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Ecogeomorphological processes within grasslands, shrublands and badlands in the semi-arid Karoo, South Africa

Short title: Ecogeomorphological processes in the semi-arid Karoo, South Africa

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Abstract

Vegetation type and cover play an important role in the operation of geomorphological processes by controlling runoff and sediment dynamics. In drylands, land degradation is particularly sensitive to these eco-geomorphic interactions. Whilst many geomorphological studies of land degradation focus on the change in hydrological response as a function of vegetation cover, few have investigated how the autogenic response of plants may influence the susceptibility of soil to erosion through a change of soil resources. This study investigates the hypothesis that shrub communities possess greater soil parameter heterogeneity compared to grasslands, and assesses how these different scales of heterogeneity can influence the susceptibility of soil to erosion.

Soil samples were taken from seven 60m x 60m plots within grasslands, shrublands and badlands situated in the Sneeuberg uplands of the central Karoo. 108 samples per plot were analysed for bulk density, organic matter, pH, conductivity and available sodium, calcium, magnesium, potassium and phosphorus. Geostatistical analyses determined that the grassland landscape was largely homogenous in its distribution of soil parameters whereas shrublands demonstrated an increase in heterogeneity. Periodicity in the semi-variograms indicated that regular patterns across the landscape were evident for all parameters and thus likely to represent the differences between shrub and intershrub regions, areas of high and low erodibility. More pronounced patterns were identified in the badlands. This indicates that, if the conditions are right, changes in plant-soil interactions caused by soil parameter redistribution in shrubland landscapes can exacerbate erosion, leading to further degradation in the form of badlands.

Key words: soil heterogeneity; land degradation; geostatistics; Karoo; South Africa; badlands

Introduction

Vegetation is commonly identified as a significant controlling mechanism of land degradation in sensitive, semi-arid environments (Abrahams *et al*., 1995; Snelder and Bryan, 1995; Parsons *et al.*, 1996; Doudill *et al*., 1998; Blomqvist *et al*., 2000; Wainwright *et al*., 2000; Maestre and Cortina, 2002; Thornes, 2005). In reality, the system is one of mutual interdependence, where vegetation dynamics influence geomorphic processes and vice versa (Thornes, 1985). Despite the more recent emergence of ‘ecogeomorphologists’, which acknowledge this ecological and geomorphological connectivity (Abrahams *et al*., 1995; Prosser *et al*., 1995; Parsons *et al*., 1996; Schlesinger and Pilmanis, 1998; Havstad *et al*., 1999; Kosmas *et al*., 2000; Neave and Abrahams, 2002; Peters and Havstad, 2006; Dunkerley, 2010; Wainwright, 2009), land degradation debates continue to focus largely on the drivers of vegetation change (Peters and Havstad, 2006; Kong *et al*., 2010; Cowie *et al*., 2011) and its subsequent impact on hillslope/erosional processes (Abrahams *et al.*, 1995; Prosser *et al*., 1995; Parsons *et al*., 1996; Wainwright *et al*., 2000). With increasing pressure on the scientific community to prevent, or at least mitigate further land degradation in the drylands of the world, a more holistic approach is needed to understand the relationship between vegetation and geomorphic processes and their feedback mechanisms. Our current understanding of these feedback mechanisms declines with increasing spatial and temporal scale; further studies of fundamental plant-soil interactions, their dynamic patterns and processes and, crucially, the impact of scale are necessary to build our understanding of ecogeomorphological processes in the landscape.

Whilst the spatial patterns of plant-limiting nutrients in drylands are well documented (Charley and West, 1975; Hook *et al*., 1991; Tongway and Ludwig, 1994; Schlesinger *et al*., 1996; Schlesinger and Pilmanis, 1998), as are the effect of vegetation change on the physical properties and hydrological responses of soil (Abrahams *et al*., 1995; Parsons *et al*., 1996; Wainwright *et al*., 2000; Maestre and Cortina 2002) few have attempted to link them, and thus relate changing spatial patterns of soil properties to the susceptibility of soil to erosion. The aim of this study is to investigate the relationships that exist between vegetation type and erosion potential in the Karoo region of South Africa. The objectives of this study were to:

1) Identify the spatial patterns of physical and chemical properties of soil in grassland, shrubland and badland landscapes.
2) Assess the impact of the spatial patterns on the susceptibility of soil to erosion.
3) Determine the importance of scale of measurement on the spatial patterns attributed to a landscape.

