



Degradation and recovery processes in arid grazing lands of central Australia. Part 1: soil and land resources

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Abstract

The distribution and quality of soil and land resources in heterogeneous grazing lands of central Australia were changed by grazing. Sites located at increasing distances from livestock watering points showed greater degrees of landscape organization and soil productive potential. The depositional strata, where resources tended to accumulate, occupied a larger proportion of the landscape as distance increased. Physical and nutrient cycling soil properties improved. All soil chemistry variables except pH and electrical conductivity increased and the trend was most apparent in the top 1 cm of the soil. Increasing erosion closer to water was a key degrading process. We showed degradation to be a systematic decline in regulation of scarce resources, which had implications for potential productivity.

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1. Introduction

Degradation of arid grazing lands is commonly described in terms of loss of palatable perennial plants, invasion of undesirable plant species and soil erosion (US Department of Agriculture, Soil Conservation Service, 1976; Golley, 1977). While

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this level of interpretation may often be a sufficient basis for management action to remedy the situation, in some cases it is not. Detection and remedy of degradation is particularly problematic in environments that are highly variable in space and time. For example, Australia's arid and semi-arid grazing lands have rainfall regimes that are low, but more importantly also unusually variable and unpredictable (Pickup and Stafford Smith, 1993). In these landscapes, soil nutrient concentrations are generally very low but patchy (Charley and Cowling, 1968; Noble and Tongway, 1986, pp. 217–242). Establishment and persistence of perennial plants and opportunities for plant invasions are strongly controlled by climate/landscape interactions, and by redistribution of soil, water and organic matter in the landscape. As a result, the impact of grazing is not readily separable from natural environmental variation (Bastin et al., 1993).

It has been proposed on theoretical grounds that concentration of scarce resources, particularly water, in patches rather than distributed evenly leads to higher production per unit area in undegraded arid and semi-arid ecosystems (Noy-Meir, 1973). Patchy distributions tend to occur on crusted soils where effective rainfall infiltration rates are low and runoff is high (Williams, 1983, pp. 507–530; Valentin et al., 1999), rather than on coarse sands, fine cracking clay or rocky soils where high effective infiltration allows evenly spread perennial plants. Groved mulga (*Acacia aneura*) shrublands, for example, occur on crusted clay-loams and are characterized by clearly defined topographic features called runoff and runon zones (Mabbutt and Fanning, 1987; Tongway and Ludwig, 1990, 1994). Water, soil and litter flow in sheets from the runoff slopes where infiltration rates are low, and are deposited in runon zones, which consequently have a greatly enhanced capacity to support perennial plant communities (Slatyer, 1961, pp. 15–26; Greene, 1992). The resources needed for long-term maintenance of these communities are thus locally sufficient in concentration and duration, and in concurrence in space and time (i.e. coupled: water and nutrients are available together). Any attempts to understand degradation and plan remedial action must incorporate these concepts and processes.

Each landscape type is likely to have characteristic modes or mechanisms by which scarce resources are regulated (Ludwig and Tongway, 1995). If this proposition is true, then degradation of any landscape can be defined in terms of a change in the manner in which scarce resources are redistributed in space and time. Tongway and Hindley (1995) proposed that a combination of terrain and vegetation properties that can be discerned in the field are indicators of the mechanisms involved, and these can be used to define whether the function of any particular landscape has changed in any way. The change may take a number of forms: the mode and scale of the redistribution system, or the efficiency of resource depletion/accumulation processes.

In arid central Australia, landscapes dominated by calcareous soils are important for commercial livestock grazing. In these landscapes, grasslands and shrublands occur widely as a mixture at catchment scale. The shrublands characteristically support perennial chenopod shrubs (e.g. *Maireana astrotricha*) and a forage layer of short-lived species, and they occur on shallow sands over calcareous red earths (Sparrow et al., 1997). The shrubs appear to act as resource traps, since they occur

on soil mounds, whereas the short-lived species grow in the inter-shrub zones when conditions are favourable. There is good evidence that, in an undegraded state, chenopod shrubs and their associated soil mounds operate in a similar way to the mulga groves in accumulating and regulating resources (Tongway, 1991, pp. 166–168). In their present state, the soil mounds appear to have lost their integrity to some extent at least. While soil still gathers under the shrubs, the landscape is also patterned into depositional strata, often bands of sandy material, alternating with runoff slopes on a scale of tens to hundreds of metres. We understand that grazing combined with years of drought and associated high winds generated this banded pattern (J. Stanes, pers. comm., 5 December 1990, describing our study area in a severe drought during the 1950s and 1960s). These patterns are now a characteristic feature and the bands are likely to function even more like mulga groves in controlling resource flows.

Extensive areas of these mixed calcareous landscapes in central Australia such as the Ebenezer Land System (Perry, 1962) appear to have lost a relatively large amount of their productive potential as a consequence of cattle grazing and the activities of feral European rabbits (Bastin et al., 1993). Remotely sensed assessments of vegetation cover across Ebenezer and related land systems detected cattle grazing impacts out to at least 10 km from watering points (Bastin et al., 1993). Impacts were indicated by a reduced cover response after substantial rains, compared to lightly grazed areas. Ground-level studies around a number of watering points in these mixed landscapes also detected vegetation change along gradients of grazing (Friedel, 1997). In this case, the number of species present was greatly reduced at heavily grazed sites and vegetation composition was less stable. Heavily grazed sites appeared to be unable to revert to their former state following conservative management, although vegetation composition stabilized, suggesting that the community had crossed some threshold into a new stable state. Neither study examined the processes that might lead to exceeding thresholds of change, nor the interventions required when change is not readily reversible.

In this study, we examine a number of sites in the Ebenezer land system which have experienced degradation to a greater or lesser extent, and describe how the basic functioning (i.e. the way in which scarce resources are regulated) has altered since the landscape became banded. We will use the term ‘geomorphic strata’ for the terrain features that occur at the patch scale in this land system. Our hypothesis is that ‘grazing alters the proportions and properties of geomorphic strata in the landscape’. This is the first of three papers: Part 2 (Friedel et al., 2003) looks at the effect of landscape degradation on vegetation and Part 3 (Sparrow et al., 2003) integrates the overall findings to provide a landscape-scale perspective of deterioration and potential for rehabilitation.

2. Study sites

The study sites were located on Eriklunda Station (25°13'S, 133°11'E), about 200 km SSW of Alice Springs, on gently undulating calcareous plains. The climate is

arid, averaging 200 mm rainfall annually, but with high intra- and inter-annual variation and any month can be rainless (Slatyer, 1962, pp. 109–128; Kalma and McAlpine, 1983, pp. 46–69). Summer rainfall averages 60% of the total. The natural vegetation is comprised of scattered shrubs/low trees (*Acacia kempeana* and *A. tetragonophylla*) over short grasses and forbs and bluebush (*Maireana astrotricha*). Authorities for all species names are from Albrecht et al. (1997, 1999), and are listed in Appendix 1 of Friedel et al. (2003).

The property is grazed by cattle. Until the first fencing was established in the locality in 1945, cattle roamed freely and stocking rates were thus not fixed in any location (J. Stanes, pers. comm., 5 December 1990). The dam which is the main focus of this study was established in 1954 (S. Stanes, pers. comm., 10 November 1993) within a paddock of 336 km², and grazing animals could still roam widely. Consequently, an exact statement of stocking rate cannot be given for the specific study area but the estimates provided by recent owners for the whole paddock indicate that the long-term stocking rate was relatively high by current standards. The dam was the focus of grazing for the majority of the time, especially during drought, because it did not run dry (J. Stanes, pers. comm., 5 December 1990).

Four sites were selected, varying principally in their distance from watering points as a surrogate for intensity of livestock use (e.g. Fusco et al., 1995) as follows:

Site 1. 0.3 km from permanent water (dam).

