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Soil crusts in the Molopo Basin, Southern Africa

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Abstract

Biological soil crusts are a common feature of many dryland soils. The cyanobacteria and algae that make up the crusts can fix atmospheric nitrogen and sequester carbon dioxide directly from the atmosphere. Crusts, therefore, have an important role in nutrient cycling as well as erosion control. This paper provides the first evidence of widespread biological soil crusts in the Molopo Basin on the southern margins of the Kalahari. The crusts appear to be more resistant to disturbance than those reported elsewhere and are able to thrive despite a relatively high vascular plant cover.

Key Words

Biological soil crusts, land degradation, Kalahari

Introduction

Drylands cover an estimated 66% of the African continent (UNEP, 1997). The United Nations estimates that up to 75% of the soils in agricultural areas of dryland Africa are degraded through erosion, salinisation, loss of organic matter, acidification and declining nutrient levels (UNEP, 1997). However, the ability of dryland soils to support natural or agricultural communities is fundamental to the sustainability of rural livelihoods. Dryland soils are typically characterised by coarse textures, low organic matter and nutrient levels, reflecting the relative lack of moisture for vegetation growth and mineralisation. Although vascular plant biomass may be low, there is evidence that the non-vascular component of microphytes growing in soils may be extensive (Karnieli *et al.*, 1996). This includes assemblages of mosses, liverworts, algae, lichens, fungi, bacteria and cyanobacteria, collectively known as a microphytic crust. Belnap (1994) estimated that such biological soil crusts could represent up to 70% of the living cover in some dryland plant communities.

Biological soil crusts have been reported in a variety of dryland settings, including; the southern and western United States (Rosentreter, 1997; Belnap *et al.*, 2001); Australia (Eldridge and Tozer, 1996), West Africa (Malam Issa *et al.*, 1999) and the Middle East (Karnieli *et al.*, 1996). They have many important functions including retaining soil moisture, discouraging weed growth, reducing wind (Belnap and Gillette, 1997) and water (Alexander and Calvo, 1990) erosion, fixing atmospheric nitrogen (Rychert and Skujins, 1974; Belnap 1994, 1995) and sequestering carbon (Beymer and Klopatek, 1991). It is surprising, therefore, that despite the extent and wide-ranging influence of biological crusts in dryland areas it is only recently that they have been recognised as having a major influence on dryland terrestrial ecosystems (Belnap *et al.*, 2001). This paper aims to provide the first classification of soil crusts found in the Kalahari sandveld of southern Africa and to quantify the extent of the different crustal types. It then tests existing crustal development theories, developed from other dryland regions, on the importance of vegetation cover, disturbance and substrate characteristics in affecting spatial patterns of crust cover and development.

The Distribution of Biological Soil Crusts

A variety of environmental factors influences the distribution of crusts at a variety of scales (Eldridge, 1999). At a continental scale temperature and rainfall are the greatest influences (Rogers, 1972). At the regional scale, substrate is the predominant control (Johansen, 1993), for example, several studies have shown how biological crusts are less likely to develop on sandy soils due to the surface mobility (Skujins, 1984; Belnap and Gillette, 1997).

Vascular plant cover has an important influence on biological crust cover at smaller scales. It is commonly reported that there is an inverse relationship between biological crust cover and vascular plant cover because they are in direct competition for light and moisture. Certain plants also have an allelopathic effect on the micro-organisms forming crusts and prevent their development (Rychert *et al.*, 1978; Skujins, 1984). Light is an essential factor to growth of the micro-organisms forming biological crusts and areas of the soil in constant shade, such as directly around a shrub canopy base, are not ideal habitats for crust formation (Friedman and Galun, 1974). However, bush canopies can provide protection from disturbance, and create shade which controls the heat and light reaching the soil surface, both of which can be beneficial to growth (Belnap *et al.*, 2001). The fine root systems of many plants can also encourage cyanobacteria to colonise soils (Scott, 1982).

Crusts are sensitive to disturbance and Belnap (1996) estimates they can take 250 years to recover after trampling by animals or humans. Soils that are frequently disturbed can support only large filamentous cyanobacteria, as later successional species are not able to form (Belnap *et al.*, 2001). Marble and Harper (1989) found biological crusts to be particularly susceptible to disturbance through mechanical damage when dry and thus trampling by livestock to be one of the major inhibitors of crust development.