The nature, extent and causes of vegetation change in the semi-arid Karoo region of South Africa are widely debated (e.g. Acocks, 1953; Dean *et al*., 1995; Hoffman *et al*., 1995; 1999; Milton and Dean, 2000; Meadows and Hoffman, 2002; Richardson *et al*., 2005). According to Acocks (1953), the predominantly perennial grasslands of the eastern Karoo experienced extensive shrub encroachment as a result of overstocking by European farmers. Acocks' (1953) 'expanding Karoo' hypothesis was widely accepted and influenced many land management policies (Meadows and Hoffman, 2002; Hoffman *et al*., 1995). However, growing contention surrounds the veracity of Acocks' (1953) model of land degradation. Hoffman *et al*. (1995) discuss the supporting and conflicting evidence for grassland degradation in the Eastern Karoo and whilst they found a general consensus that the region supported greater grassiness in the past, debate surrounds the point at which shrub encroachment was initiated. Hoffman *et al*. (1995) show that Acocks' (1953) model of vegetation change can also be challenged by evidence from a variety of sources, which show that periods of greater grassiness occurred concurrently with periods of above-average rainfall. This relationship has led to the development of an alternative model, proposed by Hoffman *et al*. (1990), Milton and Hoffman (1994) and Milton *et al*. (1994), that describes a system of alternate stable states of either grassland or shrublands in response to rainfall. The idea that grass and shrub cover fluctuates over time due to seasonal and short-term climatic variations is now widely recognised (Dean *et al*., 1995). Elsewhere, the notion of grassland and shrubland as alternate stable states has recognised that the switch between them conforms to catastrophic cusp behaviour (Turnbull *et al*., 2008), a fundamental characteristic of which is that the ecosystem exhibits hysteresis whereby the trajectory of change in one direction is different from that in the other (Turnbull *et al*., 2008, p27). A reason for this hysteretical behaviour is interplay of vegetation dynamics and geomorphic processes. If a change to the percentage of grass and shrub cover occurs as a result of a climatic variation, this change will result in a change to the geomorphic processes such that the land surface on which the former percentage of grass and shrubs no longer exists. Consequently, a return to the former climatic conditions does not imply that there can be a simple return to the former grass and shrub percentage. Indeed, quite the opposite is the case.

In order to understand the ecogeomorphic processes associated with different land cover types, we undertook an extensive sampling programme of soil physical and chemical properties at sites on Karoo grasslands, shrublands and badlands. The study employs an ergodic approach to testing the hypothesis that shrub encroachment in dryland environments initiates a change in scale of soil heterogeneity that consequently influences the landscape's biotic and abiotic interactions and potentially the susceptibility of soil to erosion. Under this approach, it is not necessary that the sites studied have undergone progressive change from grassland to shrubland (and badland), but the assumption is that such sites will exhibit *over space* the same differences as one site that was undergoing such progressive changes would exhibit *through time*. Using a hierarchical spatial framework, the distributions of soil properties in each of the three landscape types were investigated; comparisons of the spatial patterns were made to determine both the importance of scale, and whether badland development in shrublands show a continued and pronounced redistribution of soil parameters.

Field sites, materials and methods

The study site is located in the Sneeuberg uplands (31°40′–45′S and 24°32′–37′E), approximately 65km north of Graaff-Reinet (figure 1). The area feeds the upper catchment and headwaters of the Klein Seekoei River, a tributary of the Seekoei River, and drains in a northerly direction eventually supplying the Orange River. Due to the high altitude of the region, which varies from c. 1650m in the valleys to over 2000m on the peaks, the locality receives an annual rainfall of approximately 498mm (Boardman, pers. comm.). A summer rainfall regime characterises this area; approximately 70% of its annual rainfall is received between the months of October and March (Keay-Bright and Boardman, 2009).

