy' site, was located at 'Tapio' Station (34°02′S 142°10′E), a grazing property approximately 20 km northeast of Buronga and about 30 km from Mallee Cliffs National Park. 'Tapio' is a typical grazing property running Hereford cattle and some Merino sheep in large paddocks approximately 1000 ha or more in area. Both sites are close to the main regional centres of Mildura and Wentworth with combined populations of more than 45 000 people.

Soils in the area are commonly sandy and clayey calcareous sediments of Quaternary age, occurring as level to slightly undulating plains, or as areas of aligned west–east trending dunes with low relief (to 4 m). The sediments are a widespread geological formation of the Murray Basin (Northcote, 1980), and contain large amounts of calcium carbonate (3–30 per cent) in either the fine earth fraction or as concretions. At Mallee Cliffs National Park, simulations were carried out on a slightly undulating loamy flat with slopes <3 per cent. The soil are classified as calcareous earths (Gc1.22; Northcote, 1979) or Hypercalcic Calcarosols (Isbell, 1996), and consist of a yellowish-red massive, loam to sandy loam grading to an earthy loam to clay loam with diffuse hard and soft carbonate nodules at 60 cm. The soil sould be described as a Calcic Aridisol in the US Soil Taxonomy

System (Soil Survey Staff, 1975). The flats or swales occur as long bands between low, west–east trending linear or subparabolic dunes, and support an extensive cover of cryptogamic crusts (Eldridge and Kinnell, 1997).

At 'Tapio' Station, a flat to slightly undulating (<2 per cent slope) plain with scattered sandy accretions was selected for wind tunnel simulations. The soils are a mixture of poorly structured calcareous earths (Gc1.12; Northcote, 1980), with sandy to loamy sand surface textures on the level plains, and siliceous and brownish sands (Uc5.12; Northcote, 1980) or Tenosols (Isbell, 1996) in areas where sand accumulates on the rises. The principal tree, belah (*Casuarina cristata*), is patterned into a series of groves and inter-groves, with dense monospecific clumps (up to 500 m across) of belah, separated by narrower bands of treeless sandplain less than 100 m across.

The vegetation at both sites is typical of the belah–rosewood vegetation association, and is dominated by the trees belah, rosewood (*Alectryon oelifolius*), sugarwood (*Myoporum platycarpum*) and wilga (*Geijera parviflora*), as well as small patches of mallee (*Eucalyptus socialis, E. gracilis* and *E. foecunda*) interspersed among the belah–rosewood. At the time of the experiments the understorey vegetation at both sites was dominated by sparse perennial grasses such as *Stipa variabilis* spp., and sub-shrubs of the family Chenopodiaceae (*Dissocarpus paradoxus, Sclerolaena patenticuspis*), ephemerals from the family Asteraceae, and perennial forbs, particularly *Zygophyllum apiculatum*.

At both sites, areas for wind erosion experiments supported low levels of foliage cover of vascular plants (<15 per cent cover) and an extensive but spatially variable cover of mainly crustose and squamulose lichens principally from the genera *Collema, Endocarpon, Catapyrenium, Peltula, Eremastrella* and *Toninia*, and foliose lichens from the genera *Xanthoparmelia* and *Chondropsis*. Small cryptic mosses from the families Pottiaceae and Bryaceae were also common components of the soil crust (Eldridge, 1996; Eldridge and Tozer, 1996a).

*Surface Preparation*

Three disturbance levels, i.e. no disturbance (control), moderate disturbance and severe disturbance, were applied to simulate a range of disturbance created by domestic stock. Rather than use naturally disturbed areas that had high variability and an unknown site history, we simulated the disturbance in a way that would be repeatable, by using principally a sheep's foot roller. To determine the level of disturbance required, we measured soil surface conditions around a nearby stock watering point.

Field observations at a number of watering points in nearby paddocks at the grazed site ('Tapio') revealed a moderately disturbed surface characterized by fragments of detached crust and loose sediment within the imprints created by sheep hooves. On the severely disturbed areas, the crust was almost totally absent, and the loose, massive soil displayed little or no microrelief. Several sites were sampled; the surface 25·4 mm of the soil was gently hand-sieved through a 0·85 mm sieve according to the method of Leys *et al.* (1998). Results indicate that 26·0 per cent of the moderately disturbed loamy soils had dry aggregation levels (*%DA*) >0·85 mm. On the severely disturbed loamy surfaces, dry aggregation averaged 7·0 per cent. On the sandy sites however, the moderately and severely disturbed areas had dry aggregation levels of 6·3 and 3·5 per cent, respectively.