There are numerous factors influencing the development and distribution of biological soil crusts in dryland areas, notably substrate characteristics, vegetation cover and disturbance levels. It is, however, difficult to isolate each causal factor because of the complex interactions at a variety of spatial scales. The extensive heterogeneity of soil and climate conditions in dryland regions and the large number of species forming biological crusts mean that there is considerable variation in their range (Skujins, 1984).

Study Area

The southern Kalahari is a dryland area characterised by sandy soils and high vascular plant cover. There is a high degree of livelihood dependency on traditional communal grazing systems and so soil disturbance is frequent and extensive. Thus, models derived from the literature would suggest it is unlikely to be characterised by extensive biological crust cover. To date, no studies have tested these models in Kalahari settings and thus it is unknown how extensive a biological soil crust cover may be and what influence it might have on the ecosystem.

The Kalahari is an extensive basin of wind-blown, nutrient deficient sediments (Thomas and Shaw, 1990). Soils are deep, structureless fine sands with limited organic matter (Dougill *et al.*, 1998). Primary productivity is largely limited by water availability and to a lesser extent soil nitrogen and phosphorus. The Molopo Basin (Figure 1) lies

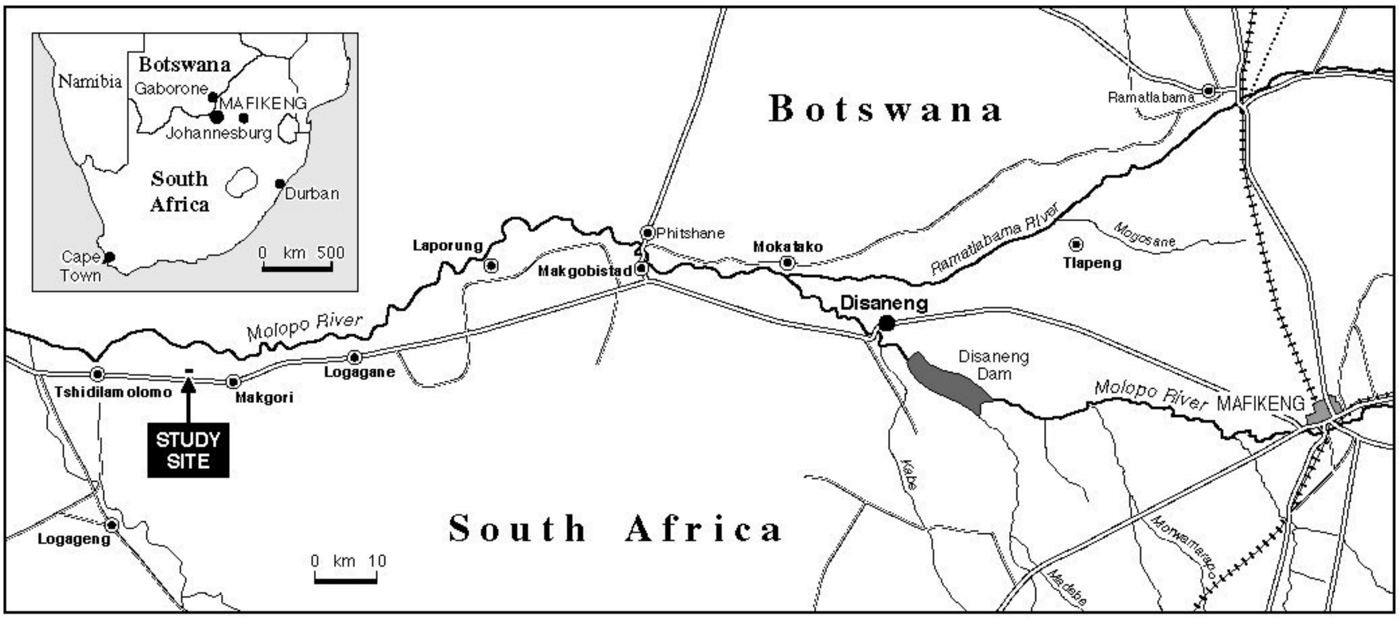

Figure 1: Study region

at the southern edge of the Kalahari basin in the North West Province, South Africa and Southern District, Botswana. It is a semi-arid region, typified by annual rainfall of *c.* 500 mm concentrated in the summer-wet season (October – March). Rangeland fertility is vital for success of semi-subsistence farmers due to their dual reliance on livestock grazing and on manure inputs for arable production and thus livelihood sustainability (Dougill *et al*., 2002). The population density and thus pressure on agricultural land is higher than elsewhere in the Kalahari because of the relocation of outside populations and intensive agricultural development projects and policies. Recent assessments by UNEP (1997) and Hoffman and Ashwell (2001) have concluded the Molopo Basin has been experiencing land degradation through a variety of processes including both water and wind erosion.