Situated near the dynamic boundary of the Nama-Karoo and Grassland biomes, Acocks (1988) defines the vegetation of this area as False Upper Karoo in the valleys and *Karroid Merxmuellera* Mountain veld in the higher altitudes. In more recent studies, these vegetation types are classified as Eastern Mixed Nama Karoo (Hoffman, 1996), Southeastern Mountain Grassveld (Lubke *et al*., 1997) and Eastern Upper Karoo (Mucina and Rutherford, 2006), respectively. However, the descriptive accounts of veld types remain congruent with Acocks' definitions. The species composition of these vegetation communities is highly dependent on seasonal rainfall events. Grasses such as *Aristida spp., Eragrostis* spp. and *Themeda triandra* (Hoffman, 1996) respond to summer rainfall events with an increase in biomass, and can dominate the shrubby landscape typically characterised by species such as *Pentzia incana, Eriocephalus ericoides, E. spinescens and Hermannia spp.* (Hoffman, 1996). These episodic swathes of grass were largely absent from the study region during the research period. A more in-depth description of the vegetation composition of the Eastern Upper Karoo can be found in Mucina and Rutherford (2006).

Soils on the rocky hillslopes are shallow and discontinuous, overlaying horizontally bedded sandstones and shales of the Beaufort and Stormberg groups (Karoo supergroup). Colluvial material of varying depths is found on the footslopes, and topsoil is generally without a modern A horizon. Unconsolidated Quaternary sediments cover mudstones, shales and sandstones on the valley floors. Dolerite ridges characterise the landscape in areas of higher relief.

Fieldwork was undertaken in the Karoo in the early summer, during the months of November and December 2003, before the start of the summer rainfall regime. Seven topographically similar plot locations were identified, avoiding anthropogenically modified land such as recent burn sites, ploughed land (past and present) and areas that varied greatly in past grazing densities. The plots represented grassland, shrubland, mixed and badland landscapes; their locations, identification number and vegetation category are shown in figure 1. An in-depth description and discussion on the origin of the badlands in this area can be found in Boardman *et al.* (2003).

Due to the paucity of expanses of pure grassland in the vicinity of the study region, only one adequate grassland plot was identified. A mixed plot of grass and shrubs (where grass was dominant) was therefore included in the study. Because this vegetation state (with varying grass-shrub ratios) was commonly observed throughout the study region, it was decided that it would be beneficial to collect these data as an indication of the spatial patterns and processes of soil properties characteristic of a mixed grass and shrub community.

A nested sampling strategy, based on previous work by Müller (pers. comm., 2004), was devised to assist in the identification of patterns at different spatial scales in the landscape. 60m by 60m plots were constructed, with three hierarchical subdivisions (30m by 30m, 10m by 10m and 1.5m by 1.5m). In each of two of the 30m x 30m cells nine randomly generated coordinates were sampled for soil properties within a 0.15m support. Each of the two remaining 30m x 30m cells was subsequently divided into nine 10m x 10m cells. Four of these cells contained nine randomly generated coordinates where soil samples were taken within a 0.15m support. Within six of the 10m x 10m cells, a randomly generated coordinate was used as the origin point of a 1.5m x 1.5m quadrat; this was divided into nine 0.5m x 0.5m cells. The centroid of each of these cells was considered the sample point, therefore a systematic sampling regime was undertaken at this scale. Figure 2 shows a schematic diagram of a typical plot layout. As badlands generally form across footslopes, the plot layout was modified to maximise rill inclusion. These plots were 30m x 120m but the cell/sampling format was consistent with the other plots. In total, 108 samples were obtained from each plot. Where a sample location fell on areas that were impossible to sample, an additional randomly generated location was used.

Groundcover photographs, vegetation cover, average shrub and grass tussock diameter measurements, shear strength readings and bulk density samples were taken *in situ*, and a second soil sample was collected for further laboratory analyses. These analyses comprised the determination of organic matter content, pH, conductivity and available sodium, calcium, magnesium, potassium and phosphorus. Notably, available nitrogen was not included in this study, despite its role as a major plant-limiting nutrient. Many studies have already established the self-sustaining relationship between plants and available nitrogen in soil and its associated redistribution concurrent with shrub encroachment (e.g. Hook *et al*., 1991; Tongway and Ludwig, 1994; Schlesinger *et al*., 1996; Müller *et al*., 2008). The focus here is on the role soil chemistry plays on the swelling and dispersive behaviour of clay particles and hence the erodibility of the soil, rather than how the spatial 'availability' of nutrients limit the growth of vegetation.