At both Mallee Cliffs and 'Tapio', we created various levels of disturbance comparable to those measured close to the stock watering point, by using a combination of a garden rake, sheep's foot roller and a rotary hoe. The moderate disturbance was achieved by rolling the surface six times with the roller (described below), which was equivalent to 228 hoof prints per square metre. The same aggregation could be achieved when the surface was lightly raked with a steel garden rake then rolled twice with the roller. We adopted the latter method because it was easier and quicker (approximately 50 per cent quicker) to perform, and produced a more uniform surface that resembled the surface surrounding the water point. The severely disturbed surface was achieved by rolling the surface 12 times with the roller, equivalent to 456 hoof prints per square metre. The same aggregation level was achieved when the surface was cultivated with a rotary hoe to a depth of 5 cm, then rolled twice with the roller. This latter method was used because again it was quicker and produced a surface more closely resembling that near the watering point. Thus, the three levels of disturbance at each site were:

(i)   undisturbed: the surface was tested without any modification;

(ii) moderate disturbance: the site was lightly raked with a steel garden rake and then rolled with a sheep's foot roller;

(iii) severe disturbance: the surface was cultivated with a rotary hoe to a depth of 5 cm, then rolled with the sheep's foot roller.

The sheep's foot roller, with dimensions of 0·5 m wide and 0·4 m in diameter, was constructed from 6 mm thick steel plate. Artificial 'hooves' were constructed using small 30 mm long pieces of rectangular-shaped (25×8 mm) steel bar, welded in pairs to the roller approximately 15 mm apart. A total of 48 pairs of artificial steel hooves were welded in eight offset rows. This roller was then filled with water to attain a total weight of 35 kg and manually pulled across the plots. The roller was used to mimic the effect of trampling by sheep on the soil; on the moderately and severely disturbed plots it was pulled over each plot twice after pretreatment with the garden rake or rotary hoe.

*Wind tunnel sediment sampling method*

The Department of Land and Water Conservation (DLWC) (formerly the Soil Conservation Service of NSW) portable field wind tunnel used in this study is described by Raupach and Leys (1990). In brief, the tunnel is a push type, powered by a 56 kW motor connected to a 1·5 m axial fan. The tunnel is rectangular in shape and is open on the floor so that it sits on the soil surface. The flow passes through the flow-conditioning section of length 4 m, then through the working section of length 7·5 m, height 0·9 m and width 1·2 m. The first 2·4 m of the floor of the working section is covered with a sand-roughened board and a boundary layer tripping fence is located at 0·5 m downwind on the board to promote boundary layer development. This leaves a 4·2 m length of exposed soil between the end of the sand-roughened board and the sediment sampler.

All testing was undertaken when the soil was dry (<1 per cent soil moisture). Ten replicate simulations were made for each disturbance treatment. The ten replicates for each treatment were randomly assigned within both sites resulting in a total of 30 plots per soil type. The sites were chosen based on the access for the wind tunnel, lack of surface vegetation, minimal disturbance to the surface crust by livestock, and a high proportion and even distribution of crust cover for the particular soil type.

Flow velocity in the tunnel is set by adjusting the engine speed. The wind velocity in the tunnel was set at about 6 m s$^{-1}$ at a height of 0·15 m and velocity maintained for 1 min. The wind velocity was then increased in about 1·2 m s$^{-1}$ increments at 1 min intervals until a maximum velocity of about 13 m s$^{-1}$ was reached.