Site 2. 4.5 km from permanent water (dam).

Site 3. 5.7 km from permanent water, but rested from grazing for 10 years prior to this study by excision from paddock (dam).

Site 4. 8.6 km from permanent water (bore and trough).

The fourth site was located just across the 1945 fenceline in a less heavily grazed paddock.

The sites were matched as closely as possible on the basis of landform, soil and plant community, as a sub-unit of Ebenezer Land System (Perry, 1962). A.D. Sparrow (unpublished data) had investigated soil features in a comparable area in the early 1990s. He was able to separate the influence of undulating terrain from grazing, and found several trends with distance from water. These included increased soil crust stability and lichen cover, higher available phosphorus and organic matter, and lower rainfall infiltration rates. As a result, we were confident that, by selecting sites on the basis of land system sub-unit characteristics, we could separate long-term grazing effects from environmental differences.

Soils were sandy clay loams in the upper 10–20 cm, overlying light clays, with horizons differing only in small changes in thickness. Nodular calcium carbonate was distributed at differing depths in the horizons (R. Grant, Pers. Comm April 1991). Soil surfaces were overlain to varying extents with aeolian sand or alluvium, or were stripped and smooth, creating patterns of geomorphic strata within each site (Table 1), but otherwise soils were broadly comparable across the sites.

Each site was defined by a transect aligned with the maximum slope, up to about 300 m long, and marked with a permanent benchmark at each end. Slopes were

Table 1
Geomorphic strata occurring on study sites

Name	Code	Description	Geomorphic function	Sites where found
Colluvium	C	Thin sandy colluvial sheets on the downslope edge of sandy bands were common close to water, and were assumed to be erosional aprons derived from sheet-wash from the bands in energetic surface flows. Texture: sand.	Erosional	1, 2, 4
Depositional zone	D	Depositional fan, comprised of currently stable alluvium eroded from higher in the local catchment, and deposited in a mid-slope position. Texture: clayey sand.	Depositional	3
Hummocks	H	Zones where sandy hummocks were numerous, in association with bluebush (<i>Maireana astrotricha</i>). These were associated with transects at intermediate distance from water, and were regarded as evidence of contemporary local sand mobilization and capture. Texture: sand.	Depositional	2, 3
Runoff slope	R	Smooth, inclined planes sometimes with a stony strew. Texture: clay loam.	Erosional	1, 2, 3, 4
Sandy band	S	Roughly linear shape, aligned on the contour. At Site 4, there was a slight depression on the upslope side of the sandy band, implying that the band/depression complex was a runon zone. This upslope depression was not in evidence on sites closer to water. Texture: loamy sand.	Depositional	1, 2, 4

generally about 2% but could be steeper locally. The transect was subdivided into geomorphic strata, using the techniques described in McDonald et al. (1990). The strata were named according to soil textural and runon/runoff criteria. Five different strata were observed in total, although only four or fewer were observed at any one site (Tables 1 and 2). The actual length of the transect was adjusted so that at least two sequences of the banded landscape pattern were encompassed.

3. Methods

Two data sets were collected by stratified random sampling within geomorphic strata along the four transects, on different dates. The data sets were initially assumed independent, but they turned out to be complementary.

Table 2

Proportion (percent) of geomorphic strata (a) on measured transects, (b) on 1 km² areas surrounding each transect, as assessed from 1:50,000 colour aerial photographs, and (c) percentages of depositional and erosional landforms derived from (a). Composite sandy band in (b) incorporates sandy band, colluvium, hummocks and depositional strata distinguished in (a)

Stratum	Site 1	Site 2	Site 3	Site 4
(a)				
Colluvium	36	3	n/a	9
Depositional zone	n/a	n/a	23	n/a
Hummocks	n/a	10	26	n/a
Runoff slope	51	72	51	47
Sandy band	13	15	n/a	44
(b)				
Runoff slope	68	64	59	38
Composite sandy band	32	36	41	62
(c)				
Total percentage of erosional landforms	87	75	51	56
Total percentage of depositional landforms	13	25	49	44

'n/a' = stratum not present.

3.1. Soil chemistry and biological activity

Soil samples were taken at random in pentuplicate in each of the geomorphic strata at depth intervals of 0–1, 1–3, 3–5 and 5–10 cm, and were returned to the laboratory for chemical analyses. Samples were not bulked and all replicates were analysed. Colluvium at Site 2 was very minor and was omitted from all analyses. The laboratory procedures were as follows: organic carbon by acid dichromate oxidation and autoanalysis using sucrose standards (Colwell, 1969); total organic nitrogen by a modified Kjeldahl procedure (Twine and Williams, 1967); potentially available (mineralizable) nitrogen by estimation of ammonium released by treating the soil with 2 M KCl for 14 h at 100°C, after having estimated pre-existing mineral nitrogen (Gianello and Bremner, 1986); available phosphorus was extracted with 0.5 M sodium hydrogen carbonate and determined by autoanalysis (Colwell, 1965); cation exchange properties were determined after equilibration with 0.01 M silver thiourea (Chhabra et al., 1975); electrical conductivity and pH were determined on aqueous extracts at 1:5 ratio with appropriate electrodes (Loveday, 1974). Soil microbial respiration was measured at Sites 1–3 only, at the same transect locations as the sampling for chemical analysis—the equipment for measuring soil respiration was not available for Site 4. An 'inverted box' technique was used in which evolved carbon dioxide was collected in M KOH solution (Hartigan, 1980), the quantity being determined by electrical conductivity (Wollum and Gomez, 1970). The period of carbon dioxide collection was about 24 h, but recorded accurately. All locations measured experienced the same temperature conditions.

3.2. Soil surface condition and hydrological features

Soil surface condition features were recorded according to the method of Tongway and Smith (1989) in 1 m² quadrats at five randomly selected locations within each stratum at each site. The features were: (i) crust stability, assessed by a field version of Emerson (1967), (ii) cryptogam (percent cover), (iii) maximum microtopographic depression depth (mm), (iv) maximum microtopographic hummock height (mm), (v) sheet eroded surface (percent cover), (vi) lag stone (percent cover), and (vii) surface wash material (percent cover).

At the same locations, water infiltration rates were measured using a disk permeameter in saturated flow mode according to the method of Perroux and White (1988), with the steady-state rate corrected for lateral flows and the estimated vertical rate expressed in mm h⁻¹. Dry soil water content (prior to the infiltration trial, and in the absence of any significant rain over the preceding 4 months) and saturated soil water content (immediately after the infiltration trial) were assessed for the top 10 cm of the soil by time domain reflectometry (Topp and Davis, 1985; Reeves and Smith, 1992) using a modified soil probe of the type described by Zegelin et al. (1989) and a Tektronics 1502B Cable Tester attached to a laptop computer for data downloading.

3.3. Landscape organization

The distribution of geomorphic strata encountered on our linear transects was not necessarily representative of that over the larger areas that encompassed our sites, and at the broader paddock-scale. Colour aerial photography was used to estimate the proportions of geomorphic strata in the wider landscape. For each site, a 1 km × 1 km area centred on each transect was classified according to geomorphic stratum and areas of each stratum were tallied. Photo-based classification was according to soil and vegetation colour and texture, ground-truthed against the transect itself. Not all geomorphic strata apparent on the ground could be identified sufficiently reliably, and thus the final classification was simplified to 'composite sandy band' and 'runoff slope'.

4. Data analysis

The effects of geomorphic stratum, site and their interaction on each of the measured soil variables in both data sets were tested for significance using analysis of variance (ANOVA) using generalized linear modelling (GLM: see Dobson, 1983) approaches in the software package S-PLUS Version 4.5 (MathSoft Inc., Seattle). All measured variables were tested for assumptions of ANOVA, especially homogeneity of variance, and transformed (square-root or log_e) where necessary to fulfil assumptions.

