KALAHARI SAND SOILS: SPATIAL HETEROGENEITY, BIOLOGICAL SOIL CRUSTS AND LAND DEGRADATION

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Received 26 November 2002; Revised 14 July 2003; Accepted 11 February 2004

This paper identifies spatial associations between surface nutrients, biological soil crusts and vegetation in the Kalahari. Four locations, with different land use and substrate characteristics were used to determine the extent of biological crust cover and the factors affecting the spatial heterogeneity in soil nutrients and ecology. Despite the sandy texture of Kalahari soils and regular surface disturbances, there is a significant biological soil crust cover (19–40%) at all locations. This is due to a combination of resistance to trampling, sub-canopy niches protected from disturbance and the prevalence of Microcoleus vaginatus cyanobacteria, which are able to rapidly reform crusts. Crust cover and diversity is enhanced on ironstone and calcrete soils. The spatial variability of soil nutrients is low but is increased by grazing-induced bush encroachment. The preferential development of nitrogen-fixing biological soil crusts under bushes could enhance the competitive advantage of Acacia mellifera favouring further bush encroachment. Whether this constitutes land degradation is dependent upon the extent to which sub-bush canopy niches retain palatable grass species. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: Kalahari soils; biological soil crusts; soil degradation; bush encroachment; spatial heterogeneity

NUTRIENTS IN DRYLAND SOILS

The spatial and temporal variability of rainfall in drylands results in an incomplete vegetation cover and a complex association between vegetation and soils, notably organic matter, nutrients and microbial activity (Bennett and Adams, 1999). Spatial heterogeneity is a vital component for landscape functioning and biodiversity. The work of Noy-Meir (1973, 1985) demonstrated that the concentration of soil nutrients in patches increases the ecological productivity compared to where resources are evenly spread. It can take the form of the regular banding of ‘tiger bush’ landscape (e.g. Valentin et al., 1999) or as irregular vegetation clumps (e.g. Tongway and Ludwig, 1994; Bennett and Adams, 1999; Puigdefabregas et al., 1999).

Existing research suggests the processes leading to elevated nutrients and organic matter under bush canopies can be grouped into two categories: (i) vegetation related, where sub-canopy soil nutrients are elevated by organic matter additions and faunal activity (e.g. Dean et al., 1999); and (ii) sediment transport related, associated with deposition of enriched eroded material (e.g. Tongway and Ludwig, 1994). The implications of this spatial heterogeneity are, however, contested and may be site specific. Some authors have questioned the link between enhanced spatial heterogeneity and increased ecological productivity. Schlesinger et al. (1990) associated the development of spatial heterogeneity in soil and water resources in the southwest United States with land degradation. They argued that intensive grazing reduced grass cover and resulted in an invasion of woody...
shrub species that, once established, was difficult to reverse due to the development of ‘islands of fertility’ under bushes.

The two-fold causation model for sub-canopy nutrient enrichment may be oversimplistic in that it fails to address internal processes within dryland soils. Dryland soil nutrients are preferentially concentrated at, or near, the soil surface (Tongway and Ludwig, 1994; Dougill et al., 1998; Bennett and Adams, 1999). In part, this is due to the widespread occurrence of biological soil crusts consisting of cyanobacteria, algae, microfungi, lichens and bryophytes, which live within the top few millimetres of soil (Belnap et al., 2003). Crusts are able to fix atmospheric nitrogen (Belnap, 1994, 1995, 2003; Evans and Lange, 2003) and sequester carbon (Beymer and Klopatek, 1991; Evans and Lange, 2003). They typify all dryland soils, but their composition and distribution varies between locations with substrate, vegetation cover and disturbance (Belnap and Lange, 2003). The relationship between crusts and vegetation is particularly complex. Bush canopies can deter crust development as they reduce the amount of light reaching the surface. However, they also provide protection from disturbance and trap fine sediment, both of which can be beneficial to crust development.

To fully understand the spatial and temporal dynamics of soil fertility and degradation processes in any dryland environment this additional layer of complexity needs to be investigated. This study aims to provide new analyses of the spatial associations between soil nutrients, biological soil crusts and vegetation canopies for the Kalahari Sand soils of Southern Africa.