The eroded sediment was collected at each 1 min intervals in a modified Bagnold vertically integrating trap of width 0·005 m and height 0·5 m, which is described in more detail in Shao *et al.* (1993). Sediment flux ($q$) was determined from the weight of soil collected by the relationship $q = m/YT$, where $m$ is the mass of soil collected after a time interval $T$ (1 min) with trap width $Y$ (0·005 m). The $q$ values were corrected for saltation overshoot for the reasons discussed in Leys *et al.* (1996). We used the correction equation provided by Shao *et al.* (1996) based on data from Shao and Raupach (1992):

$$Q = q_{4.2}[0.55 + 0.45 \exp(-q_{4.2}/q_*)] \tag{1}$$

where $q_{4.2}$ is the sediment flux measured in the tunnel at $x = 4.2$ m, and $q_*$ is a scaling flux that determines the shape of the correction factor as a function of $q_{4.2}$ and is reported as 10 g m$^{-1}$ s$^{-1}$ by Shao *et al.* (1996). Sediment fluxes $q$ corrected from 4·2 m to 14·5 m (using Equation 1) are denoted by $Q$ in this paper.

*Wind velocity correction to 10 m*

Comparisons of the sediment fluxes between soils and surface conditions should be undertaken at the same wind velocity. Because the wind velocity close to the surface, such as in the wind tunnel, varies according to the surface roughness, it is necessary to select a wind away from the surface. A wind velocity measured at 10 m is used because this is the standard height for measurement of wind data in Australia.

The method used by Leys *et al.*, (1996) was applied to convert the wind tunnel velocities to equivalent velocities at 10 m height. In brief, wind velocity profiles were taken in the wind tunnel for each plot. Wind velocity measurements were taken at 0·05, 0·10 and 0·15 m height using Dwyer Pitot static tubes with a dynamic port size of 1 mm. Readings were taken at 1 s intervals and averaged over each 1 min period. The

measured wind velocity profiles were used to calculate the friction velocity $u_*$ and surface roughness length $z_o$ as outlined in Leys and Raupach (1991) and using the log law in the form:

$$U_{(z)} = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \quad (2)$$

where $z$ is the height above the mean ground level, $U_{(z)}$ is the wind velocity at height $z$, $k$ is the von Karman constant (taken as 0·4), $u_*$ is the friction velocity (measured in $m\,s^{-1}$), and $z_o$ is the surface roughness length. To convert the wind velocity at 0·15 m in the wind tunnel to the equivalent wind velocity at 10 m height we used the equation

$$\frac{U_1}{U_2} = \frac{\ln(z_1 / z_0)}{\ln(z_2 / z_0)} \quad (3)$$

to determine the ratio of wind velocity at 10 m ($U_1$) to the wind velocity at 0·15 m ($U_2$) in the wind tunnel. The $z_o$ can be calculated from the velocity profile, as previously shown by Leys and Raupach (1991). With $z_o$, $z_1$ and $z_2$ known, $U_1/U_2$ can be calculated. Multiplying $U_2$ by the ratio gives the wind velocity at 10 m.

All wind velocity measurements within the wind tunnel are converted to wind velocities at 10 m ($U_{(10)}$) using Equation 3 and form the wind data set used in this paper.

*Calculation of sediment flux at 65 km/h*

To enable comparisons to be made between the two soils and three treatments, the sediment flux for each soil at a wind velocity of 65 km/h was determined using the graphical method outlined by Leys *et al.* (1996). The wind velocity of $65\,km\,h^{-1}$ was chosen because it is well above the threshold for erosion, it is typical of the less than 1 per cent occurrence of wind velocities in the study area, and $65\,km\,h^{-1}$ has previously been used for erodibility determinations (Chepil, 1959).

*Dry aggregate sieving method*

The method for dry aggregate determination by dry hand sieving is described by Leys *et al*. (1998). This method is similar to the flat sieve method used by the US Department of Agriculture for determination of dry soil fraction >0·84 mm (Soil Conservation Service, 1988), except that we used British standard sieve No. 18 (0·85 mm) as specified in the Australian Standard (No. AS 1289.C6.2-1977). Semple and Leys (1987) suggested that eight replicates were necessary to characterize a $400\,m^2$ area; however, ten replications were used for the present study.

*Cryptogamic cover levels*

At each site, ten 1·6 m transects were laid out to measure the cover components on each plot. Each transect comprised 16 points 10 cm apart under which the following cover components were recorded: bare soil, lag layer (usually coarse sand grains), litter, cryptogamic crust and vascular plants. Data on cryptogamic crust cover were collected according to genus or species where possible for the lichens, and morphological group for most mosses. The cryptogamic crust category includes cyanobacteria. These measurements resulted in a total of 160 points for each plot.