Soil chemical variables, except for microbial respiration, were analysed using three-factor ANOVA, with soil depth, geomorphic stratum and site as the predictor effects. The model was tested as a split-plot design, with stratum and site tested at the

plot level with pentuplicate sampling points within strata as replicates, and depth tested at the subplot level with depth subsamples as replicates. All two- and three-way interactions were tested. Since not all combinations of geomorphic stratum and site were observed, the analysis design was unbalanced and thus the order of effects in the GLMs was critical. Given that the key aim of the research was to examine site-dependent effects in the landscape, site and its interactions were added to the GLMs after stratum, thereby making the tests of site and its interactions as conservative as possible (i.e. minimizing the likelihood of falsification of the respective site-based null hypotheses). Thus any site effects detected must have been at least as significant as indicated by the probabilities on the ANOVA output. Microbial respiration, all soil surface variables and all hydrological variables were tested with simple two-factor ANOVAs; stratum, site and their interaction were the predictors, and were added to the model in that order. Note that because of the similarity of the ANOVA structures for microbial respiration and soil surface variables, microbial respiration will hereafter be treated as a soil surface variable.

For the soil chemical variables, interactions of stratum with depth and site with depth were examined by interaction plots. For the site-depth interaction plots, the response was corrected for the effects of stratum (the third factor) in order to minimize confounding of stratum and site effects in the unbalanced design. For all variables (chemical, surface and hydrological), the unbalanced design constrained examination of the effects of the interaction of site and stratum to a table of means and standard deviations.

To reduce the many, sometimes collinear, soil variables to two principal axes that represent the essential trends in soil characteristics, standardized principal component analysis (PCA) was employed using the software package S-PLUS Version 4.5 (MathSoft Inc., Seattle). Geomorphic stratum and site effects were examined by separately plotting strata and sites within strata against the two axes.

5. Results

5.1. Landscape organization

The proportion of erosional geomorphic strata declined with increasing distance from water, with a concomitant increase in depositional strata (Table 2b and c). While there is a small increase between Sites 3 and 4 in the proportion of erosional surfaces on the transects (Table 2c), we assume that the value at Site 4 is an overstatement for the wider landscape, in view of the estimate for the proportion of runoff slopes over a large area (Table 2b). The available data do not permit statistical analysis of this trend.

5.2. Soil chemistry

The soils of the Ebenezer land system showed a strong and statistically significant overall trend in all measured chemical characteristics, except pH, with respect to

geomorphic strata (Table 3). Depositional zones had higher concentrations of organic carbon, organic and potentially available nitrogen and available phosphorus, notably near the soil surface (Fig. 1a, c, e and g). Sandy bands and colluvium had the lowest concentrations, and runoff slopes and hummocks had low to intermediate concentrations. Cation exchange capacity was high on runoff slopes and depositional zones, but low in sandy bands and hummocks (Fig. 1i).

Site was a significant effect for potentially available nitrogen, available phosphorus and pH (Table 3). The effect was marginally insignificant for organic carbon ($p = 0.087$). All variables in the surface 1 cm layer increased from Sites 1 to 4, i.e. with increasing distance from water—except for pH and electrical conductivity, which declined with distance from water (Fig. 1). Some soil variables showed approximately regular (almost linear) trends with respect to distance from water. For example, organic carbon and cation exchange capacity, especially in the surface 1 cm, showed a gradual increase from site to site in order from water (Fig. 1d and j). However, other variables would be better described as step functions. For example, potentially available nitrogen concentrations were very similar at Sites 1 and 2, thereafter increasing out to Site 4 (Fig. 1f) and pH showed a comparable, but inverted, trend (Fig. 1n). In addition, available phosphorus increased from Site 1 to Site 2, Site 3 was then similar to Site 2, and there was another increase from Site 3 to Site 4 (Fig. 1h).

The stratum by site interaction term was significant at $p < 0.001$ in the model for pH (Table 3). Because of the unbalanced design of the ANOVA models (i.e. each site had a unique combination of strata), it is difficult to interpret this dependence on stratum of between-site differences and vice versa. The relative pH of sandy bands and runoff slopes changed from Sites 1 to 4 (Table 4). At Site 1, the pH was higher on sandy bands than on runoff slopes; at Site 2, the pH is the same; and at Site 4, the pH is lower on sandy bands than on runoff slopes. The three other strata were observed at too few sites to be able to comment meaningfully on comparative trends.

All chemical variables were significantly different with respect to depth, except electrical conductivity, which was marginally insignificant ($p = 0.054$, Table 3). The concentrations of variables that can be considered as resources with a biological origin (organic carbon and nitrogen, and potentially available nitrogen) generally had high values in the surface 1 cm layer and then declined steeply with depth, in the manner of a negative exponential function (Fig. 1a, c and e). The non-biological resource variables (cation exchange capacity, electrical conductivity and pH) all increased with depth (Fig. 1i, k and m). Available phosphorus fell between these broad classes; it had higher values in the upper 3–5 cm and then declined more nearly linearly with depth (Fig. 1g).

There was a significant stratum by depth interaction for organic carbon, organic nitrogen, available phosphorus and cation exchange capacity (Table 3). This interaction describes the differences between the geomorphic strata in the rate at which the resource concentration declines with depth. On depositional zones the decline was steeply exponential or approaching linear, while colluvium showed

Table 3

Summary of generalized linear models for soil chemistry variables; details of model effects can be found in the Data Analysis section

Effect	df	Organic carbon	Organic nitrogen	Potentially available nitrogen	Available phosphorus	Cation exchange capacity	Electrical conductivity	pH
Transformation		sqrt	sqrt	sqrt	log	none	log	none
Stratum	3	0.0017	0.0045	0.0242	0.0027	0.0001	0.0494	0.1576
Site	4	<i>0.0869</i>	0.5282	0.0429	0.0020	0.5344	0.4483	0.0001
Stratum:site	4	<i>0.0612</i>	0.1002	0.3359	0.7987	<i>0.0570</i>	0.6131	0.0008
Plot level error	12	—	—	—	—	—	—	—
Depth	3	0.0000	0.0000	0.0000	0.0000	0.0000	<i>0.0537</i>	0.0000
Stratum:depth	12	0.0000	0.0003	0.5186	0.0000	0.0032	0.9838	0.7732
Site:depth	9	0.0000	0.0000	0.4364	0.4215	0.0045	0.7761	0.0000
Stratum:site:depth	12	0.2644	0.8059	0.4479	0.0018	0.0115	0.8292	0.2143
Subplot level error	162	—	—	—	—	—	—	—

Tabulated values are probabilities for model effects and those significant at $p < 0.05$ are highlighted in bold. Those that are marginally insignificant are italicised. All log transformations use natural logs.

