



Exploring some relationships between biological soil crusts, soil aggregation and wind erosion

David J. Eldridge*[★] & John F. Leys[†]

[★]*Department of Land and Water Conservation, Centre for Natural Resources, c/o School of Biological, Earth and Environmental Sciences, University of New South Wales Sydney 2052, NSW Australia*

[†]*Department of Land and Water Conservation, Centre for Natural Resources, P.O. Box 462, Gunnedah NSW 2380, Australia*

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A portable wind tunnel was used to test the contribution of biological and physical elements to overall soil aggregation on a soil dominated by biological soil crusts in south-eastern Australia. After moderate disturbance and simulated wind erosion, 90% of surface aggregates on the loamy soil and 76% on the sandy soil were dominated by biological elements (cryptogams). Lower levels of biological bonding were observed on the severely disturbed treatment. Linear regression indicated a significant positive relationship ($r^2 = 0.72$) between biological soil crust cover and dry aggregation levels greater than 0.85 mm. To maintain sediment transport below an erosion control target of $5 \text{ g m}^{-1} \text{ s}^{-1}$ for a 65 km h^{-1} wind at 10 m height, a crust cover of approximately 20% is required. When a multiple regression model which sequentially fitted biological crust cover and dry aggregation greater than 0.85 mm was applied to the data, dry aggregation accounted for more of the variation in sediment transport rate than biological crust cover. These data were used to develop a conceptual model which integrates crust cover and dry aggregation, and provides a useful framework within which to predict the likely impacts of changes in soil crust cover and aggregation.

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Introduction

In semi-arid and arid Australia, wind erosion is one of the predominant forms of erosion due to the nature of the soils and landuse. The frequency of wind erosion events in Australia tends to increase with decreasing rainfall and to be more frequent in drier years (McTainch & Leys, 1993). The simple reason that wind erosion events increase with decreasing rainfall, whether it is across climatic regions or between years, is that the level of protection afforded to the soil surface by vascular plants or their residues is drastically reduced. Land management activities, however, have a

*Corresponding author. Fax: +61 64 2 9385-1558. E-mail: d.eldridge@unsw.edu.au

large influence on surface erosion rates (McTainsh & Leys 1993, Leys & Eldridge 1998).

The critical levels of cover of both vascular plants and their residues, required to provide effective protection to the soil, have been identified for both rangelands and arable lands (Leys, 1998). However, wind and water erosion is often not a problem for soils with plant cover levels below these critical levels. In rangelands, biological (or cryptogamic) soil crusts provide an important barrier on the soil surface during dry times. In average seasons, vascular plant cover is often sufficient to protect the soil against erosion. During drought, however, when the bulk of the soil cover has been removed, biological crusts provide vital protection against water and wind erosion (Eldridge & Greene, 1994; Williams *et al.*, 1995; Leys & Eldridge, 1998).

Field-based wind tunnel studies in the United States, Europe and Australia (Gillette *et al.* 1982; Pluis & de Winder, 1989; Pluis & Boxel, 1993; Williams *et al.*, 1995; Leys & Eldridge, 1998), and laboratory wind tunnel studies in Europe and Canada (McKenna-Neuman *et al.*, 1996; Rice *et al.*, 1997) demonstrate that soil crusts effectively control wind erosion. Previous research in eastern Australia has demonstrated a negative exponential relationship between a soil transport rate at 65 km h^{-1} and soil aggregation (as assessed by the proportion of aggregates $>0.85 \text{ mm}$ in diameter), and suggests that aggregation may be a function of the biological crust cover (Leys & Eldridge, 1998). This aggregation on the surface may consist of both biological aggregates (formed by the cementing or binding of aggregates by biological agents), and physical aggregates (formed by the wetting and drying of the soil). Indeed, when biological soil crusts are trampled, the surface often remains covered in 'partially aggregated pieces' (Williams *et al.*, 1995).

Cyanobacteria and other crust organisms stabilize the soil by binding together small particles into larger particles (Shields & Durrel, 1964). This binding is achieved by several mechanisms (Bar-Or & Danin, 1989) including: physical binding of soil particles by entangled filaments, adhesion to mucilaginous sheaths or slime layers excreted by cyanobacterial trichomes, and attachment of particles to sites along the cyanobacterial cell walls. This binding increases the organic matter content of the crust (Danin *et al.*, 1989), increasing the soil's resistance to both wind and water erosion.