## RESULTS AND DISCUSSION

*Wind characteristics*

This section describes the wind flow velocities, surface drag and aerodynamic roughness of the surface for the range of surfaces and treatments studied.

Table I. Measured and derived properties of soil and wind measurements for both the loam Mallee Cliffs loam and the 'Tapio' sand sites. $U_{(10max)}$ is the equivalent maximum wind speed at 10 m above the ground, $u_*$ is the friction velocity, $z_0$ is the aerodynamic roughness length, $I_w$ is the soil flux at 65 km h$^{-1}$ as determined from Figure 2, *%SC* is the percentage cover of cryptograms, *%DA* is the percentage mass of dry aggregates >0·85 mm, and SED is the standard error difference of the mean. Sites with the same superscript are not significantly different at the $P=0·05$ level.

| Site / Treatment | $U_{(10max)}$ (km h$^{-1}$) | $u_*$ (m s$^{-1}$) | $z_0$ (mm) | $I_w$ (g m$^{-1}$ s$^{-1}$) | *%SC* | *%DA* |
|---|---|---|---|---|---|---|
| Loam | | | | | | |
| Nil | [a]69·43 | [a]0·68 | [a]0·16 | 0·30 | [f]55·3 | [a]60·31 |
| Moderate | [b]74·33 | [b]0·78 | [b]0·32 | 0·40 | [d]30·0 | [b]44·47 |
| High | [c]66·89 | [c]0·56 | [c]0·02 | 8·00 | [a]4·5 | [c]32·39 |
| Sand | | | | | | |
| Nil | [c]65·10 | [c]0·54 | [c]0·03 | 8·20 | [e]36·6 | [c]37·87 |
| Moderate | [c]67·03 | [c]0·58 | [c]0·04 | 12·50 | [c]24·0 | [d]24·80 |
| High | [c]65·62 | [c]0·55 | [c]0·05 | 33·70 | [b]13·5 | [e]14·81 |
| SED | 1·89 | 0·05 | 0·06 | | 1·9 | 2·80 |

Averaged across all treatments and sites, mean maximum wind velocity $U_{(10max)}$ (± standard error difference of the mean, SED) was $68 \pm 2$ km h$^{-1}$. Values of $U_{(10max)}$ for each treatment are given in Table I. The friction velocity $u_*$ and surface roughness $z_0$ were inferred from the velocity profiles in the wind tunnel.

The wind tunnel applies a standard wind. Any differences in the $u_*$ and $z_0$ values are associated with the surface properties, in particular surface roughness. On the loam soil there were significant differences in $u_*$ and $z_0$ for each treatment (Table I). The surface roughness, as indicated by $z_0$, was highest for the moderately disturbed treatment ($z_0=0·32$ mm) which appeared to be the roughest owing to the partial fracturing of the crust and the imprints caused by the roller. The undisturbed plots were relatively rough ($z_0=0·16$ mm) owing to the presence of cryptogams, and the severely disturbed plots were the smoothest ($z_0=0·02$ mm), because the roller pulverized the surface and then flattened it out, producing the low $u_*$ and $z_0$ values.

There was no significant difference ($P>0·05$) in $U_{(10max)}$, $u_*$ or $z_0$ between the three disturbance levels at the sandy site at 'Tapio', and the severely disturbed loamy site at Mallee Cliffs (Table I). Water erosion studies show that cryptogams increase surface roughness, increasing the sinuosity of water flow (West, 1990) and potentially also increasing wind drag on the surface (Anderson *et al.*, 1982; Williams *et al.*, 1995). Overall, the loamy soil had a significantly greater cover of cryptogams (49·9 per cent) compared with the sandy soil (31·7 per cent; $F_{1,18}=34·4$, $P<0·001$) and would be expected to be rougher. Squamulose lichens such as *Psora decipiens, Endocarpon* spp. and the pyramid-shaped *Eremastrella crystallifera*, which have a strong preference for loamy, calcareous soils (Eldridge, 1996), were well represented at the loamy site. Where these lichens cover extensive areas of the surface, particularly in large monospecific clumps, they enhance local microrelief by up to 5–10 mm (Scott, 1982). While these species also occurred on the sandy soil, the greater coverage of patches of squamulose lichens on the loamy soil probably accounted for the rougher surface.