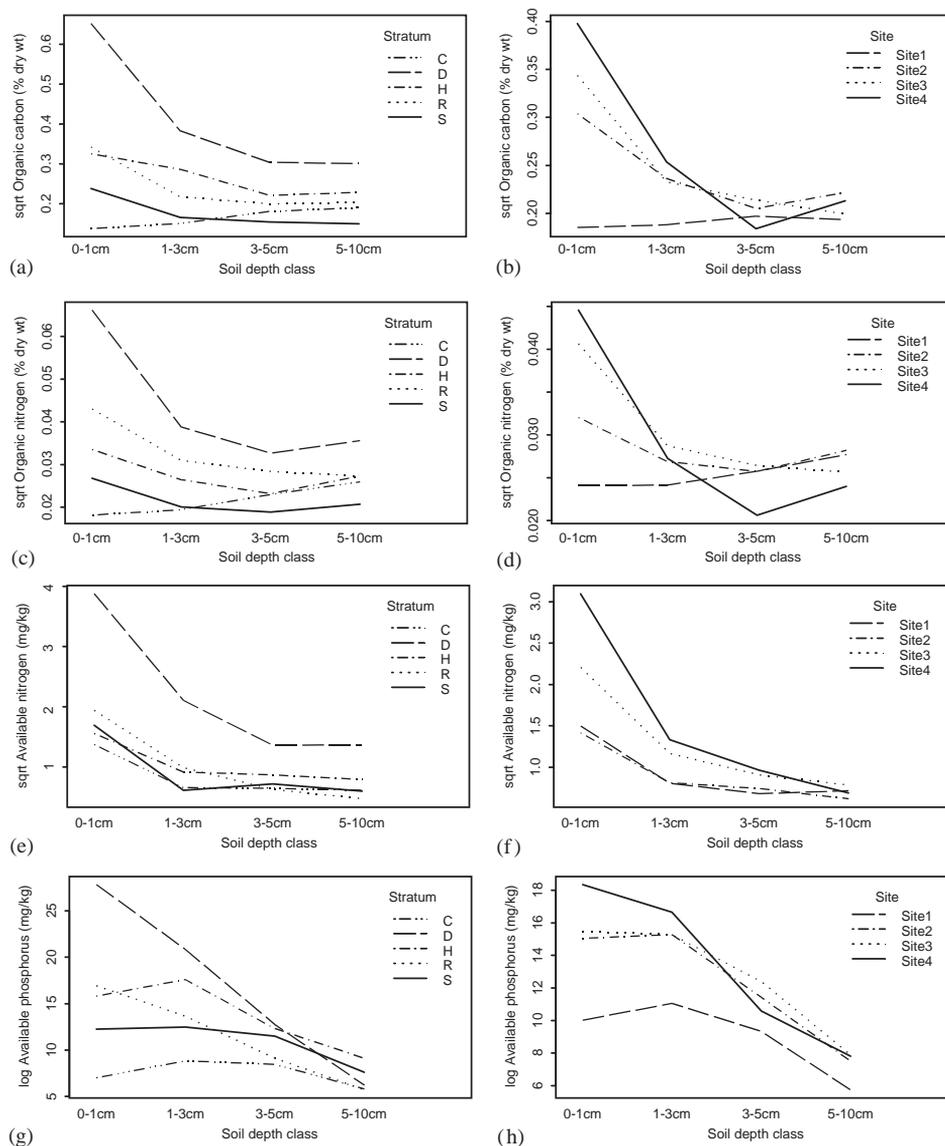


Fig. 1. Interaction plots of the responses of soil chemistry variables to geomorphic stratum by depth (left-hand subplots) and site by depth (right-hand subplots); see Table 1 for letter codes identifying strata. For the geomorphic stratum by depth subplots, curves show the mean depth profile for the response variable for each of the geomorphic strata. For the site by depth subplots, curves show the mean depth profiles corrected for stratum differences in the unbalanced design for each of the sites (see Data Analysis for rationale). Plotted values are means of transformed data; all log transformations use natural logs.

almost no trends with respect to depth and other strata showed intermediate trends (Fig. 1a, c and g). For cation exchange capacity, depositional zones and runoff slopes had higher values that gradually increased down the soil profile, sandy bands

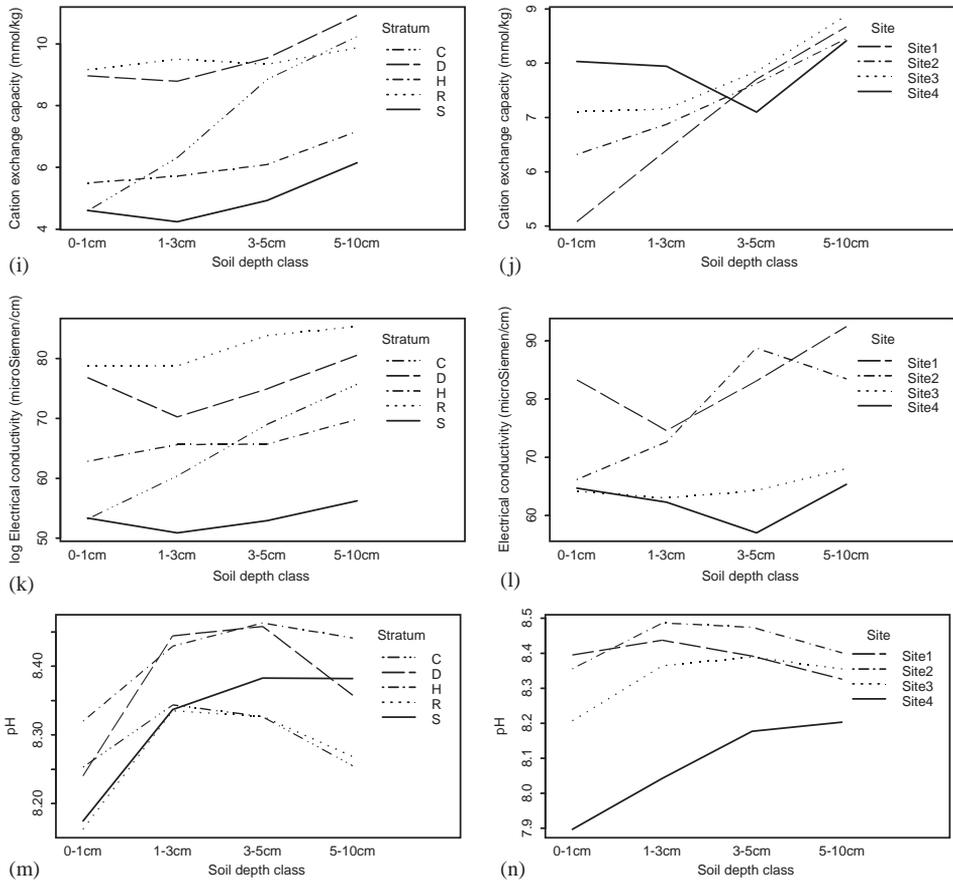


Fig. 1 (continued).

Table 4
Summary of the interaction between stratum and site for pH

Stratum	Site 1	Site 2	Site 3	Site 4
Colluvium	8.31 ± 0.14	n/a	n/a	8.26 ± 0.15
Depositional zone	n/a	n/a	8.38 ± 0.12	n/a
Hummocks	n/a	8.43 ± 0.10	8.39 ± 0.12	n/a
Runoff slope	8.26 ± 0.09	8.45 ± 0.09	8.31 ± 0.11	8.12 ± 0.31
Sandy band	8.51 ± 0.07	8.55 ± 0.20	n/a	7.70 ± 0.33

Values are means ± standard deviations. n/a indicates stratum-site combinations not observed in the field.

and hummocks had lower values which gradually increased down the profile, and colluvium showed a mid-depth transitional behaviour down the profile where the thin surface sandy layer gave way to the loamy soil underneath (Fig. 1i).

Organic carbon, organic nitrogen, cation exchange capacity and pH were significantly affected by the site by depth interaction (Table 3), a term which indicates that the shape of the response of each variable down the depth profile depends on site. In the case of organic carbon, organic nitrogen and pH, Site 4 (furthest from water) showed a strong trend down the soil profile, while Site 1 (close to water) showed little trend or even a weak inverse trend relative to Site 4 (Fig. 1b, f and n). The opposite was true for cation exchange capacity, where the trend down the soil profile was weak at Site 4, but strong at Site 1 (Fig. 1j). Consequently, between-site differences were most apparent in the surface 1 cm layer. For both potentially available nitrogen and pH, the depth profile of Site 2 was similar to that of Site 1, while the profile of Site 3 lay between those of Site 1 and Site 4. For organic carbon and cation exchange capacity, Sites 2 and 3 both showed intermediate profiles.

Two three-way interactions were significant—available phosphorus and cation exchange capacity.