Studies reported here were conducted at sites approximately 100 km west of Mafikeng, between the villages of Loporung and Tsidilamalomo, typified by a series a low parallel ridges of calcrete and ironstone cutting across the Kalahari sand deposits (Figure 2). The soils and consequently the vegetation developed on the ridges vary within a relatively short distance. This enabled the investigation of a wide range of different soil, vegetation and disturbance characteristics on crust development in a relatively small area.

Research Design and Methods

Six locations along a 1500m transect running perpendicular to the ridges were selected and soil crust characteristics determined within $50m^2$ or $30m^2$ grids (depending on vegetation density). The grids were located on Kalahari sands, the ironstone ridge, colluvium derived from the ironstone, alluvium adjacent to an ephemeral channel in the valley bottom, colluvium derived from the calcrete and finally on top of the calcrete ridge. Site details are given in Table 1. Within the grids, a metre square quadrat was placed every 5m or 1.5m (depending on the grid size) and the following characteristics determined: percentage crust cover and type, vegetation species and cover, crust depth, crust hardness (using a penetrometer).

Samples of all crust types and unconsolidated soil were collected and air-dried prior to laboratory determination of grain size, organic matter and total chlorophyll and chlorophyll *a*. Grain-size distributions were determined on dispersed samples sieved at half-phi intervals in the range - 1.0 to + 4.0 phi (2 mm to 0.063 mm) after removal of organic matter using H_2O_2. Silt and clay was determined on the less than 0.063mm fraction using the sedimentation method outlined in Rowell (1994). Organic matter was determined using loss-on-ignition (Rowell, 1994). Total chlorophyll and chlorophyll *a* were determined colorimetrically using a Palintest® Photometer 5000 after extraction with 85% v/v acetone according to the method of Allen (1989). A relative level of disturbance was determined at each site using cattle track frequency and dung density parameters, according to the methods of Perkins and Thomas (1993).