*Sediment flux*

This section discusses how the disturbance of the crust influences the sediment flux ($Q$) of two soils with different erodibilities.

For this study, and for the reasons outlined in Leys *et al.* (1998) and reported elsewhere (Leys and Heinjus, 1990), an erosion control target of $Q<5$ g m$^{-1}$ s$^{-1}$ for a 65 km h$^{-1}$ wind velocity is used as a cutoff between the condition when erosion is controlled and when it is not.

Differences in maximum sediment flux ($Q_{max}$) were measured at each site and for each treatment. Figure 1 shows the measured soil flux rates at $U_{(10max)}$. As expected, $Q_{max}$ was greater on the sandy soil compared with the loam. For both soils, $Q_{max}$ increased with soil disturbance. The loam soil could maintain a $Q_{max}$ below the erosion control target after moderate disturbance but not after severe disturbance. Although the sandy soil was unable to maintain a $Q_{max}$ below the erosion control target, even with no disturbance the crusts played a major role in reducing the sediment flux for both soils.
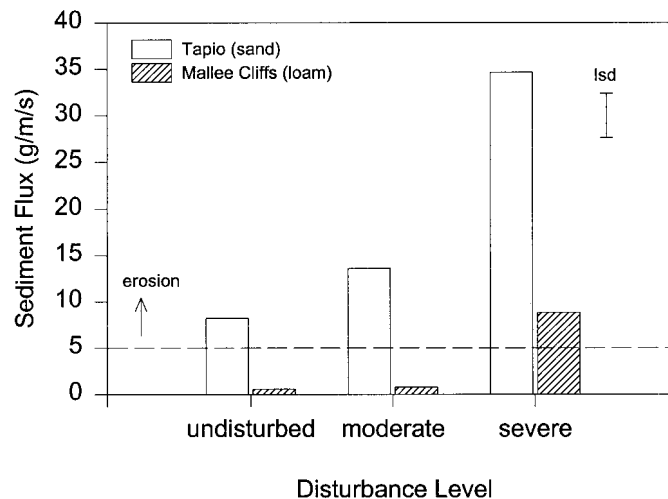
Figure 1. Maximum sediment fluxes ($Q_{max}$) measured on two soil types and for three levels of disturbance for the maximum wind velocity in the wind tunnel $U_{(10max)} = 68 \pm 2\,km\,h^{-1}$.

The sediment flux $Q$ was measured for each of ten replications at six different wind velocities $U_{(10)}$, then averaged. For each level of ground disturbance, there was an increase in soil flux with wind velocity (Figure 2). Sediment flux at $65\,km\,h^{-1}$ ($I_w$) is indicated by the point at which the sediment flux curves intersect the vertical broken line (Figure 2). Values for sediment flux at $65\,km\,h^{-1}$ for each soil type and disturbance level are given in Table I.

For the loamy soil, when crust was undisturbed or moderately disturbed, there was insignificant increase in $Q$ with wind velocity, showing that resilience of the surface to controlling erosion (i.e. $I_w < 5\,g\,m^{-1}\,s^{-1}$) for a wide range of wind velocities. The undisturbed crust on the loamy soil reduced $I_w$ to 4 per cent of the $I_w$ of the disturbed crust. While the reductions in percentage terms are large, in $I_w$ units, they only represent $8\,g\,m^{-1}\,s^{-1}$. Once the surface was severely disturbed, the $I_w$ exceeded the erosion control target by a factor of 1·6, indicating that the crust disturbance is an important aspect of soil erodibility by wind for loam soils.

For the sandy soil, surfaces from all disturbance levels were eroding above the erosion control target of $I_w = 5\,g\,m^{-1}\,s^{-1}$. Even with 37 per cent crust cover on the control, erosion was still evident with an $I_w$ of $8.2\,g\,m^{-1}\,s^{-1}$ that was 1·6 times the erosion control target. This is very similar to the $Q$ values of the severely disturbed crust on the loamy soil. The $Q_{(max)}$ rates were statistically the same for the undisturbed sandy soil and the highly disturbed loamy soils. This highlights the differences in erodibility of the two soils and how the crust is critical for maintaining low $Q$ values. The crust had a major influence in reducing the $Q$ value for the sandy soil to 24 per cent of the $Q$ value when the crust was fully disturbed. This represents a major drop in $I_w$ of $26\,g\,m^{-1}\,s^{-1}$. Once the crust was disturbed, the $I_w$ exceeded the erosion control target by 2·5 times for the moderately disturbed treatment, and 6·7 times for the severely disturbed treatment.