5.3. Biological activity, soil surface condition and hydrological features

Geomorphic stratum had a highly significant effect on all soil variables in this group, except for saturated soil water content (Table 5). Microbial respiration rates were highest in the depositional zone, lowest on runoff slopes, and intermediate on sandy bands, hummocks and colluvium (Fig. 2a). Depositional areas also had the most highly developed microtopography, in terms of both depressions and hummocks (Fig. 2g and i). Runoff slopes had the most stable soil crusts and the highest cover of cryptogams (Fig. 2c and e), high soil water content when dry and

Table 5

Summary of generalized linear models for biological activity, soil surface condition and hydrological features; details of model effects can be found in the Data Analysis section

Effect	Transformation	Stratum	Site	Stratum:site	Residual
Df		4	2	2	34/36
Microbial respiration	None	0.0001	0.2021	0.8049	
Crust stability	None	0.0000	0.0000	0.0053	
Cryptogam cover	Log	0.0000	0.0000	0.0007	
Microtopography depressions	Log	0.0000	0.0191	0.0709	
Microtopography hummocks	Log	0.0001	0.1261	0.0032	
Sheet erosion cover	None	0.0000	0.0000	0.0001	
Stone cover	Log	0.0000	0.0388	0.0750	
Washed material cover	None	0.0000	0.0006	0.0643	
Dry soil water content	None	0.0000	0.0000	0.0821	
Saturated soil water content	None	0.1986	0.0034	0.0187	
Infiltration rate	Log	0.0000	0.0003	0.1545	

Tabulated values are probabilities for model effects and those significant at $p < 0.05$ are highlighted in bold. Note that residual degrees of freedom are 36 for all models except that for microbial respiration, for which there were two missing values. All log transformations use natural logs.

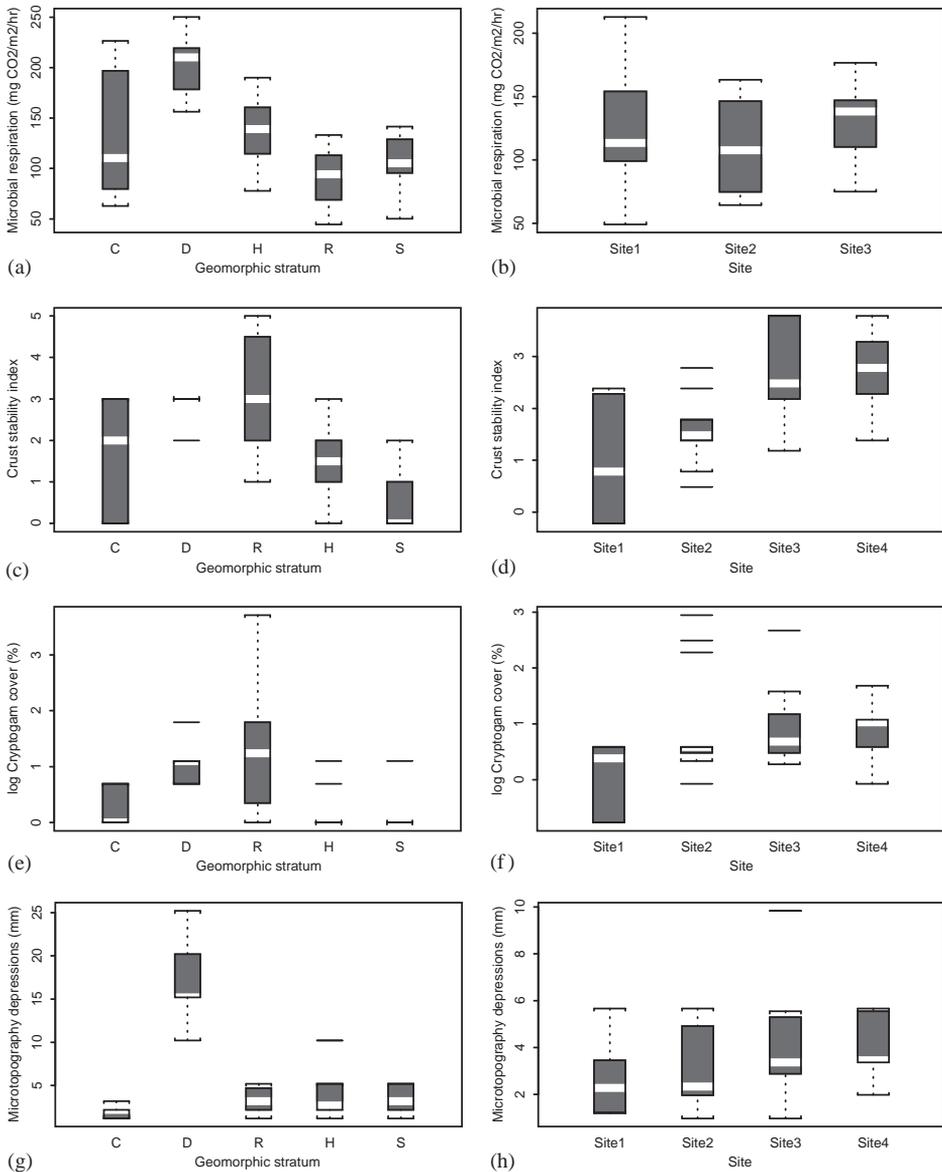


Fig. 2. Boxplots of the responses of biological activity, soil surface condition and hydrological features to geomorphic stratum and site; see Table 1 for letter codes identifying strata. For the site plots, the boxes show the response corrected for stratum differences in the unbalanced design (see Data Analysis for rationale). For crust stability index, 5 = most stable. All log transformations use natural logs.

low water infiltration rates (Fig. 2q and u), the greatest evidence of sheet erosion and high cover of stones (Fig. 2k and m). Sandy bands and hummocks showed the opposite characteristics—unstable soil crusts, low water content when dry, high