The aims of the research reported here are two-fold; (1) to examine the relationships between the cover of biological soil crusts and dry aggregation using empirical data collected from two sites dominated by biological soil crusts, and (2) to explore how these relationships can be used for predicting the impacts of management strategies on crusts and aggregation, and therefore wind erosion processes.

Methods

The study area

This study was carried out in a semi-arid woodland on two soil types in the Mallee Region of south-eastern Australia. One site, the 'loamy' site, was in Mallee Cliffs National Park ($34^{\circ}16'S$ $142^{\circ}31'E$) and had been ungrazed by domestic stock since the late 1970s. The other 'sandy' site was at a grazing property 'Tapio' where sheep and cattle are continuously grazed in large paddocks of about 1000 ha. A detailed description of the soils and vascular plants of the area is given in Leys & Eldridge (1998). The soil crust community at the sites was typical of communities on calcareous sites, and was dominated by crustose lichens and small mosses. The crust

comprised approximately 15 lichen species from the genera *Collema*, *Endocarpon*, *Placydium*, *Peltula*, *Psora*, *Toninia*, *Xanthoparmelia*, *Chondropsis* and *Diploschistes*, and a similar number of cryptic mosses from the families Pottiaceae and Bryaceae (genera *Bryum*, *Goniomitrium*, *Desmatodon*, *Crossidium*, *Barbula*, *Didymodon*; Eldridge, 2001). Although cyanobacteria were not identified from this study, *Microcoleus paludosus*, *Nostoc* spp. and *Scytonema* spp. are known to be common species in these soils (Eldridge, 2001). Mosses tended to be more dominant on the sandy soils.

Wind tunnel experiments

Surface preparation

Three levels of disturbance, i.e. no disturbance (control), moderate disturbance and severe disturbance, were applied to simulate the influence of domestic grazing. The 'moderate' treatments consisted of raking the soil with a steel garden rake then rolling it with a sheep's foot roller. The 'severe' treatment was cultivation with a rotary hoe to a depth of 5 cm, then rolling with the sheep's foot roller. These treatments and the justification for using them are described in more detail in Leys & Eldridge (1998).

Wind and sediment transport measurements

We used the Department of Land and Water Conservation wind tunnel to test soils in the field at low levels (<1%) of soil moisture (Leys & Eldridge, 1998). Ten replicates of each of the three treatments were randomly assigned at both sites resulting in a total of 30 plots per site. Methodologies for the wind tunnel experiment are described elsewhere (Leys & Eldridge, 1998).

Assessment of soil crust cover and dry aggregate structure

On each of the 30 plots at each site, biological crust cover (%CC) was estimated within six 0.25 m² quadrats. These estimates were supported by measurements of crust composition using a point quadrat with 160 points per plot. Using this technique, the components of bare soil, coarse sandy material, litter, cryptogamic crust (comprising lichens, mosses, liverworts, filamentous cyanobacteria), and vascular plants were recorded.

On each plot we collected a sample of surface soil for determination of the level of dry aggregation > 0.85 mm (Leys & Eldridge, 1998). Ten replicates were obtained per disturbance level. The percentage mass of soil aggregates bound together with biological elements (%DA_b) as distinct from physical aggregates (%DA_p) was measured after completion of wind erosion measurements on the moderate and severe disturbance plots. This method could not be used on the control treatment as there were no aggregates on the surface due to the lack of disturbance. For the moderate and severe disturbance plots, a 500 × 60 mm² transect was laid out on each plot at 2 m from the start of the wind tunnel working section. Within this quadrat, we collected all soil aggregates > 1 mm in diameter with a small spatula, gently passed them through a sieve to remove loose material, and separated them into two samples; those showing evidence of a biological crust (e.g. moss, lichen, cyanobacterial filaments), and those with no obvious evidence of a biological crust. Physical and biological aggregates were then oven-dried at 80°C overnight and weighed separately.