Field and Laboratory Techniques

Shear Strength was measured on unsaturated soil using a Pilcon hand-held shear vane with a 33mm diameter. The vane was inserted to the depth of 50mm, the full length of the vane blades. The shear vane was then rotated at a speed equivalent of approximately 1 revolution per minute until the soil sheared. A direct measurement in kPa was taken from the vane. To avoid biased results involving the positioning of the vane, a method was employed that involved alternating the sampling site between adjacent samples at a set distance of 150mm either at a 0° or 180° angle from the sample origin. Where the ground was impenetrable, as occurred in some in badland locations, these points were assigned a maximum value.

Organic matter (OM) content of each soil sample was determined using the loss-on-ignition (LOI) method as described by Rowell (1994). The analysis was conducted on a thoroughly mixed sample derived from the top 8mm of soil at each sample location.

Soil moisture was calculated for every sample point from a sealed soil sample brought back from the field. The soil used to measure the moisture content was the same sample used to measure the soil bulk density. This measurement was taken from the top 80mm of soil. Soil moisture was calculated using the method described by Rowell (1994).

Dry bulk density samples were acquired using a guide plate, driving tool and $0.0001m^3$ cylinder. Care was taken to retain the natural structure of the soil by minimising the compaction and disturbance. The measurement was taken from the top 80mm of soil. To avoid biased results involving the positioning of the cylinder, the sampling site was alternated between adjacent samples at a set distance of 150mm either at 90° or 270° from the sample origin. Where the ground was impenetrable with the cylinder, as evident in a few cases at badland sites, these points were classified as 'no data'. In the laboratory, the dry bulk density was calculated using the method described by Rowell (1994).

Soil pH and *electrical conductivity* were measured in the laboratory using a Sartorius PP-25 bench-top pH/conductivity meter. Due to the large sample size and related time constraints it was decided that the procedure most appropriate to determine the pH was that of a 1:1 water to soil suspension. A minimum of a 30-second stabilisation time was adopted as suggested by Rowell (1994). Electrical conductivity was measured using a 1:2 water to soil ratio. To reduce potential error three measurements per sample were taken and the average calculated. A full description of these techniques can be found in Soil and Plant Analysis Council Inc 1999 (2000).

Nutrient analyses: 100g bulk samples were taken from approximately the top 80mm of soil at each sample location. In the laboratory each sample was air-dried, passed through a 2mm sieve, mixed well and a 10g sub-sample derived. The major cations; magnesium, calcium, potassium and sodium as well as phosphorus were extracted using the Mehlich No. 3 extraction method as described in the Soil Analysis Handbook of Reference Methods (Soil and Plant Analysis Council, Inc. 1999, 2000). The levels of nutrients were determined using an ICP-AES.

Statistical analyses

The means and coefficients of variation of all soil parameters were calculated for each plot to indicate the variability within the datasets.

Non-parametric statistical tests were used to compare datasets as normality could not be assumed. Mann-Whitney analysis was used to identify whether the parameter distributions varied among grassland, shrubland and badlands and to understand the importance of the spatial patterns of soil parameters in relation to erosion. The interconnected nature of the soil properties were analysed using the Spearman's Rank correlation coefficient test. Although cause and effect cannot be determined from correlation analysis, inferences about these relationships can be made on the basis of known soil interactions.

Geostatistical analyses

Geostatistical techniques were employed to quantify the spatial distribution of the soil parameters. Omni-directional semi-variograms were calculated using the multiple scales of data collected through the nested sampling strategy and were used to identify evidence of spatial autocorrelation. Before calculating the semi-variograms, the data were standardised by subtracting the mean and dividing by the standard deviation. If trends were identified, regression analysis was carried out and the residuals were used to calculate the semi-variograms (Webster and Oliver, 2001).