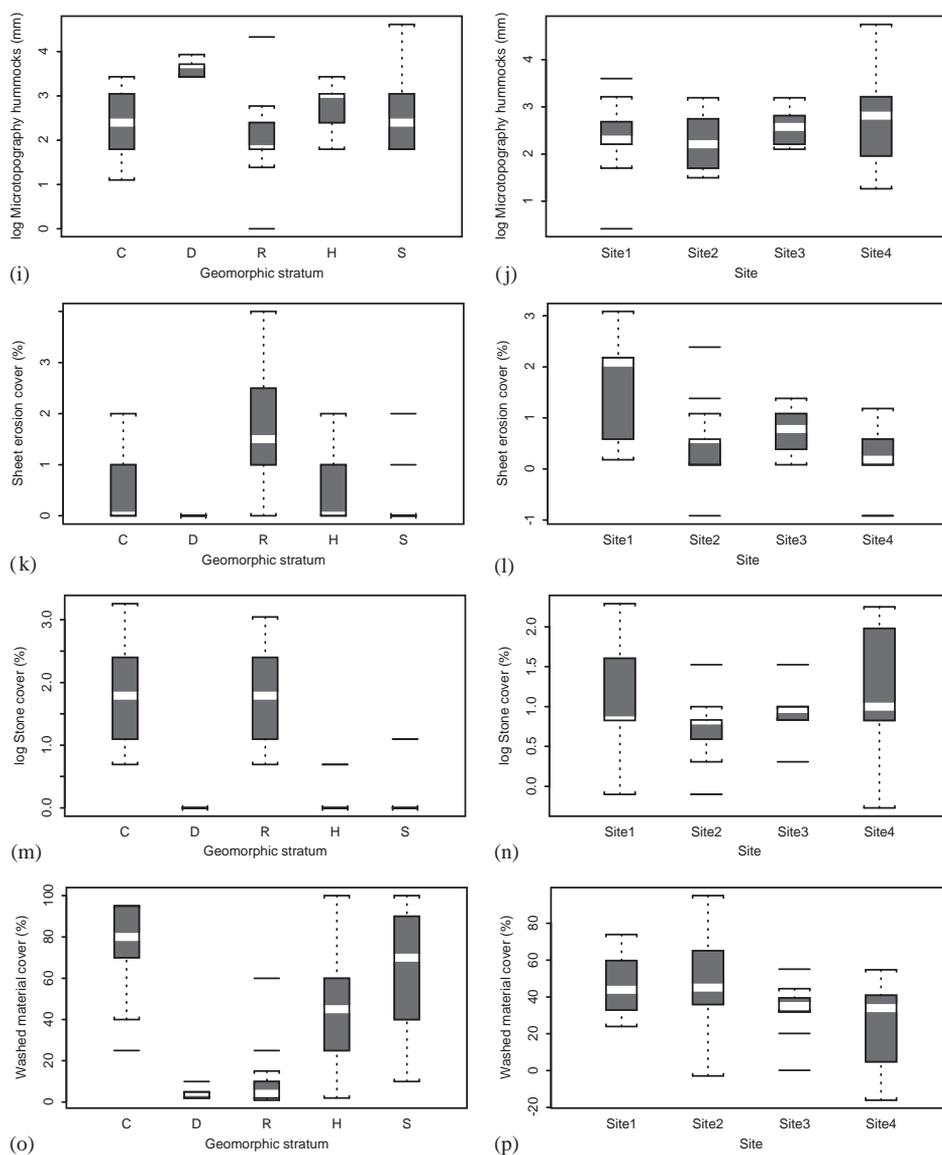


Fig. 2 (continued).

infiltration rates, little evidence of sheet erosion and few stones. These soil surface characteristics generally formed a strongly correlated set (Table 6), that is, increasingly fine-textured (loamier) soils with higher water-holding capacity had increasingly stable crusts, lower infiltration rates and more evidence of surface erosion. Colluvium showed intermediate characteristics, generally closer to sandy bands than erosion slopes.

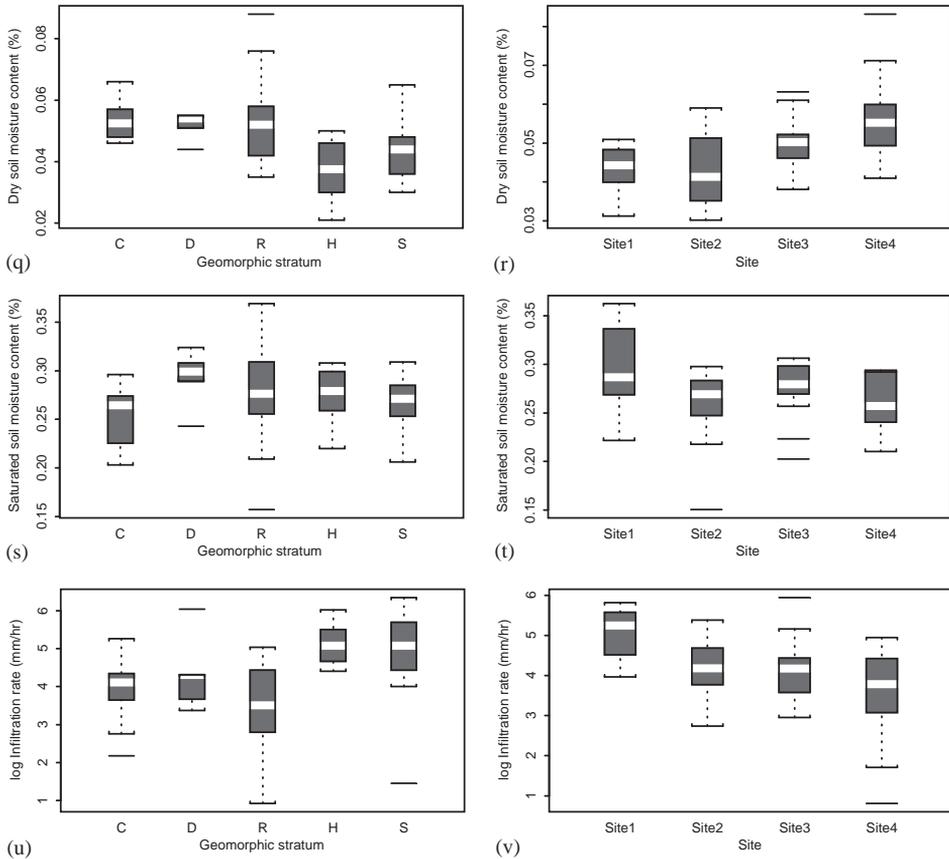


Fig. 2 (continued).

Site did not have a significant effect on microbial respiration, but had a significant effect on nine out of ten surface characteristics (Table 5). Five variables showed a monotonic increase with distance from water: crust stability, cryptogam cover, microtopography depressions, cover of stones (only very weakly) and dry soil water content (Fig. 2d, f, h, n and r). Sheet erosion, washed material, saturated soil water content and infiltration rate all decreased close to monotonically with distance from water (Fig. 2l, p, t and v). These two groups of variables correspond somewhat with the two poles of the cross-correlated set of surface characteristics (Table 6), although here the correlations are shown to be robust between sites within strata, as well as between strata as per the description above.

The stratum by site interaction term was significant for five surface characteristics (Table 5). As with the soil chemistry data, the nature of this interaction is difficult to assess in the unbalanced design. For crust stability (Appendix), runoff slopes showed increasing values from Sites 1 to 3, and then a decline to Site 4, while sandy bands showed a slight decrease from Sites 1 to 2, and a larger increase to Site 4.

Table 6
Correlations amongst soil surface condition and hydrological features

	Crust stability	Cryptogam cover	Microtopography depressions	Microtopography hummocks	Sheet erosion cover	Stone cover	Washed material cover	Dry soil water content	Saturated soil water content
Cryptogam cover	0.715								
Microtopography depressions	0.267	0.239							
Microtopography hummocks	−0.043	−0.023	0.480						
Sheet erosion cover	0.203	0.016	− 0.344	− 0.395					
Stone cover	0.467	0.312	− 0.287	− 0.427	0.407				
Washed material cover	− 0.669	− 0.551	− 0.374	−0.024	− 0.432	− 0.300			
Dry soil water content	0.493	0.301	0.082	−0.010	0.018	0.557	− 0.313		
Saturated soil water content	−0.063	−0.038	0.015	− 0.210	0.383	−0.018	− 0.297	−0.073	
Infiltration rate	− 0.656	− 0.537	−0.013	−0.051	− 0.148	− 0.497	0.374	− 0.658	0.429

Values significant at $P < 0.05$ are highlighted in bold.

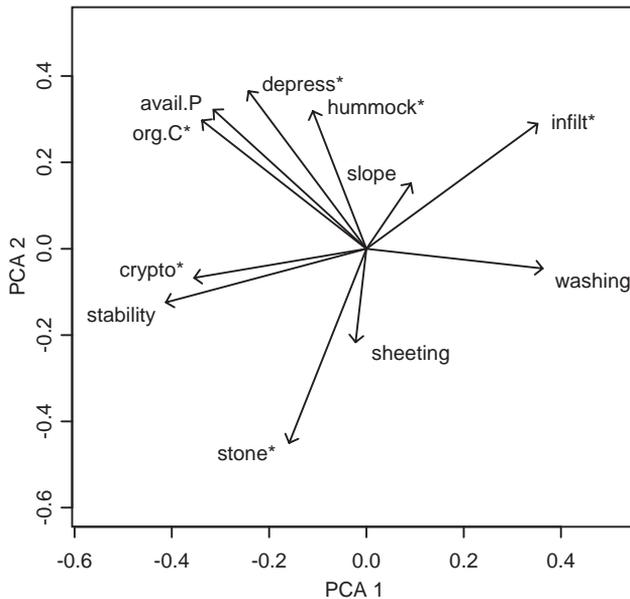


Fig. 3. Scatterplot of the first two axes of the PCA of soil variables. Variance accounted for by axis 1 = 32.9% and by axis 2 = 22.6%. Asterisks indicate that variables were \log_e -transformed prior to analysis. Key to variables: depress = microtopography depressions; avail. P = available phosphorus; org. C = organic carbon; hummocks = microtopography hummocks; infiltr = water infiltration rate; slope = percent slope; crypto = cryptogam cover; washing = washed material cover; stability = crust stability; sheeting = sheet erosion cover; stone = stone cover.