The results indicate that crusts play an important role in erosion on sandy soils because of their inherently high erodibility. The loamy soil, however, has a lower erodibility owing to its higher clay content. The physical protection, plus the greater organic binding and rougher surface provided by the crust, result in a considerably more stable soil surface in terms of protection against wind erosion.

*Threshold wind and friction velocities*

This section discusses the changes in threshold friction velocity $u_{*t}$ and threshold wind velocity $U_{(10)t}$ resulting from disturbance to the crust.

From the $Q$ curves (Figure 2) it is possible to calculate the wind velocity at which erosion commences ($U_{(10)t}$). Similarly, the threshold friction velocity ($u_{*t}$) can be calculated from sediment flux/friction velocity curves. Erosion was taken to begin when $Q = 0·1\,g\,m^{-1}\,s^{-1}$. Table II gives the threshold wind velocities at

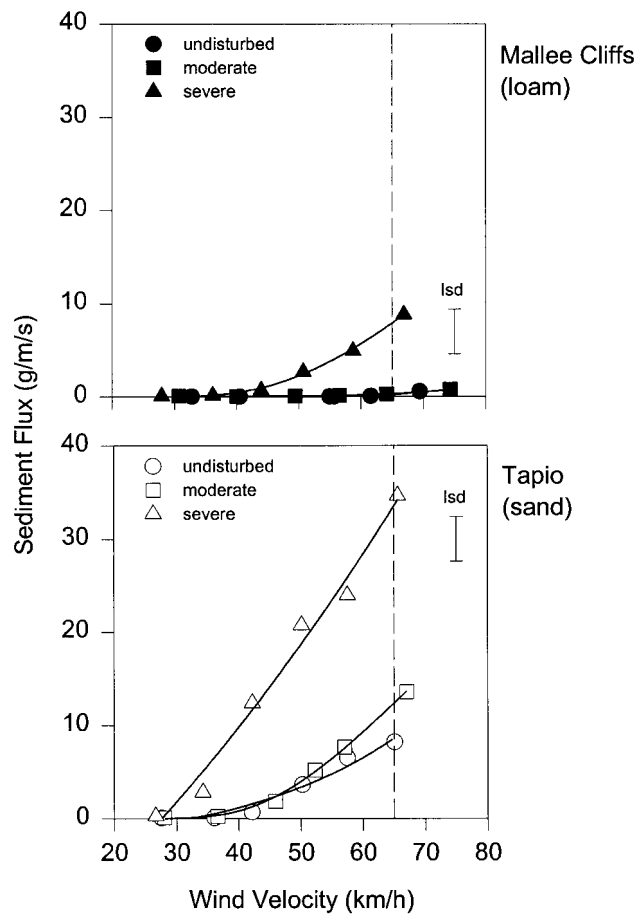Figure 2. Sediment flux curves for each site and disturbance level. Sediment flux at $65\,\mathrm{km\,h^{-1}}$ ($I_\mathrm{w}$) for each site and disturbance level is indicated by the intersection of the curves with the broken vertical line.

Table II. Threshold wind velocities* at 10 m above the ground $U_{(10)\mathrm{t}}$, percentage probability of occurrence of the wind speed $P_\mathrm{(wind)}$, and threshold friction velocity readings from this study ($u_{*\mathrm{t\,(obs)}}$), for soils G and A from Leys (1991b) ($u_{*\mathrm{t\,(Leys)}}$) and Gillette (1988) ($u_{*\mathrm{t\,(Gil)}}$) for the loam and sand soils for each of the three disturbance levels