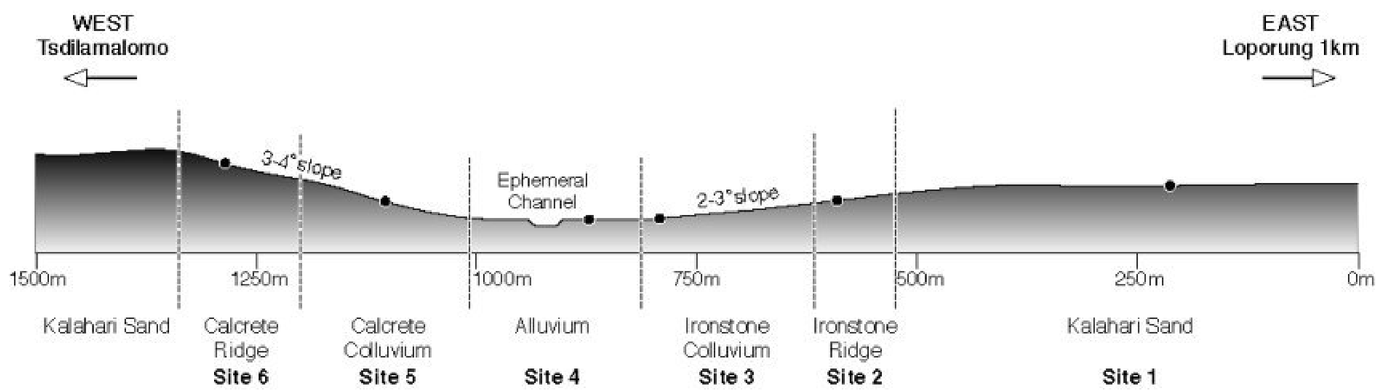

Figure 2. Profile of Sample Sites

Table 1: Grain size, disturbance and vegetation cover at each site

Location	Grain Size (%)				Vegetation Cover (%)				Disturbance	
	Coarse sand	Fine sand	Silt	Clay	*Acacia* Spp.	*Grewia flava*	*Brach Rot.*	Grass Spp.	Cattle tracks (/ 30 m)	Dung density (/ 25 m^2)
Kalahari Sands	22.3	69.3	3.1	5.3	11	1	0	6	2.5	0.9
Ironstone Ridge	26.9	61.8	4.0	7.3	15	4	10	13	2.4	0.2
Ironstone Colluvium	22.5	65.2	7.7	4.6	25	3	12	5	3.3	0.4
Valley Alluvium	25.8	67.0	0.5	6.7	5	29	0	26	6.0	2.3
Calcrete Colluvium	23.8	60.2	11.2	4.8	20	13	13	10	4.3	1.4
Calcrete Ridge	21.1	64.9	8.5	5.5	16	13	16	9	4.3	1.5

Results and Analysis

1. Crust Classification

There are problems associated with the field identification and classification of biological soil crusts largely due to the small size of the crust components and the difficulty of identifying to species level (Eldridge and Rosentrenter, 1999). Most classification schemes are therefore based on form and morphology of crusts, as there is a strong relationship between crust morphology and their ecological function. The classification developed and used in this study (Figure 3) therefore uses form and morphology, in order to provide an objective and reliable classification of soil surface conditions.

Crusted sites away from the alluvial channel and with no visible mycelium were classified as physical crusts, presumably forming through processes of raindrop impact and relocation of fine sediments (Casenave and Valentin, 1992). Thereafter, crusts are assumed to have an increasing biological component and represent different stages in crustal succession. This is reflected in increasing surface discolouration, increasing hardness and chlorophyll content (Table 2). The chlorophyll content of the biological crust samples was remeasured after wetting. In all cases this led to an increase in both total chlorophyll and chlorophyll *a*, signifying that the initial determination was measuring cyanobacteria in the soil which respond to wetting in this way (Table 2).

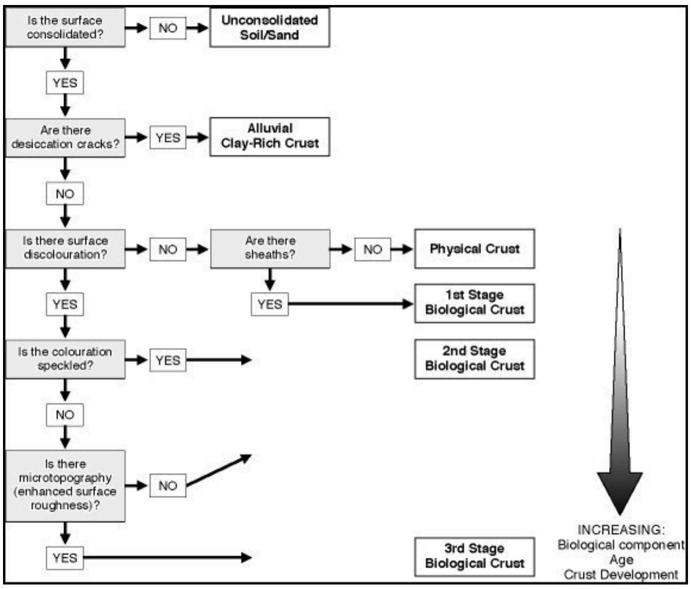

Figure 3: Soil crust classification system

Figure 4: Physical crust

Figure 5: Stage 3 biological crust

The first stage biological crusts (Figure 4) appear broadly equivalent to Belnap and Gillette's (1997) class 1 crusts, which they described as 'flat crusts, no visible lichen cover, low cyanobacteria biomass, disturbed within 1 year'. Under the same system, class 2 crusts are described as, 'moderately bumpy crust, no lichen or moss, moderate cyanobacteria levels, disturbed 5-10 years previously' which appear equivalent to the third stage biological crusts in this study (Figure 5).