KALAHARI SAND SOILS, ECOSYSTEMS AND DEGRADATION

The Kalahari is ‘the extensive elevated, flat, sand-covered plain that occupies a substantial part of the Southern Africa interior’ (Thomas, 2002, p. 21). The geological unit of the Kalahari Sands covers 2.5 million km² (Thomas and Shaw, 1991). Recent intensification of pastoral land use in the semi-arid core of the Kalahari (comprising much of Botswana, eastern Namibia and northern South Africa) based on the drilling of deep boreholes, has led to concerns of widespread land degradation (Government of Botswana, 1997; SADC, 1997).

Kalahari Sand soils typically consist of over 95% fine sand-sized, aeolian-deposited sediment (Thomas and Shaw, 1991) and are predominantly deep, structureless and lacking in N, P and organic matter (Skarpe and Bergström, 1986; Dougill et al., 1998). The natural flora of the Kalahari is well adapted to low water and nutrient availability and therefore the vegetation is sensitive to changes in soil properties (Skarpe, 1990). For example, extensive bush encroachment associated with grazing intensification has been linked to increased leaching of water and nutrients (Walker and Noy-Meir, 1982; Perkins and Thomas, 1993). However, research has failed to identify any association between soil water and nutrient availability and ecological changes (Dougill et al., 1999) implying that Kalahari Sand soils are resilient to chemical degradation. The processes leading to this resilience remain unclear, and the spatial association with the main ecological degradation concern of bush encroachment unknown.

RESEARCH OBJECTIVES

This paper aims to identify spatial associations between surface nutrients, biological soil crusts and vegetation in the Kalahari. Four locations across the Kalahari are used to examine the processes retaining nutrients at the surface. The objectives of this paper are:

- To determine the extent of biological crust cover in contrasting Kalahari environments.
- To determine the factors affecting the spatial heterogeneity in soil nutrients.
- To examine the association between the spatial heterogeneity in soil biochemical characteristics and the ecological communities found at different locations.

In addressing these issues a clearer assessment of the factors contributing to the resilience of Kalahari soils and ecosystems to degradation will be obtained.


RESEARCH DESIGN AND METHODS

Site Selection

Four sites across the Kalahari were selected to incorporate a range of land uses and climatic conditions (Figure 1). They are the commercially owned Makoba Ranch Block, in the Eastern Kalahari; the mixed farming area of the Molopo Basin in the South East Kalahari; communal rangelands of Omaheke District, in the Western Kalahari; and in southern Kgalagadi District, South Western Kalahari. This provides a diverse range of substrates, grazing intensities and ecological community characteristics.

Field Measurements

Ecological and soil-based studies at the sites have been ongoing for the last decade. The research focus and approaches have evolved through time and thus the exact nature of the methods at each site differs.

Makoba Ranch Block. Integrated soil nutrient and ecological analyses were conducted at plot- (4 m²), site- (30 m x 30 m) and ranch- (8 km x 8 km) scales (see Dougill et al., 1999). Topsoils (n = 23) were taken from

![Figure 1. Locations of study sites and Kalahari Sand soils.](image-url)
random points across 30 m × 30 m sites in both an intensively-grazed bush-dominant site (800 m from Uwe Aboo borehole) and a less intensively-grazed grass-dominant site (4 km from Uwe Aboo borehole). Inorganic nutrients (NO₃⁻-N, NH₄⁺-N and PO₄³⁻-P) were determined using methods outlined by Anderson and Ingram (1993).

*Molopo Basin, South Africa and Botswana.* This site was approximately 100 km west of Mafikeng in an area with a series of low parallel ridges of calcrete and ironstone cutting across Kalahari sand deposits. Six sites along a 1500 m transect perpendicular to the ridges were selected and soil crust characteristics determined within 30 m by 30 m grids. Topsoils from Kalahari Sand, ironstone, alluvium and calcrete were analysed. A disturbance index was calculated for each site based on the number of cattle tracks, surface dung density and grass height. At all sites the percentage crust cover and type, vegetation species and cover was determined in 1 m² quadrats every 1.5 m along three parallel 30 m line transects. The crust type was assigned using a classification scheme based on crust form and morphology (Figure 2). Soil nutrients and grass biomass were also determined underneath the three main bush species (*Acacia mellifera, Grewia flava* and *Brachylaena rotundata*) at each of the sites and compared to adjacent open sites.