| Site/ treatment | $U_{(10)\mathrm{t}}$ $(\mathrm{km\,h^{-1}})$ | $P_\mathrm{(wind)}$† (%) | $u_{*\mathrm{t\,(obs)}}$ $(\mathrm{m\,s^{-1}})$ | $u_{*\mathrm{t\,(Leys)}}$ $(\mathrm{m\,s^{-1}})$ | $u_{*\mathrm{t\,(Gil)}}$ $(\mathrm{m\,s^{-1}})$ |
|---|---|---|---|---|---|
| Loam | | | | soil G | |
| Nil | 63 | <0·05 | 0·62 | 0·64 | >1·50 |
| Moderate | 50 | 0·05 | 0·54 | – | – |
| High | 30 | 21·50 | 0·25 | 0·46 | 0·67–0·91 |
| Sand | | | | soil A | |
| Nil | 38 | 4·50 | 0·30 | 0·38 | >0·90 |
| Moderate | 29 | 21·50 | 0·24 | – | – |
| High | 21 | 21·50 | 0·18 | 0·17 | 0·22–0·42 |

* Threshold is taken when $Q=0\cdot01\,\mathrm{g\,m^{-1}\,s^{-1}}$

† Probability data are for Mildura at 1500 hours for the summer months (Dec–Feb) over the period 1946–94. Probability tables are for wind speed classes of $10\,\mathrm{km\,h^{-1}}$ increments, thereby explaining the same probability of occurrence for 21 and $29\,\mathrm{km\,h^{-1}}$.

$U_{(10)t}$ and the $u_{*t}$ values for each soil and disturbance level and the $u_{*t}$ values for soils A and G from Leys (1991) and Gillette's (1988) studies.

The $u_{*t}$ values are highest for the undisturbed plots, and lowest for the severely disturbed soils (Table II). When these values are compared with the results of Leys (1991) (Table II), we see that these values are similar. The one exception is the loam, which in the present study has a considerably lower $u_{*t}$ than the loam soil reported by Leys (1991) in Table II. Consequently, these results are within tolerable ranges of previous Australian data.

Leys (1991b) reports that the measured $u_{*t}$ values of cultivated Australian soils are similar to those reported by Gillette (1988). However, for uncultivated soils (or crusted soils) Australian $u_{*t}$ values are smaller (by a factor of two) than those reported by Gillette (1988). This study continues to support this claim (Table II) with Australian $u_{*t}$ values smaller by a factor of two to three. In addition, the $u_{*t}$ values for the least erodible loamy soil in this study were smaller by a factor of five to six for both the undisturbed and severely disturbed crusted surfaces compared with those reported by Williams *et al.* (1995) who worked on loamy sand textured soils in Utah, USA. These differences have been attributed to the higher silt fraction of North American soils which provides stronger binding of the surface (Leys 1991b).

The threshold wind velocities $U_{(10)t}$ for each soil type and level of disturbance are given along with the percentage probability of occurrence in Table II. The probability data for Mildura used in this analysis are for the summer months (December to February) because this is the period when vascular plant cover is least and thus when cryptogamic crust cover is most important for ground protection. There is also some insensitivity in the probability data because they are based on wind velocity classes in $10 \, \mathrm{km \, h^{-1}}$ increments. Consequently, the risk of erosion for a soil with $U_{(10)t} = 21$ and 29 may appear the same because they are grouped into the same wind velocity class ($21–30 \, \mathrm{km \, h^{-1}}$). In reality, erosion risk is different.

The loamy soil, except for the severely disturbed crust, has a very low risk of erosion (<0·5 per cent) owing to the lack of high wind velocities in summer that can initiate erosion. In contrast, once the sandy soil is disturbed, its risk of erosion increases from 4·5 to 21·5 per cent.

When the threshold velocity risk data are coupled with the soil flux data, it is apparent that the cryptogamic crusts are essential for stability of these sandy soils. The removal of the crust on these soils increases the risk of erosion five-fold, and the $Q$ is 6·7 times the erosion control target of $I_w = 5 \, \mathrm{g \, m^{-1} \, s^{-1}}$. In contrast, while removal of the crust on the loamy soil increases the risk by more than 20-fold, the erosion level is still only 1·6 times the erosion control target. Therefore the sand soil is almost totally reliant on the crust for protection, while the loamy soil benefits from the crust and its inherently higher clay content and corresponding aggregation levels.