2. Crust Characteristics

With the exception of alluvial crusts (which are formed under very different conditions) the hardness of surface soil crusts increases with biological content and therefore, succession of the biological crust (Table 2). This has obvious implications for soil surface erodibility, which will be greatly reduced, where crust development is most advanced. The considerable hardness of the crusts (measured as resistance to penetration) is despite modest depths, with the average depth of biological crusting at the surface no more than 4mm for most crusts.

3. Crust Cover

There are clear differences between the sites in terms of both total and type of crust cover (Table 3). The ironstone soils have the greatest crust cover (>50 %), followed by the alluvial soils of the valley bottom. Crusts are least likely to develop on the Kalahari sands. The pattern of total crust cover is matched by the cover of biological crust stage 3 crusts, such that soils with the greatest total cover also have the highest proportion that is of the higher successional stage.

Table 2: Crust characteristics at all locations - means and (standard deviation)

Surface type	n	Depth (mm)	Hardness (kg/cm^2)	Total chlorophyll (%)	Chlorophyll *a* (%)	Increase in chlorophyll *a* after wetting (%)
Alluvial crust	10	9.82 (4.7)	4.05 (1.4)	–	–	–
Physical crust	22	3.48 (3.1)	1.37 (0.73)	–	–	–
Bio stage 1 crust	50	4.22 (1.98)	2.91 (1.67)	0.034 (0.012)	0.012 (0.004)	15.8
Bio stage 2 crust	72	4.04 (1.74)	3.44 (1.74)	0.043 (0.032)	0.020 (0.012)	45.6
Bio stage 3 crust	104	3.73 (2.02)	4.57 (1.71)	0.066 (0.029)	0.029 (0.021)	18.2

Table 3: Crust type characteristics at each site (% ground cover)

Location	Physical crust	Bio 1 crust	Bio 2 crust	Bio 3 crust	Alluvial crust	Total crust
Kalahari Sands	8.0	16.0	1.3	–	–	25.3
Ironstone Ridge	–	2.7	12.0	36.4	–	51.1
Ironstone Colluvium	–	11.4	11.7	32.7	–	55.8
Valley Alluvium	–	5.1	4.6	14.6	15.1	39.4
Calcrete Colluvium	0.8	2.7	13.7	14.8	–	32.0
Calcrete Ridge	–	1.1	7.6	20.7	–	29.4

Each site has a unique combination of vegetation, soil and disturbance characteristics, all of which are likely to affect the development of surface crusts. Figure 6 shows the relationship between the level of disturbance at each site and the cover of each crust type. From this it is clear that most crust types are resilient to relatively high levels of disturbance. The only exception to this is the development of the high-end successional crusts, which are best developed in areas of low disturbance.

Vascular plants are in direct competition with the cyanobacteria of the biological crusts. Thus it has been reported in many studies that there is a direct inverse relationship between crust and vegetation cover. Results from this study show no such relationship (Figure 7), but, there are clear differences between physical and biological crusts. Sites of low occurrences of physical crusts tend to have low vegetation cover.