*Omaheke District, Namibia.* The extent of biological crust cover and the nutrient content of the surface soil was determined at four sites in Omaheke District, Eastern Namibia. Studies were undertaken at three communally-managed farms (Netso in Tsjaka Farm Block; Corridor No. 4 Farm and Okonyoka in Aminuis Reserve) and a commercially owned ranch (Hogusrus). At all locations, sampling sites were designated at 0, 100, 200, 400, 800, 1600, 3200 and 4000 m from a waterpoint along a ‘piosphere’ of declining grazing intensity (Perkins and Thomas, 1978).

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**Figure 2.** Soil crust classifications based on crust form and morphology.
At each site, soil crust and vegetation cover was determined within sixteen systematically located 1 m² quadrats and crust samples collected for total-N, total-P and organic matter analysis (Anderson and Ingram, 1993).

**Southern Kgalagadi District, Botswana.** Soil crust cover, nutrients and bush and grass cover were determined on a communal rangeland adjacent to Berry Bush farm, 10 km north east of Tshabong in Kgalagadi District, Botswana using the methodological framework established at the Omaheke District site.

## RESULTS AND ANALYSIS

### Distribution of Biological Soil Crusts

Despite the fine-sand texture of Kalahari soils and regular surface disturbances, there is a significant biological soil crust cover (19–40%) at all locations (Table I). This is a result of a combination of resistance to trampling, shown by the high compressive strengths of between 2.9 (mean for crust type 1) and 4.6 kg cm⁻² (mean for crust type 3); sub-canopy niches protected from livestock disturbance; and the prevalence of *Microcoleus vaginatus* cyanobacteria, which rapidly reform crusts. At the Molopo sites, the extent of all but the most well-developed crusts appeared unaffected by disturbance (Figure 3), reflecting the dominance of cyanobacterial crusts. Similarly, significant crust cover is retained throughout ranches in the Namibian and Kgalagadi rangelands (Figure 4), except around the small ‘sacrifice zone’ surrounding waterpoints.

The Molopo Basin sites enabled an assessment of the impact of different parent material on crust formation. Table II summarises the cover of the different crust types for soils on the four substrates. This shows that crust formation is least prevalent, and includes fewer better-developed type 2 and 3 crusts, on Kalahari Sand soils. In contrast, on ironstone soils there is over 50% crust cover and a high proportion of type 2 and 3 crusts. This implies that any landscape-scale spatial variations in parent material will add to crust extent and development.

### Spatial Heterogeneity in Soil Biochemical Characteristics

Previous studies on Kalahari soils have assessed the impacts of grazing regimes on mean soil nutrient concentrations and ecology (e.g. Skarpe, 1990; de Queiroz, 1993; Perkins and Thomas, 1993; Dougill *et al.*, 1999). These studies have found no significant differences in soil chemical characteristics between intensively grazed bush-encroached sites and the less intensively grazed grass-dominant sites. This, however, could be a consequence of examining differences in mean nutrient concentrations where there is high spatial variability and low concentrations. In addition, some studies (e.g. Perkins and Thomas, 1993) integrate nutrient concentrations from a range of depths, rather than just the surface layer where nutrients are focused.