Results

Aggregation across sites

At the loamy site, mean (\pm standard deviation) percentage mass of all dry aggregates >0.85 mm ($\%DA_t$) ranged from 60.3 (± 11.3)% on the control to 32.4 (± 5.5)% on the severely disturbed sites. At the sandy site, however, $\%DA_t$ ranged from 37.9 (4.2)% to 14.8 (2.3)% for the control and severe treatments, respectively (Table 1).

Effect of cultivation on crust cover and dry aggregation

Predictably, disturbance reduced percentage biological crust cover ($\%CC$) on both soil types, and this reduction was slightly greater on the sandy soil compared with the loam. For example, a moderate level of disturbance reduced crust cover by 44% on the loam and 50% on the sand. The severe disturbance however reduced crust cover by 84% on the loam and 95% on the sand (Table 1). Most of the effect of the disturbance on the loamy soil was to break large soil aggregates into smaller aggregates which, though generally smaller, remained intact through either physical or biological bonding. On the sandy soil, however, many aggregates, particularly those less than about 5 mm in diameter, disintegrated under even the moderate disturbance treatment.

As with biological crust cover ($\%CC$), disturbance markedly reduced dry aggregation levels. Within a soil type, $\%DA$ was significantly greater on the control treatment, followed by the moderate treatment, and least on the severe treatment ($F_{2,27} = 30.65$, $P < 0.001$ and $F_{2,27} = 93.7$, $P < 0.001$ for the loam and sand, respectively; Table 1). Interestingly, $\%DA$ of the undisturbed surface on the sandy soil was of a similar magnitude to that of the severe treatment on the loamy soil.

Soil aggregation comprises both biological aggregation, that is, aggregation contributed by biological elements (Chaney & Swift, 1986; Lee & Foster, 1991; Degens, 1997), and aggregation caused by physical factors (Bullock *et al.*, 1988). The strong inverse relationship between soil strength and sediment transport rate means that the stronger the interparticle forces within a soil, the greater is its resistance to wind erosion (Rice *et al.*, 1997). The percentages of the soil comprising biologically stabilized ($\%DA_b$) and physically stabilized ($\%DA_p$) aggregates are given in Table 1. Pooled across treatments, compared with the sandy soil, significantly more of the surface of the loamy soil comprised biological aggregates ($P = 0.016$). As the severity of the disturbance treatment increased, there was a corresponding decline in the proportion of soil comprising biological aggregates. Similarly, pooled across soils types, there was a significantly higher proportion of biological aggregates on the moderate treatment compared with the severe treatment ($F_{1,38} = 5.57$, $P = 0.024$).

Crust cover, aggregation and wind erosion

As discussed above, biological soil crusts contribute markedly to dry aggregation levels in the soil. Using data from our study, a strong linear relationship was found between biological crust cover ($\%CC$) and dry aggregation ($\%DA_t$, $R^2 = 0.72$, $P < 0.001$, Fig. 1B). Within the range of the data, this relationship is of the form:

$$DA_t = 18.03 + 0.79\% \quad (\text{Eqn 1})$$

indicating that, as the level of crust cover increases, so does the dry aggregation level for the sites studied.

Table 1. Sediment transport rate at 65 km h^{-1} Q_{20} $\text{g m}^{-1} \text{s}^{-1}$, percentage crust cover (%CC), percentage total dry aggregation (%DA_t), and the proportion of dry aggregation contributed by biological elements (cryptogams; %DA_b) and physical elements (%DA_p) for both soil types and treatments.

	Loamy soil			Sandy soil		
	Control	Moderate	Severe	Control	Moderate	Severe
Sediment transport rate (Q_w)	0.3 (1.2)	0.4 (0.4)	8.0 (2.8)	8.2 (8.3)	12.5 (6.4)	33.7 (7.6)
Biological crust cover (%CC)*	49.9 ^a (6.8)	27.8 ^b (5.3)	7.8 ^c (2.2)	31.7 ^b (7.1)	15.8 ^b (2.7)	1.5 ^b (1.8)
Total dry aggregation (%DA _t)†	60.3 ^a (11.3)	44.5 ^b (5.8)	32.4 ^b (5.5)	37.9 ^b (4.2)	24.8 ^b (4.5)	14.8 ^b (2.3)
% bio-aggregation (%DA _b)	ND	90.5 ^a (6.6)	74.5 ^b (10.7)	ND	75.7 ^b (15.0)	62.2 ^b (27.3)
% physical aggregation (%DA _p)	ND	9.5 (6.6)	25.5 (10.7)	ND	24.3 (15.0)	37.8 (27.3)

Note: *Standard deviations are given in parentheses.