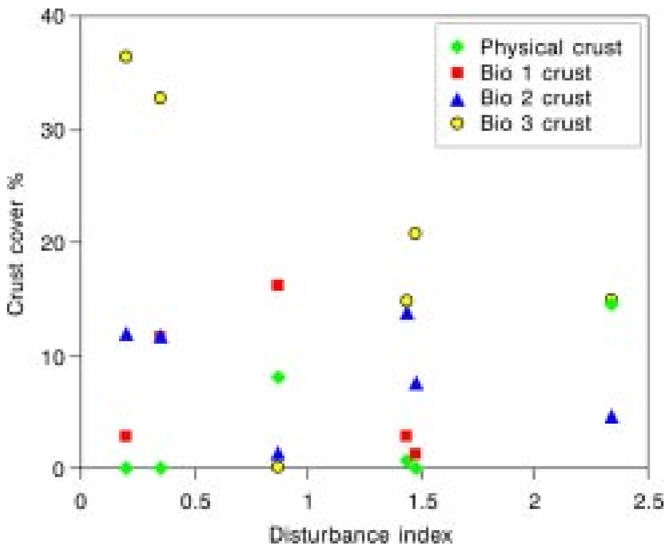

Figure 6: Crust cover and type and disturbance at all locations

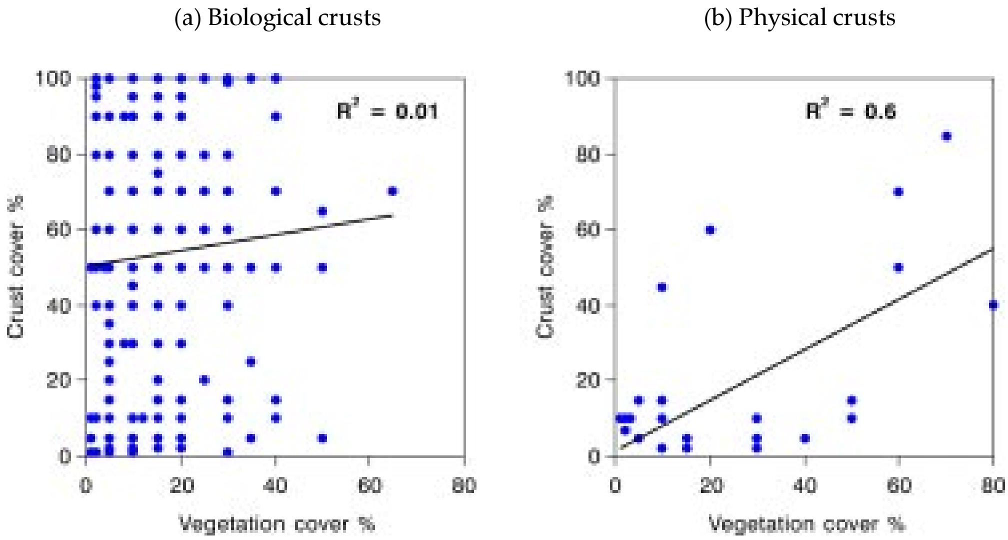

Figure 7: Correlation between total vegetation and crust cover at all locations

The relationship between crust cover and vegetation cover is not simple. Around all bush species, there is a concentric pattern of unconsolidated soil and crust (Figures 8 and 9). The size of each of the zones varies with bush species and the morphology of the canopy and leaves (Table 4). *Acacia mellifera* is a bush species with a dense canopy covered in double thorns, thus it is highly effective at reducing grazing under the canopy. The leaves of the *Acacia spp.* are small and produce an incomplete cover on the soil surface. The bush, therefore, provides ideal conditions for crust formation with minimal disturbance and high light levels reaching the surface soil. *Grewia flava*, in comparison, has no thorns and large leaves producing a thick cover of litter on the soil. Consequently, despite the similar canopy dimensions, crust development is greatly reduced under this species. It is reasonable to expect that such patterns will be repeated across wide areas of the Kalahari where the substrate and vegetation cover are similar.

Figure 8: Crust cover around a bush canopy

Table 4: Crust cover and bush species (mean values with s.d. in parentheses)

Bush species	**Canopy height (m)**	**Canopy width (m)**	**Area of crust under bush (m^2)**	**Crust:canopy height ratio**	**Crust:canopy width ratio**
Acacia mellifera	1.50 (1.27)	1.87 (1.19)	2.13 (1.52)	0.42 (0.18)	0.33 (0.18)
Grewia flava	1.26 (0.29)	1.41 (0.47)	1.19 (0.71)	0.29 (0.12)	0.28 (0.15)
Brachylaena rotundata	1.57 (0.45)	1.43 (0.55)	1.64 (2.18)	0.29 (0.21)	0.31 (0.19)