### Table I. Soil physical characteristics, crust cover and environmental conditions at each location (see Figure 1)

<table>
<thead>
<tr>
<th>Site</th>
<th>Land use</th>
<th>Climate (mean annual rainfall—c. mm p.a.)</th>
<th>Soil texture analysis</th>
<th>Soil crust cover (mean %)</th>
<th>Vegetation status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Makoba Ranch Block</td>
<td>Commercial ranch</td>
<td>380</td>
<td>97.6 1.8 0.6</td>
<td>40</td>
<td>Mixed bush:grass savanna—extensive bush encroachment</td>
</tr>
<tr>
<td>Molopo</td>
<td>Communal rangelands</td>
<td>450</td>
<td>95.9 1.9 2.2</td>
<td>39</td>
<td>Mixed bush:grass savanna—extensive bush encroachment</td>
</tr>
<tr>
<td>Omaheke</td>
<td>Communal rangelands</td>
<td>300</td>
<td>95.6 2.9 1.5</td>
<td>39</td>
<td>Grass:bush savanna—extensive bush encroachment</td>
</tr>
<tr>
<td>Omaheke</td>
<td>Commercial ranch</td>
<td>300</td>
<td>95.2 2.8 2.0</td>
<td>19</td>
<td>Grass:bush savanna remains due to bush clearance</td>
</tr>
<tr>
<td>Berry Bush</td>
<td>Commercial ranch</td>
<td>320</td>
<td>97.9 1.5 0.6</td>
<td>26</td>
<td>Grass:bush savanna—extensive bush encroachment</td>
</tr>
</tbody>
</table>

*Sources: Particle-size data summarized from Dougill *et al.* (1998, 2002), Metcalfe (unpublished) and van der Linde (unpublished).*
In this study nutrients were determined for 23 randomly located topsoils from 30 m by 30 m plots at both intensively grazed bush-dominant, and less intensively grazed grass-dominant sites at the Makoba site. Table III shows the mean nutrient concentrations, and the coefficient of variation, used as an index of the spatial variation in soil properties. The spatial variability within a plot was low (11 to 28%) compared to shrublands in the

Table II. Soil crust type (classification as detailed in Figure 2) at sites of different substrate (% ground cover) at Molopo Basin site

<table>
<thead>
<tr>
<th>Location</th>
<th>Biological soil crust 1</th>
<th>Biological soil crust 2</th>
<th>Biological soil crust 3</th>
<th>Alluvial crust</th>
<th>Total crust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalahari Sand</td>
<td>24</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td>25</td>
</tr>
<tr>
<td>Ironstone</td>
<td>7</td>
<td>12</td>
<td>35</td>
<td>—</td>
<td>54</td>
</tr>
<tr>
<td>Valley alluvium</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>Calcrete</td>
<td>2</td>
<td>11</td>
<td>18</td>
<td>—</td>
<td>31</td>
</tr>
</tbody>
</table>

In this study nutrients were determined for 23 randomly located topsoils from 30 m by 30 m plots at both intensively grazed bush-dominant, and less intensively grazed grass-dominant sites at the Makoba site. Table III shows the mean nutrient concentrations, and the coefficient of variation, used as an index of the spatial variation in soil properties. The spatial variability within a plot was low (11 to 28%) compared to shrublands in the
southwestern United States (Schlesinger et al., 1996), where the coefficient of variation in N and P ranged from 59 to 103%. The significant difference in variance of phosphate availability between bush- and grass-dominated plots indicates that a shift to more bush-dominated cover with intensive grazing will increase the spatial heterogeneity of nutrients (Table III).

Analysis of the impact of bushes on the spatial heterogeneity in soil fertility at the Molopo site supports this assumption. Table IV shows that sub-bush canopy sites have enhanced ammonium and phosphate concentrations, organic matter and grass biomass. The lower nitrate concentration under bush canopies results from the efficient plant uptake of this nutrient, due to the synchrony of nitrification after rains and plant uptake. This has been shown to leave significantly lower nitrate than ammonium concentrations where a plant cover exists (Dougill et al., 1999).

Efficient N uptake remains prevalent in bush-encroached sites due to the extensive surface layer rooting system of encroaching Acacia species (Skarpe, 1990) and the grass cover remaining under canopies (Table IV). Previous work in the Molopo Basin has shown that wind transported sediments deposited under bushes are not significantly enriched in nutrients (Dougill and Thomas, 2002) and that elevated nutrient concentrations under bushes are due to autogenic processes. This differs from the findings for other drylands such as the southwestern United States (e.g. Reynolds et al., 2001) and Sahelian Africa (e.g. Sterk, 2003), where enhanced nutrient concentrations in aeolian dust are recorded. The small increases in organic matter under bushes are not sufficient to explain all the nutrient enrichment. Thus we also investigated the impacts of biological soil crusts in contributing to the enhanced nutrient concentrations under bushes.