†Different letters within a row indicate a significant difference at $P < 0.05$. ND = no data available.

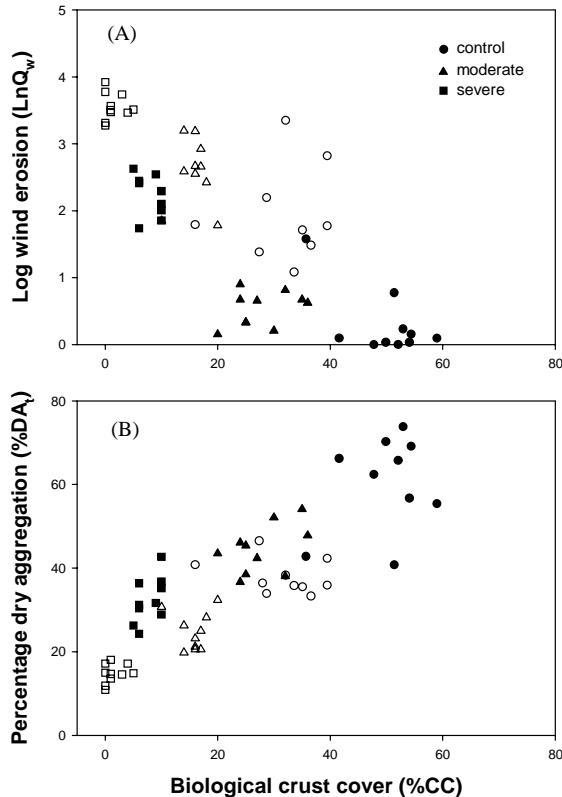


Figure 1. Relationship between biological soil crust cover (%CC) and (A) wind erosion ($\ln Q_w$) and (B) percentage dry aggregation (% DA_t) for loamy soils (filled symbols) and sandy soils (open symbols).

A log-linear relationship (Fig. 1A) was identified between the biological crust cover data (%CC) and the sediment transport rate at a wind speed of 5 km h^{-1} as measured at 10 m above the ground (Q_w) (see Table 1 for data). This is of the form:

$$\ln(Q_w) = 3.34 - 0.089\% \quad (\text{Eqn } 2)$$

where biological soil crust cover explained 66% of the variation in sediment transport rate ($P=0.05$). For these data, the critical crust cover level required to maintain the sediment transport rate below the erosion control target of $5 \text{ g m}^{-1} \text{ s}^{-1}$ is $20 \pm 4\%$.

Testing the influence of biological crust cover (%CC) and dry aggregation (% DA_t) on the sediment transport rate at a wind speed of 5 km h^{-1} (Q_w), results in a multiple variable regression equation of the form:

$$\ln(Q_w) = 5.93 - 0.151\%DA_t + 0.036\%C \quad (\text{Eqn } 3)$$

with a R^2 of 0.86 and a significance level of $P=0.05$, an increase of the regression statistic of 20 percentage points compared to Eqn (1). The above empirical equations were selected because they gave the best regression statistic and in no way are they considered to be directly describing the erosion process. Despite this, they have applicability in predicting sediment transport rates at the test sites. Equations (2) and (3) raise the question about which variable, %CC or % DA_t , contributes the greatest to explaining the variation in Q_w .

The percentage mass dry aggregation >0.85 mm diameter ($\%DA_t$) was significantly altered by the surface disturbance treatments as described in Leys & Eldridge (1998). The results show a highly significant ($R^2 = 0.84$ $P = 0.009$) log-linear relationship between $\%DA_t$ and Q_w (Eqn 3) of the form:

$$\ln(Q_w) = 5.39 - 0.113\%DA_t \quad (\text{Eqn 4})$$

Using Eqn (4), an erosion control target of $Q_w = 5 \text{ g m}^{-1} \text{ s}^{-1}$, $33.5 \pm 2.3\%DA_t$ was calculated as the critical dry aggregation level to provide effective erosion protection. This value is very close to the 31% critical aggregation level reported in Leys *et al.* (1996) for a range of disturbed bare soils.