PCA axis 1 described a gradient from soil with high nutrient levels (organic carbon and available phosphorus) and a stable, cryptogam-encrusted surface to soil with high infiltration rate (sandy texture) and a tendency for washing of surface material (Fig. 3, left to right). PCA axis 2 described a gradient from high nutrient, high infiltration soils with high microtopography to soil with a more crusted surface and experiencing surface erosion as evidenced by surface sheeting, exposed stone and washed materials (Fig. 3, top to bottom). The soils of the five geomorphic strata were well discriminated along both PCA axes (Fig. 4a), but site effects within individual strata were only evident as shifts with respect to PCA axis 1 (i.e. with decreasing grazing, soils shift leftwards towards increasing soil surface stability and nutrient levels, and decreasing infiltration) (Fig. 4b–d). Runoff slopes (Fig. 4c) showed a greater shift along PCA axis 1 than either colluvium or sandy bands (Fig. 4b and d).

6. Discussion

We recognize at the outset that the study design does not include replication of sites, but argue that true replication is not possible over the large distances

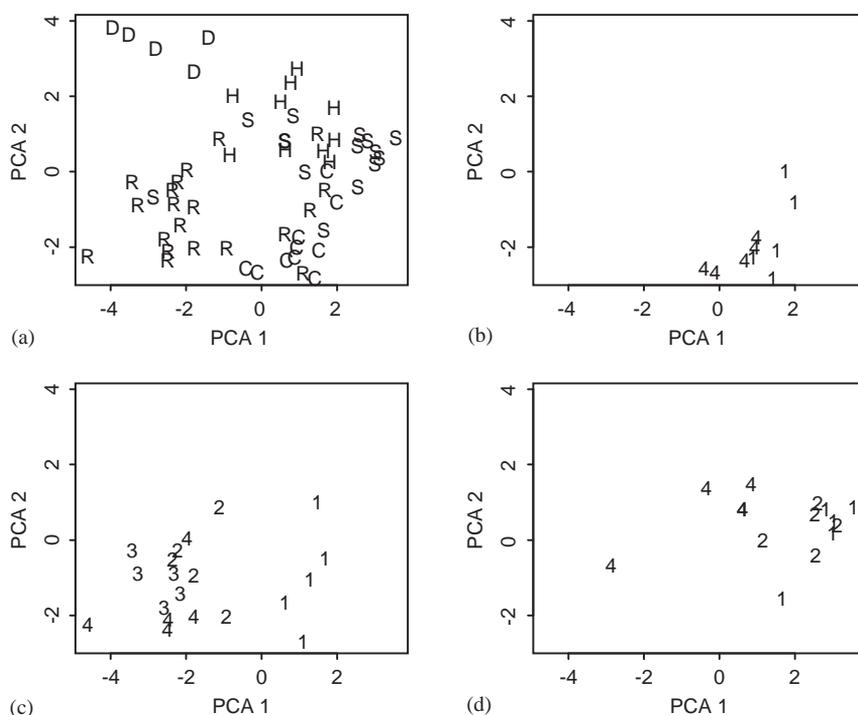


Fig. 4. Annotated PCA of soil variables to illustrate geomorphic stratum and site effects, showing: (a) geomorphic strata effect across all sites; (b) site effect within colluvium; (c) site effect within runoff slopes; (d) site effect within sandy bands. Key to strata in (a) are as per Fig. 2; numbers in (b)–(d) represent sites.

characteristic of central Australia. By selecting sites on the basis of land system sub-unit characteristics, including soil horizons, as described in Study sites, we are confident that we can extrapolate our findings over the larger grazing gradient under study wherever the sub-unit characteristics match. Taking specific quantitative predictions beyond that would be unwise in the heterogeneous landscapes of the region, but the general principles will still apply.

The basic hypothesis, that grazing alters the proportions and properties of geomorphic strata, is supported by the data. Distance to water clearly influenced the organization and status of geomorphic strata and the soil properties that reflected biological activity, stability and potential productivity. The proportion of depositional strata in the landscape was found to increase with increasing distance from water (Table 2), indicating that cattle grazing had affected the nature and abundance of geomorphic strata and hence landscape function, especially at sites closer to water, by causing greater mobilization and possibly loss of resources. Further from water, the landscape was more resource-conserving (*sensu* Ludwig and Tongway, 1997, pp. 1–12).

6.1. Soil chemistry

Where soils were least disturbed (Fig. 1), the nutrient profiles were typical for the arid zone, with pronounced surface accumulation of biologically mediated elements, such as nitrogen and carbon, and exponential attenuation with depth (Charley and Cowling, 1968; Tongway and Ludwig, 1990). This reflects the concentration of biological/microbial activity at the surface, due to fine root growth and death, litter fall and decomposition processes.

The profile of available phosphorus (Fig. 1) was intrinsically more complex than those for the 'biological' nutrient variables. Carbon, nitrogen and phosphorus are all involved in plant uptake and decomposition cycles but, unlike carbon and nitrogen, phosphorus has no source extrinsic to the soil, and it is involved in complex immobilization reactions with calcium carbonate in the soil (Kuo and Lotse, 1972; Murrmann and Peech, 1968, 1969). The bicarbonate extraction method used here accesses both the phosphorus associated with surficial organic residues and some which is loosely bound to carbonates occurring deeper in the profile. The pH 8.5 extractant used will not extract phosphorus bound to calcium carbonate, so that increased phosphorus at depth was not attributable to increased calcium carbonate with depth.

The pH and cation exchange capacity profiles are mainly due to increasing amounts of calcium carbonate with depth or the exposure of subsoils at the surface by erosion, as indicated particularly by values for the 0–1 cm layer.

Site differences for all chemical attributes were most apparent at the 0–1 cm soil depth (Fig. 1), which is consistent with normal processes of accumulation in this horizon in functional landscapes and also with the consequences of loss by erosion of the top soil layer (Ludwig and Tongway, 1995). Biologically derived resources such as organic nitrogen and organic carbon showed greatest site differences at the surface, whereas there was no significant site by depth interaction for available phosphorus (Table 3). Two opposing processes were likely to be at work on our set of sites. Depositional geomorphic strata support most perennial vegetation, which tends to retain, augment and cycle organic chemicals, whilst maintaining a soil fabric that permits leaching of soluble salts into the subsoil (Tongway and Ludwig, 1990). When this soil and vegetation complex is disturbed to the extent that plant activity is sporadic, as with systems dominated by annual plants, and the soil is mobilized, carbon and nitrogen are readily removed by wind or water and their depth profile becomes truncated. Available phosphorus, on the other hand, is not so markedly different if the top 1 cm of soil is lost because its complex chemistry means it is more likely to be retained on clays at depth.