Around all bushes, there was a concentric pattern of unconsolidated soil and crust with the size of each zone varying with bush species (Table V). The understorey of Acacia mellifera is better suited to crust formation due to the grazing deterrent effect of its double thorns and the small leaves, which allow light to reach the soil surface. Grewia flava, in comparison, has no thorns and larger leaves producing a thick cover of litter on the soil.

### Table III. Surface soil nutrient concentrations and variability within bush-encroached and grass-dominant sites on Uwe Aboo Ranch, Makoba Ranch Block

<table>
<thead>
<tr>
<th>Soil chemical characteristic</th>
<th>Coefficient of variation (%)</th>
<th>Coefficient of variation (%)</th>
<th>Statistical implication</th>
<th>Statistical implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₃⁻-N (mgN100g⁻¹)</td>
<td>4.7 ± 2.5</td>
<td>6.3 ± 2.0</td>
<td>16</td>
<td>x</td>
</tr>
<tr>
<td>NH₄⁺-N (mgN100g⁻¹)</td>
<td>5.1 ± 1.3</td>
<td>5.1 ± 1.3</td>
<td>13</td>
<td>x</td>
</tr>
<tr>
<td>PO₄³⁻-P (mgP100g⁻¹)</td>
<td>1.1 ± 0.4</td>
<td>1.2 ± 0.3</td>
<td>11</td>
<td>x *</td>
</tr>
</tbody>
</table>

x No significant difference; *significant difference at 95% confidence interval.

### Table IV. Mean nutrient concentrations (and standard deviations) and grass biomass for sub-bush canopy and neighbouring open sites at Molopo Basin

<table>
<thead>
<tr>
<th>Environmental parameter</th>
<th>Sub-bush canopy sites</th>
<th>Open sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₃⁻-N concentration</td>
<td>54.2</td>
<td>102.0</td>
</tr>
<tr>
<td>(mgN100g⁻¹)</td>
<td>(40.9)</td>
<td>(92.4)</td>
</tr>
<tr>
<td>NH₄⁺-N concentration</td>
<td>283.9</td>
<td>45.8</td>
</tr>
<tr>
<td>(mgN100g⁻¹)</td>
<td>(204.4)</td>
<td>(22.4)</td>
</tr>
<tr>
<td>PO₄³⁻-P concentration</td>
<td>115.5</td>
<td>87.5</td>
</tr>
<tr>
<td>(mgP100g⁻¹)</td>
<td>(97.0)</td>
<td>(63.2)</td>
</tr>
<tr>
<td>Organic Matter Content (%)</td>
<td>2.8</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>(1.2)</td>
<td>(0.6)</td>
</tr>
<tr>
<td>Grass biomass cover (gm⁻² dry weight)</td>
<td>17.2</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>(5.2)</td>
<td>(0.6)</td>
</tr>
</tbody>
</table>

Source: Nutrient data summarized from Dougill and Thomas (2002).
Consequently, despite the similar canopy dimensions, crust development was greatly reduced under *Grewia flava*. This has important implications for persistence of *Acacia mellifera* in the landscape as once established the crust will supply additional nutrients to the plant.

### Spatial Variability in Vegetation Characteristics

The ecological implications of soil crust formation under bushes depend on the associated herbaceous grass cover in these niches. At the Molopo study site, there was increased grass biomass under bushes (Table IV), as well as differences in the herbaceous species between sub-canopy and open locations. Grass species cover was grouped (Table VI) according to ‘Grazing Value’ classes, as assigned by van Oudtshoorn (1999). Grazing values are based on the species palatability, production, nutritional value, growth vigour, digestibility and habitat preference. There is evidence that more nutritious grasses are protected from grazing under bush canopies (Table VI). Enhanced grass biomass, and prevalence of nutritious grass species, under bushes was also found at the Makoba study sites (Perkins and Thomas, 1993; Dougill and Trodd, 1999). Although the dry season cover of these grasses is low, the enhanced nutritious grass cover under bushes is important in retaining a seed resource for future germination and maintaining ecological fodder diversity for livestock.