The use of partial regression techniques, which sequentially fit the two predictors ($\%DA_t$ and $\%CC$) in Eqn (3), indicates that the addition of $\%CC$ to the model does not add significantly to the predictive power of the model. Thus, the major controlling factor of Q_w in this research is $\%DA_t$, rather than $\%CC$. Percentage dry aggregation explains 84% of the variation in Q_w , and the addition of $\%CC$ into a multiple variable regression only increases the predictive power of the model by two percentage points.

For both soil types and across all treatments, biological elements contribute more to total aggregation than physical (non-biological) elements (Table 1). As the surface becomes more disturbed, the proportion of biological aggregates as percentage of total aggregates declines (Table 1). This suggests that in a cryptogam-dominant environment, aggregates stabilized by cryptogams are likely to be more affective than those stabilized by soil physical forces.

Discussion

Our studies at Mallee Cliffs National Park and 'Tapio' in eastern Australia indicate that cryptogam cover is an important determinant of aggregate stability of both loamy and sandy-textured aeolian soils. Previous research on these soils (Leys & Eldridge, 1998) has emphasized the strong and significant relationship between crust cover and wind erosion. Given this, crust cover can be viewed as a useful indicator of the risk of wind erosion, particularly at levels of crust cover $< \sim 20\%$ which correspond to a sediment transport rate of $> 5 \text{ g m}^{-1} \text{ s}^{-1}$.

The importance of micro-organisms for enhancing the stability of soil aggregates is well recognized (Whitford, 1996; Degens, 1997). Bailey *et al.* (1973) demonstrated enhanced aggregation when soils were inoculated with algae or cyanobacteria. Similarly, Tisdall & Oades (1982) demonstrated how fungal hyphae bind micro-aggregates of soil < 0.25 mm into stable macroaggregates > 0.25 mm thereby reducing erosion. In the semi-arid woodlands in eastern Australia, Greene *et al.* (1990) showed how aggregates from soils dominated by biological crusts had greater stability than aggregates from bare soils. This aggregation is generally greatest within 1–2 mm of the surface (Eldridge & Greene, 1994), and in low rainfall environments is responsible for reducing wind erosion on sandy soils.

On coarse-textured aeolian landscapes dominated by mallee vegetation (*Eucalyptus* spp.), the sandy surface soils have characteristically low levels of soil aggregation and organic carbon compared with loamy soils. In these landscapes, biological crusts occur at significantly reduced cover levels (8.6%) compared with loamy landscapes (24.3%; Eldridge, 2001). In the absence of cryptogamic crusts, natural levels of aggregation through physical inter-particle bonding are relatively low, and may be insufficient to hold coarse-textured soils in place. Similarly in sandy dunefields in Israel's Central western Negev, cyanobacteria form a thin biological crust on the north-facing flanks of mobile sand dunes (Danin *et al.*, 1989). In the short term, stability is dependent on the rapid growth of annual plants which reduce wind velocity sufficiently to entrap

aeolian silts and clays (loess). Cyanobacteria develop only after a threshold level of fine particles in the soil is exceeded, and these eventually coalesce to form a stable cyanobacterial crust (Yair, 1990). The importance of cyanobacteria and other micro-organisms in stabilizing sandy areas should not be underestimated (Pluis & de Winder, 1989).

The resilience of the soil to disturbance-induced wind erosion is, however, not merely a function of biological aggregation, but is related to total soil aggregation (i.e. biological plus physical aggregation). Given the low levels of physical aggregation on sandy soils therefore, it is reasonable to infer that cryptogam-induced aggregation dominates total aggregation. We hypothesized a greater reliance upon cryptogams for aggregation on sandy soils compared with soils containing higher amounts of clay. However, this hypothesis was not supported by our data, and we found that the proportion of biological to total aggregates declined as soils became sandier. This was probably due to the fact that our method of discriminating between biological and physical aggregation requires refinement. Aggregates showing no apparent evidence of biological aggregation and assigned to the 'physical' category were likely occupied by cyanobacterial filaments, which are visible only after incubation (Metting, 1981) or by correlating chlorophyll densities with cyanobacterial biomass from field-derived samples (Wheeler *et al.*, 1993). Thus, we may have underestimated the biological component of aggregates, in particular the contribution by cyanobacteria which are ubiquitous in rangelands soils (Rogers, 1989).