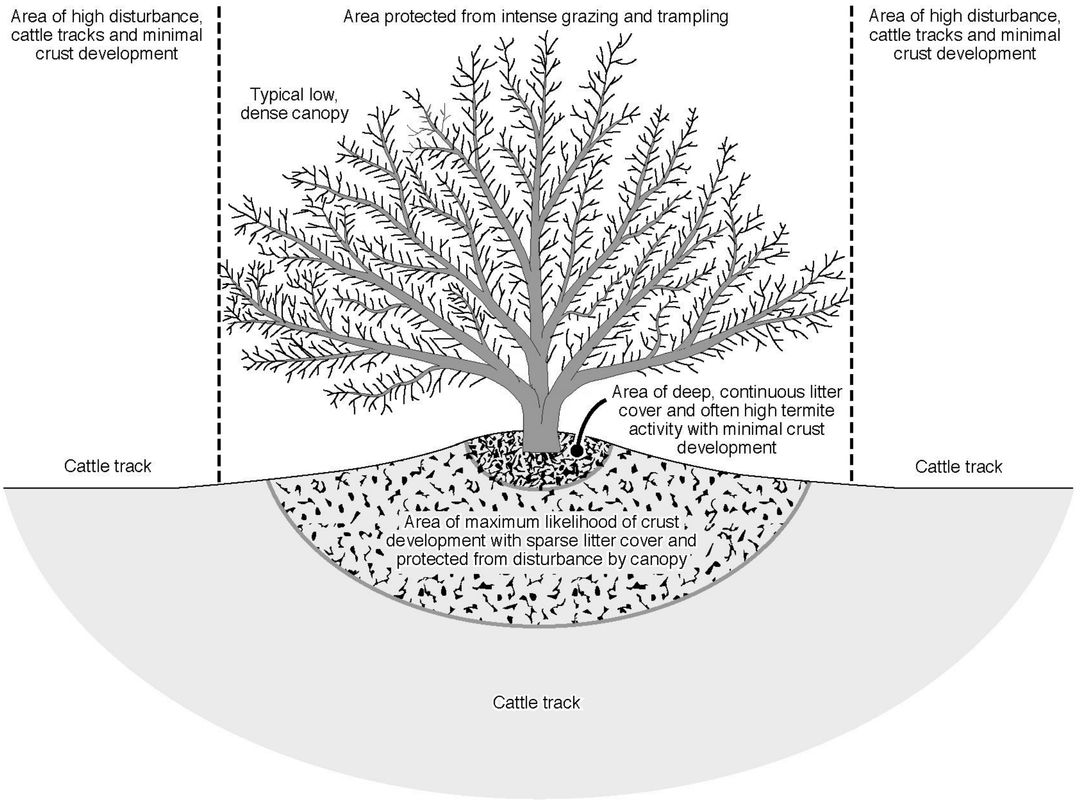

Figure 9: Relationship between bush canopies and crust cover

Discussion and Conclusions

This paper has presented the first account of the widespread occurrence of biological soil crusts in the Kalahari and detailed the factors affecting their spatial distribution in a small area of differing substrates. It has provided an objective field-based classification of crustal types which has been verified by laboratory measurements of crust chlorophyll content and *in situ* hardness measurements (Table 2). The results demonstrate the relative resistance of the Kalahari crusts to disturbance, in comparison to the more comprehensively studied biological soil crusts of Australia and North America (Eldridge, 1999; Belnap *et al.*, 2001). In addition, it has shown that the relationship between crust cover and vegetation is not a simple inverse linear relationship as reported for these other dryland environments. There is a complex relationship with individual bush species, with for example *Acacia mellifera* encouraging crust development and *Grewia flava* restricting it.

The implications of these findings are wide ranging. Biological soils crusts have an important role to play in influencing erodibility. The soils and ultimately the ecology of this dryland system are strongly affected by wind blown sediment movements (Dougill and Thomas, 2002). The results provide further evidence of the complex inter-relationships between soils and vegetation. The occurrence of crusts also influences soil fertility. Crusts fix atmospheric nitrogen and sequester carbon. Crustal development will improve soil fertility and have an important (but largely unknown) influence over regional atmospheric fluxes of carbon and nitrogen that requires further investigation.

Rangelands in southern Africa play an integral part in both farming systems and regional ecology. In order for the success of mixed farming systems, which rely on good rangeland grazing for livestock health and for manure inputs to arable fields, it is vital that the fertility of the soils is understood. These preliminary results indicate that the development, occurrence and functions of surface soil crusts are a vital, and previously under-estimated, part of this understanding.

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