Experimental variograms were calculated for each parameter using the VARIOWIN software (Pannatier, 1996). These graphs plot half the average squared difference in value for every pair of data locations against the distance between the data pairs, also known as the lag interval. Our analysis extends to a lag of 30m, 50% of the maximum lag distance; intervals were chosen by calculating multiple experimental variograms for 0.5m, 1m, 2m, 3m, 4m, 4.5 m, 5m and 6m intervals and assessing which interval displayed the strongest spatial structure. Models were fitted to the experimental variograms using the manual fitting function in the VARIOWIN software (Pannatier, 1996). The most appropriate fit was chosen from Gaussian, spherical, exponential and linear models. Where the variance was random, nugget models were applied.

There are three main components to the semi-variogram, the sill, the range and the nugget value. If the data are randomly distributed, there will be little change in the semi-variance with increasing distance. If a pattern in the data exists, the semi-variogram will rise. The semi-variance value at which the curve levels off is known as the *sill* and the *range* is the lag value at which the semi-variogram reaches the sill value. The range is therefore the distance at which the samples become independent. The nugget value is the variance at zero lag distance, and represents a combination of the variance that exists at a finer scale than the sampled area and measurement error.

Results

Vegetation cover and average plant size

Vegetation cover was estimated for each plot, the results are shown in table 1. The badlands have the lowest percentage vegetation cover, varying from 14% to 26%, the shrublands vary considerably, with covers of 44% and 70%, and the grassland and mixed plot are consistent with 63% and 62% cover, respectively. The species composition was not measured as this study only focuses on the dominant vegetation type; however, the high percentage cover of plot 3 can be attributed to grass that grows amongst the shrubs.

The diameter of every shrub and grass tussock was measured in each of the six 1.5m x 1.5m quadrats and the mean diameter of the plant and its standard deviation were calculated. The mean shrub size is 0.45m (standard deviation: 0.28) and the mean grass tussock is 0.34m (standard deviation: 0.21). Note, only the diameters of identifiable grass tussocks were measured, not all grass species, for comparison with the mean shrub size.

Means and coefficients of variation

The mean and coefficient of variation (CV) of each soil variable from each of the three vegetation states are presented in table 2. Patterns of difference associated with the vegetation are evident; with the exception of shear strength and available calcium, variable means either increase or decrease consistently across the degradation gradient. Organic matter content, soil moisture, conductivity, available potassium and available phosphorus all decrease from grasslands to badlands, whereas bulk density, pH, available magnesium and available sodium all increase. These directional 'responses' indicate that the soil parameters undergo a 'step-wise' progression of change.

Bulk density, pH and organic matter content had the lowest CV values; these were consistently the lowest across the three vegetation states and nearly always <30%. The parameters with the highest CVs were not consistent across all three states; available sodium had the highest CVs in the grasslands and badlands (≥80%), whereas available calcium had the highest in the shrublands (77%). Shear strength and soil moisture had relatively high CVs in all three vegetation states, nearly always >55%. Notably, a higher CV for available phosphorus was found for the badlands compared to the two other vegetation states.

Mann-Whitney analyses

Mann-Whitney analyses are presented in table 3. At a 95% confidence level, organic matter, available calcium and available sodium showed no significant differences between the shrubland and badlands. Shear strength showed no significant differences between the grassland and badlands and available magnesium showed no significant differences between the grassland and shrubland. Significant differences between the vegetation states were found for all other parameter distributions.

Spearman's rank correlation coefficient

Table 4 presents the parameters that displayed strong correlations (greater than 0.5) for the grasslands and shrublands. There were no strong correlations in the badlands.

The results suggest that the physical properties of soil are largely controlled by organic matter, due to its iterative impact on the other properties. The strong negative correlation between organic matter content and bulk density and that between bulk density and water content highlight the importance of organic matter for soil quality and in this case, its susceptibility to erosion. No strong correlations with shear strength were evident and all correlations amongst the soil nutrients were positive.