*Soil aggregation*

The percentage mass dry aggregation (*%DA*; mass of aggregates <0·85 mm diameter) was significantly altered by the surface disturbance treatments. Despite the extreme treatment of ploughing with the rotary hoe, *%DA* levels were not reduced to the low levels measured near the watering point resulting from animal activity. For the loamy soil near the watering point, the moderately and severely disturbed *%DA* were 26 per cent and 7 per cent, respectively. In comparison, our treatments produced surfaces with *%DA* levels of 44 per cent and 32 per cent, respectively, showing that our disturbance method was less aggressive than long-term stock movements. The same trend was evident at the sandy site, with the moderately and severely disturbed *%DA* being 6 per cent and 4 per cent, compared with our treatments with *%DA* levels of 25 per cent and 15 per cent respectively. This shows the efficiency with which stock can pulverize the surface and reinforces the conservative nature of the treatments we used in relation to stock trampling. Although we did not reproduce the low *%DA* of the naturally stocked area, the results show a highly significant ($R^2 = 0·98$ $P = 0·0002$) relationship between *%DA* and $I_w$ (Figure 3) of the form:

$$I_w = 115·37 / \exp (0·082 \, \%DA) \tag{4}$$

Williams *et al.* (1995) suggest that destruction of the crust would leave the surface covered with 'partially aggregated pieces'. Our observations suggest that the aggregation on the surface consists of both biological aggregates (formed by the cementing or binding of aggregates by biological agents) and physical aggregates
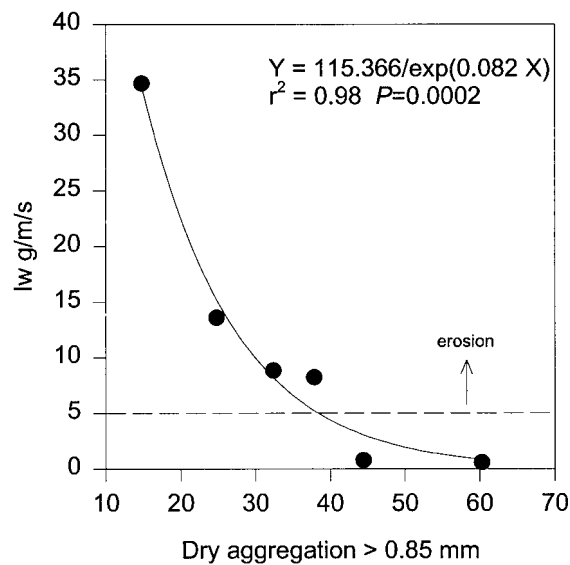
Figure 3. Relationship between sediment flux at 65 km h$^{-1}$ ($I_w$) and dry aggregation (%DA).

(formed by the wetting and drying of the soil). The importance of biological crust in aggregate formation forms the basis for a further study that will be reported elsewhere.

## CONCLUSIONS

This study demonstrated that cryptogamic crusts are effective for controlling wind erosion on both loamy and sandy rangeland soils. On loamy soils with inherently lower erodibilities, biological soil crusts were still important for restricting sediment flux to levels below an erosion control target of 5 g m$^{-1}$ s$^{-1}$ at a wind speed of 65 km h$^{-1}$. On the loam, severe disturbance of the crust resulted in a sediment flux 1·6 times the erosion control target. In contrast to the loam, the erosion control target on the sandy soils was exceeded even with 31·7 per cent crust cover. Further, moderate and severe disturbance of the crust on the sandy soil increased the sediment flux to 2·5 and 6·7 times the erosion control target. We conclude that, unlike the loams which are inherently stable owing to their levels of natural aggregation, sandy soils are dependent on the crust for their stability in rangelands.

Disturbance of the crust also lowered the threshold friction velocities of the soil. The levels recorded here were two to six times lower than other data reported from North America (Gillette, 1988; Williams *et al.*, 1995). Threshold wind velocities were approximately halved for both the loam and the sand when the crust was severely disturbed. This had the effect of increasing the risk of erosion from <5 per cent to 21·5 per cent during the summer months in the study area.

The disturbance of the crust resulted in lower dry aggregation levels. A strong negative exponential relationship ($R^2=0·98$ $P=0·0002$) was observed between dry aggregation and sediment flux. The contribution of the crust to the aggregate population is identified as an area of future research.

Strong with data collection and analysis. Neil Douglas and John Lemon are thanked for constructing the sheep's foot roller.

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