Further investigations of the complex interrelationships between bush canopies, soil biochemical characteristics and herbaceous vegetation assemblages therefore remains a key area for future research to better understand ecological change and potential processes of degradation in Kalahari rangelands.

### DISCUSSION AND CONCLUSIONS

Findings from across the Kalahari are used to provide an insight into the factors controlling soil surface nutrient dynamics. Dryland soils are characterized by low fertility, with a surface concentration of nutrients (Bennett and
Adams, 1999) and in ‘islands of fertility’ (Schlesinger et al., 1990). There is an ongoing debate on the implications of nutrient spatial heterogeneity for land degradation (e.g. Noy-Meir, 1985; Schlesinger et al., 1990; Ludwig et al., 1999). Our findings suggest that in the Kalahari, the spatial heterogeneity of soil nutrients is relatively low. Nutrient enrichment of wind-eroded material is limited (Dougill and Thomas, 2002), and therefore not the principal cause of nutrient heterogeneity. Some nutrient enrichment under bush canopies results from organic inputs from vegetation canopies. However, further processes are required to explain the nutrient heterogeneity with biological soil crust formation the most likely process.

Our research shows that biological soil crusts are widespread across the Kalahari. They exist in a variety of settings and are able to persist in landscapes where there is a high level of disturbance from livestock. This is a result of the predominance of Microcoleus spp., which are able to rapidly reform after disturbance and their colonization of protected sites under bushes. High levels of disturbance restrict the formation of better-developed crusts with mixed bacterial and lichen compositions.

The implications of the widespread occurrence of simple Microcoleus crusts in the Kalahari are uncertain. They will enhance soil-surface stability and, therefore, reduce erosion. In addition, they are able to fix nitrogen (Evans and Lange, 2003) and thus increase soil fertility. Nitrogen fixation usually occurs in specialized cells or heterocysts within the bacteria. Microcoleus, however, is non-heterocystous but can still fix N$_2$ using a variety of strategies which exclude O$_2$ from microzones or through association with other bacteria (Belnap, 2003). Our findings show that crusts develop preferentially under Acacia mellifera, which is the major bush encroaching species in the Kalahari (Skarpe, 1990; Thomas, 2002). As such, nutrient enrichment is not evenly distributed across landscapes, but is concentrated under encroaching bush species and may encourage the persistence of A. mellifera at the expense of other species. The shallow rooting system of A. mellifera (Skarpe, 1990) secures many of these nutrients for the bush. Whether this bush encroachment represents degradation depends upon the degree to which the sub-canopy niche can also support more nutritious grass species. The evidence presented here suggests that for our study sites there are small increases in the most nutritious grass species under bushes that could offset reductions in ecological fodder diversity associated with A. mellifera encroachment. The net effect of these processes in the Molopo and Makoba sites is to increase the bush cover, but also to retain a grass cover and seed resource, that enables continued livestock utilization. However, degradation concerns remain due to evidence elsewhere in the Kalahari (e.g. Skarpe, 1990; Adams, 1996; Twyman et al., 2001) that when A. mellifera occurs in dense thickets the palatable grasses may no longer be accessible to livestock. It is these ecological changes that reduce the overall fodder diversity that represent a process of land degradation.

ACKNOWLEDGEMENTS

Research in Botswana was conducted with the Republic of Botswana Research Permit No. OP46/1XCVI(87). Funding was provided by the Royal Geographical Society (HSBC Holdings Grant), Royal Society (Dudley Stamp Memorial Fund), Manchester Geographical Society and the Universities of Leeds, Sheffield and Salford.

Field assistance provided by Kate Berry, Jenny Byrne, George Davies, Liz Metcalfe, Ed Sherratt, Nigel Trodd and Eleanor van der Linde is gratefully acknowledged.

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