Geostatistics

A summary of the geostatistical analyses is given in table 5. The results show that modelling spatial patterns of soil parameters quantitatively at a scale representative of a vegetation community is difficult; we are unable to satisfactorily model approximately one third of variables measured (depicted as 'na' in table 5). Consistently, periodicity was identified in these data, particularly in the badland plots. Where strong cyclic patterns are evident, no models are applied. Weaker periodicity is present in some datasets that have been fitted to a model, including the nugget model; we have identified all parameters that show evidence of periodicity by highlighting them in italics in table 5. Another interesting pattern that is not restricted to any one vegetation state is evident in the semi-variograms for organic matter, bulk density, conductivity, available potassium, magnesium and sodium. These semi-variograms display a decrease in variance with an increase in lag distance (depicted with an asterisk in table 5). According to Brunsdon (pers. comm.) this may suggest checkerboard patterning in the landscape.

Spatial autocorrelation is evident for a number of parameters, particularly among the physical properties in the grassland and shrubland plots, and to a lesser degree in the badlands. Of the two grassland plots, plot 2 has consistently higher ranges of spatial autocorrelation than plot 1. This can be explained by the slightly different nature of the two plots; plot 1, whilst being included in the grassland analyses, has a higher proportion of shrub cover within the plot (approx. 30%). The longer ranges of autocorrelation in plot 2 reflect the more uniform grass cover. With this in mind, in general organic matter, bulk density and soil moisture have shorter ranges of spatial autocorrelation in the shrublands. These results suggest that a redistribution of soil resources accompanies shrub invasion. Shear strength, in contrast, displays shorter ranges in the grasslands. This may be attributed to grassland 'patchiness', a common feature in semi-arid landscapes (Cerdà, 1997; Blomqvist *et al*., 2000); 'patches' can vary in size, from small mosaics to areas several metres across.

pH and available magnesium and phosphorus demonstrated shorter ranges in the shrubland plots compared to those found for the grassland plots, suggesting chemical parameter redistribution. Nevertheless some spatial autocorrelation is evident for the chemical properties in the grassland plots; however, the ranges all exceed 10m and the remaining parameters are largely represented by the nugget model and, therefore, can generally be described as exhibiting uniform distributions.

Complex spatial structures are evident for many of the badland soil parameters, as such 22 out of 33 parameters were not fitted to any of the models. Of the parameters where ranges of autocorrelation were calculated, only organic matter content and shear strength showed similar responses from at least two of the plots, the ranges of the other parameters vary significantly. The geostatistical results of the nutrient content of the three badland plots show a variety of spatial patterns and ranges of spatial autocorrelation. Only calcium and magnesium show some evidence of spatial autocorrelation and only magnesium demonstrates spatial autocorrelation in all three badland plots. Of the ranges derived for each of the two nutrients, no consistent results were evident. Although none of the other experimental variograms had models applied to them, periodicity is evident in the majority of the unmodelled variograms. Therefore this cyclic behaviour can be classed as a characteristic of badland landscapes. A decrease in variance with an increasing lag distance is displayed by some of the plots for organic matter content, bulk density, conductivity, available potassium and sodium suggesting that the distribution of these nutrients follow a checkerboard pattern.

Discussion

Grassland-shrubland transitions: patterns, periodicity and scale

It is evident from the semi-variograms that, at a scale representative of vegetation communities, the spatial structures of soil parameters are complex. Nevertheless, where levels of spatial autocorrelation were derived, the shrubland ranges were generally less than those from the grasslands. Organic matter, bulk density and available phosphorus, parameters that are directly linked to the presence/absence of vegetation, had either uniform distributions or longer ranges of autocorrelation in the grasslands and shorter ranges in the shrublands, which supports the idea that shrubland landscapes are more heterogeneous in nature than grasslands (Schlesinger *et al*., 1990; 1996; Tongway and Ludwig, 1994; Maestre and Cortina, 2002; Rietkerk *et al*., 2002). Over half the chemical properties of soil from the grasslands displayed a uniform pattern and those that were spatially autocorrelated had ranges greater than 10m. In these cases, local landscape variation, such as subtle changes in slope or soil type, may be responsible rather than the autocorrelation being directly related to vegetation. In the shrublands, only conductivity showed no evidence of any spatial patterns in either of the plots. All other parameters are either spatially autocorrelated or show evidence of periodicity, indicating some form of spatial pattern.