6.2. Cryptogam cover and hydrology

Cryptogam cover was inversely related to infiltration rate (Table 6). Infiltration measured as saturated flow with a disc permeameter was much greater on bare, dispersive surfaces than on cryptogam-encrusted surfaces, suggesting that cryptogam cover inhibits infiltration. Our results may or may not accurately reflect infiltration

of rainfall. Firstly, Greene (1993, pp. 79–80) compared infiltration rates measured by disk permeameter and rainfall simulator and found that the former method overestimated the infiltration rate on bare soils. He attributed this to the formation of a physical seal on bare soils during rainfall, whereas cryptogam-crusts soils maintain their structure under rain (Mucher et al., 1988). Secondly, the intensity of the rain needs to exceed the infiltration capacity of the soil in order to have a realized effect. Many rainfall events in the arid zone are low intensity (Parkinson, 1986). Thus, we expect that the 10-fold difference in infiltration rates amongst our sites (Fig. 2v) might somewhat overestimate the differences under real rainfall. However, we still believe that infiltration rates are markedly higher on bare dispersive surfaces than on surfaces with a well developed cryptogamic crust. This is consistent with Eldridge et al. (2000), for patterned landscapes in the Negev, Israel.

The role of cryptogams in landscape function extends beyond an effect on rainfall infiltration. Cryptogam cover was found to be strongly related to crust stability (Table 6). Cryptogamic crusts stabilize soil against erosion as has been well documented elsewhere (Bailey et al., 1973; West, 1990; Belnap and Gardner, 1993; Eldridge, 1993; Eldridge and Greene, 1994), and they are also active in organic nutrient cycling and the mineral nutrition of vascular plants (Skujins and Klubek, 1978, pp. 543–552; Belnap and Harper, 1995). The net effect of a cryptogamic crust will be complex, and will include the positive effects of stabilization and nutrient conservation and the negative effect on water infiltration.

Dry soil water content was highest at our Site 4 (Fig. 2 and Table 5), implying that this landscape was able to retain water more effectively than the other sites. This finding is in keeping with the presence of a stable geomorphic structure and with higher proportions of clay remaining in the surface layers overall (D.J. Tongway, pers. obs.). The pool size of nutrients at Site 4 relative to other sites is also consistent with a functionally effective landscape and implies a more conservative use of resources.

6.3. *Integrating soil and land resources*

Noy-Meir (1973) argued that, in arid environments, maximum productivity occurs when resources are patchily distributed. A logical extension of this argument is that maximum productivity should occur when the spatial patterns of non-substitutable resources coincide, for example, water and nutrients are spatially coupled. Since organic carbon and available phosphorus were also assessed at our soil surface condition and hydrology sites (soil chemical data not previously presented), they can be cross-correlated with infiltration rate to test for coupling. Crossplots of infiltration rate and organic carbon or available phosphorus were similar and only the former is presented (Fig. 5). If water and nutrients were coupled, we would expect to see a positive correlation between and within strata. There was no correlation either between or within strata; instead each stratum had a broad spread of water and nutrient combinations along one or other axis. It could be argued that high values of both water and nutrients in the depositional zone are indicative of local coupling. The depositional zone is the most likely place for

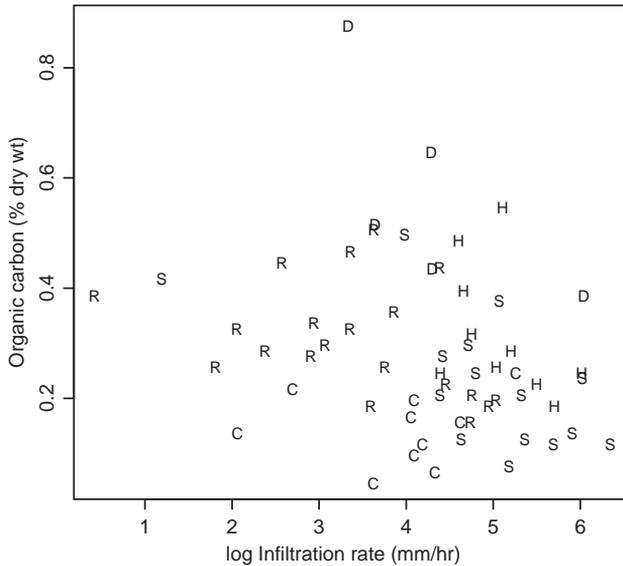


Fig. 5. Crossplot of organic carbon and infiltration rate and strata by site, for all geomorphic strata; see Table 1 for letter codes identifying strata. Infiltration rate is log_e-transformed.

coupling of water and nutrients to be maintained, as geomorphic and biological processes favour high levels of both. The lack of evidence of coupling elsewhere (see also Figs. 3 and 4) probably reflects a change in the balance of soil crust effects on infiltration, surface stabilization and nutrients, as discussed above, due to grazing.

Our data reflect the complexities of function in disturbed landscapes not at equilibrium. Resources were being stripped from some locations in the landscape, but the efficiency of their recapture and accumulation nearby varied with distance from water and, by implication, with grazing-induced stress and disturbance. Rates of mobilization, transport and interception are critical to the capture or loss of resources, but we do not have dynamic data available to us. Once sandy bands or encrusted runoff slopes are subject to physical breakdown, differential transport of sand, silt and clay particles leads to complex patterns on slopes. Water and nutrients become decoupled. New surface types form but they lack soil cohesion and are meta-stable in the sense of Pickup (1985). For example, colluvial deposits were comprised of a spill of sand derived from a sandy band, washed clean of fine particles and organic matter, and highly vulnerable to further mobilization. Depositional zones were also only meta-stable despite their mix of deposited topsoil, macro-organic matter and seeds, and a high potential for plant growth.

In summary, how does the regulation of scarce resources change as degradation proceeds? We surmise that, initially, the sandy bands (a probable product of earlier

degradation) are relatively stable and form a relatively large proportion of the geomorphic strata. They, plus the shrubs which grow on them (Friedel et al., 2003), provide fairly stable traps for any material which blows or washes over the area. Well-developed microtopographic depressions also trap mobile resources. As a result, water and nutrients move relatively short distances before they are recaptured. The colluvial apron below each sandy band is small, indicating that water washes only a limited amount of sand out of the bands over time. The cryptogamic crust is relatively intact and provides stability to the erosional surfaces between the sandy bands. It also contributes to and helps to retain plant nutrients, which are concentrated in the top 1 cm of the soil. While the cryptogamic crust inhibits water infiltration to some degree, the soil retains moisture under dry conditions.

As this system degrades, the sandy bands break down and sand is mobilized. The erosional surfaces expand and the cryptogamic crust deteriorates. Resources 'leak' (Ludwig et al., 2002) more readily from one banded element to the next. At an intermediate stage, material mobilized by wind can be locally trapped in hummocks, whereas water-washed material can be retained in meta-stable depressions and colluvium. Further degradation remobilizes this material and it may be lost from the system entirely because physical barriers to movement are scarce. With the breakdown of the cryptogamic crust, biologically based nutrients like carbon and nitrogen decline disproportionately because of their concentration in the topmost 1 cm of the soil. Since phosphorus occurs at greater depths, its loss is less severe. On the other hand, water infiltration is enhanced, so that nutrients and water become increasingly decoupled from one another.

This paper has examined soil- and landscape-related properties in a grazed landscape. The data strongly support the notion that grazing has caused the degradation of sites close to livestock watering points by changing the proportions and properties of geomorphic strata. In Friedel et al. (2003) we will consider the implications for vegetation and thresholds of change and in Sparrow et al. (2003) we will review the landscape-scale outcomes and prospects for recovery.

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Appendix

Summary of the interaction between stratum and site for crust stability

Stratum	Site 1	Site 2	Site 3	Site 4
Colluvium	0.8 ± 1.1	n/a	n/a	2.6 ± 0.6
Depositional zone	n/a	n/a	2.8 ± 0.5	n/a
Hummocks	n/a	0.8 ± 0.5	2.2 ± 0.5	n/a
Runoff slope	1.2 ± 0.5	3.0 ± 0.7	4.8 ± 0.5	3.8 ± 0.8
Sandy band	0.4 ± 0.6	0.2 ± 0.5	n/a	1.2 ± 0.8

Values are means ± standard deviations (as stability scores). 'n/a' indicates stratum-site combinations not observed in the field.

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