A crust-aggregation model

As discussed earlier, there are strong relationships between biological soil crust cover and aggregation, and therefore wind erosion. Together with empirical data for clay loam soils from Yathong Nature Reserve in the semi-arid woodlands (Eldridge & Rath, 2002), these data provide a useful framework within which to examine the role of biological crusts in moderating the effects of erosion in rangelands (Fig. 2). The model indicates that for each soil texture tested (sand, loam, clay loam), increasing crust cover results in higher total dry aggregation levels, and the rate of increase of aggregation is similar for each soil texture. Equation (4) indicates that erosion will exceed our control target level at $\%DA_t > 33\%$. Therefore, the sandy soil relies on the crust cover to give it adequate soil aggregation. The loam soil requires low levels of

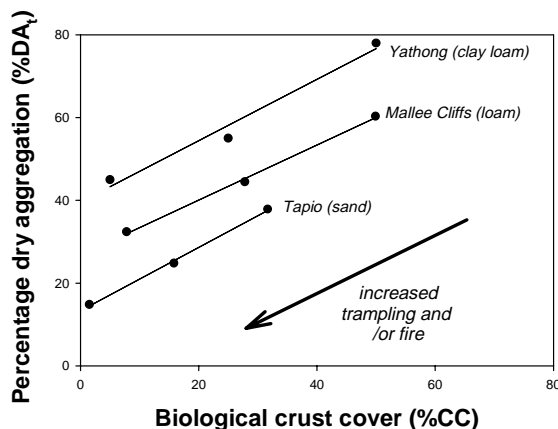


Figure 2. Relationships between biological soil crust cover (%CC) and dry aggregate structure (%DA_t) for three soil texture types.

crust cover to keep it above the threshold $\%DA_t$ level. The clay loam has sufficient inherent aggregation that crust cover is not required to attain a $\%DA_t$ level above threshold.

Within the topright-hand corner of Fig. 2 are sites of high aggregate stability structure ($>40\%$) and moderate cryptogam cover ($>25\%$) corresponding to rangelands soils in good health with little or no accelerated wind erosion, apart from local redistribution of sediments. The lower left-hand corner of Fig. 2 is a critical area for both crust cover and soil aggregation, being above the threshold of $5 \text{ g m}^{-1} \text{ s}^{-1}$ (Leys, 1998), at least for the sand and loam soils. Intermediate sites, where cryptogam cover has been destroyed, but aggregation levels are still moderate, will be highly reliant on aggregate structure for soil stability.

The model indicates that management strategies which reduce either cryptogam cover (see West, 1990; Eldridge & Greene, 1994) or aggregate stability are likely to be more influential as soil texture becomes coarser, i.e. as the soils become more sandy. In extensive (rangeland) grazing systems, reductions in cryptogam cover occur predominantly through trampling and burning (Eldridge & Greene, 1994). Burning reduces aggregate stability of rangeland soils and destroys cryptogamic crusts, resulting in reduced infiltration. However, not all reductions in cryptogam cover are likely to result in increased erosion, and this will clearly depend on inherent levels of dry aggregation, which are naturally greater on finer-textured soils. Thus, the input of considerable energy on the clay loam soil at Yathong may fail to drive the system into one where the soil is unstable merely by virtue of its surface texture and hence aggregation.

Management practices which reduce trampling on the soil will eventually result in the re-establishment of biological crusts and their associated organisms, and ultimately lead to lower levels of wind erosion. Re-establishment of biological soil crusts can only be accomplished when stocking rates mimic the disturbance regime in which the crusts evolved, which, in most cases, will be limited to a very conservative, low-risk stocking rate. Additionally, strategies should be developed to distribute livestock evenly across paddocks and the landscape in order to avoid concentrated zones of impact. Such strategies may include the development of multiple water sources and multiple feeding locations where supplements are required. Where possible, livestock usage should be minimized during dry seasons of the year, and destocking will likely be required during periods of prolonged drought.

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