The results of the spatial analyses imply that scale of measurement is indeed a significant consideration when determining the spatial patterns of soil parameters. The ranges of spatial autocorrelation derived for the grassland parameters vary from 5.98m to 21.09m (a minimum range of 9.24m if we only take the values from plot 2, the 'pure' grassland plot) and, out of 22 semi-variograms, 9 suggest that no spatial patterns exist. These measurements were taken from a 60 x 60m plot and calculated using a maximum lag distance of 30m and a minimum scale of measurement of 0.5m. The results from this study suggest that, at a scale more representative of a grassland community, the spatial distribution of most soil parameters can be classed as being relatively homogenous. However, these results differ significantly from those presented by Schlesinger *et al*. (1996) who derived their results from 8 x 12m plots and calculated the semi-variograms using a maximum lag distance of 7m. A comparison of the ranges of autocorrelation of grassland and shrubland nutrients derived from this study and Schlesinger *et al*. (1996) is provided (see tables 6 and table 7, respectively). It is evident from these results that scale of measurement strongly influences the derived ranges of spatial autocorrelation in grassland environments and to a lesser degree, shrublands.

The impact of scale on the spatial patterns of soil parameters in shrubland landscapes presents itself through the presence of periodicity in the datasets. The study by Schlesinger *et al*. (1996) attributed the ranges of autocorrelation in essential plant nutrients to the mean shrub size indicating that biotic factors are responsible for the redistribution. In contrast, the ranges of autocorrelation in this study are more likely to be representative of the intershrub zones as even the minimum range (organic matter – 4.5m), is larger than the average shrubs in the study regions (approximately 0.45m in diameter). Upon inspection of the semi-variograms derived from shrublands in the study by Schlesinger *et al*. (1996), some evidence of the 'hole effect' is present in the datasets, where there is a decrease in variance followed by an increase towards the sill producing a 'hole' in the variogram (Webster and Oliver, 2001). This effect possibly indicates that periodicity would be present if the scale of measurement was increased.

Although there has been some debate over the interpretation of cyclic patterns in ecological datasets, a study by Radeloff *et al*. (2000) investigated the relationship between periodicity and landscape patches. A number of significant observations were made: i) periodic spatial patterns produced periodicity in correlograms; ii) the lag distances at which the correlograms peak correspond to the average distances between patch centres and iii) the strength of periodicity increases when the diameter of patches is equal to the distance between patch edges. These observations would suggest that where periodicity in the shrubland data is evident, there is regular variation in the parameter values across the landscape. Such periodicity is indicative of the differences between the soil parameters in shrub and intershrub zones.

Grasslands to badlands – a step-wise progression?

All parameters but shear strength and available calcium show a consistent change in mean content through the three vegetation types. This change would initially suggest that badland development is part of the progressive process of land degradation induced by vegetation change. Nevertheless, the characteristics of soil shear strength are very important in terms of the susceptibility of soil to erosion (Nearing *et al*., 1991; 1994; Parsons and Wainwright 2006). Although the highest mean shear strength value is found in the badlands, statistically, the grasslands have a similar variance. The reduction in mean shear strength from the grasslands to the shrublands implies that the structure of the soil in the shrublands is weaker than that of the grassland communities. According to research undertaken by Maestre and Cortina (2002), Gyssels and Poesen (2003), Gyssels *et al*. (2005) and de Baets *et al*. (2005), the reduction in near-surface root mass associated with shrub communities will increase the soil's susceptibility to erosion. However, these authors argue that only sheet and rill erosion are affected as deeper roots associated with shrubs can, in fact, provide resistance to gully erosion.

The higher shear strength values in badlands are a consequence of the lack of vegetation causing higher bulk densities, lower soil moisture and lower organic matter contents which combine to produce very compact soils. In this study, the shear strength values were measured in dry conditions. If the measurements had been taken under saturated conditions it is possible that the shear strength values of the badlands would be very different. This type of measurement would represent the conditions under which soil detachment occurs and therefore reflect more accurately the increased susceptibility of soil to erosion that can be expected to be seen in badland landscapes. The shrublands display a mean shear strength value that is significantly less than the other two communities. This suggests that a threshold value must exist that determines whether the presence or absence of vegetation is more significant in controlling the shear strength of soil. Despite the higher shear strength value in the badlands, it should also be noted that the coefficient of variation is also highest in this landscape. Such a result indicates that the variability of shear strength values is greater in the badlands, which is consistent with the work of Nearing *et al*., (1991) and Parsons and Wainwright (2006).

Despite the evidence of increased heterogeneity in shrublands compared to grasslands, and the consistent responses of the mean values of soil parameters across the vegetation states, no obvious relationships exist between the ranges for the shrublands and badlands. A comparison of the results from the three individual plots indicates that, in most cases, the responses seem to be site specific. However, over 80% of the badland semi-variograms display some evidence of periodicity. Although no characteristic relationships can be identified between the ranges of spatial autocorrelation from the shrublands and badlands, the significant increase in parameters displaying evidence of cyclic patterns in the badlands shows that progressive heterogeneity occurs concurrently with the development of these landscapes. A common wavelength of c. 8m is evident in approximately half of all soil parameters; we initially hypothesised that these patterns reflected the gullied nature of the landscape, representing the differences between gully floors and interfluve areas. However, subsequent measurements have since disproved this idea and further investigation of these findings is required.

How do the changing spatial patterns of soil properties influence the erodibility of the soil?

In comparison to the grasslands, the shrubland and badland landscapes both demonstrate an increase in spatial heterogeneity of organic matter, whether through measurable autocorrelation or evidence of periodicity in the data. Whilst Geddes and Dunkerley (1999) show that leaf litter and organic matter are redistributed throughout the shrubland landscape by rainsplash, our results suggest that this process does not redistribute the organic matter significantly and areas of high and low organic matter develop.

The relationships between organic matter and the other physical soil properties are significant for both the erodibility of soil and growing conditions for vegetation. The correlation analyses showed that organic matter has a negative relationship with bulk density, and bulk density has a negative relationship with water content. Higher organic matter and water content and lower bulk densities create more favourable growing conditions, not only for existing plants but also for the germination of seeds. These conditions have been found to occur under plant canopies (e.g. Schlesinger *et al*., 1996, Bochet *et al*., 1999). In contrast, areas low in organic matter will not only have weaker structures due to a decrease in particle binding agents but it will be affected by higher bulk densities resulting in poorer infiltration capabilities and thus making it more susceptible to runoff and erosion (e.g. Abrahams *et al*., 1995, Neave and Rayburg, 2007). These conditions are representative of the intershrub regions.

The absence of any significant correlations with shear strength in this case is surprising. Shear strength has a significant role in controlling soil stability (Bryan, 2000) and has proven links between soil moisture and bulk density (Zhang *et al*., 2001), which themselves are controlled by organic matter and vegetation cover (Oades, 1984).

Nevertheless, the highly complex nature of these interactions makes disaggregating the individual effects of the parameters on the erodibility of soil extremely difficult.

Positive correlations exist amongst the soil nutrients, thereby demonstrating the interconnected nature of both the plant-limiting nutrients (P, K, Mg) and the non-limiting nutrients (Ca and Na). However, the spatial patterns are the significant element when considering these relationships with respect to the erodibility of the soil. Although it is commonly thought that only the physical and biological properties of soil are significant in determining indices of erodibility, the soil chemistry also has a role (e.g. Mamedov *et al*., 2002; Faulkner *et al*., 2004). The calcium and sodium content of soil are important determining factors of the dispersive behaviour of the soil particles. Sodium is known to increase the dispersibility of clay particles whereas calcium is known to have the opposite effect. However, as the sodium and calcium contents did not display significant differences between the shrublands and badlands in the Karoo, nor did they display significant correlations with the clay content, neither can be identified as a possible cause of the increased erodibility that has led to the development of badlands.

The nutrients demonstrate an increase in spatial heterogeneity or periodicity from grassland to shrublands, suggesting that vegetation controls the redistribution. However, as no data are available on where the high and low values are in relation to vegetation it cannot be concluded that greater quantities of plant-limiting nutrients are under the shrubs and greater quantities of sodium and calcium are in the intershrub areas. Nevertheless, assumptions can made about the nature of the distributions as studies by Schlesinger *et al*. (1996), Bochet *et al*. (1999) and Titus *et al*. (2002) all suggest that vegetation regulates the cycling of biologically limiting nutrients whereas abiotic factors control the cycling of non-limiting nutrients. We propose that areas of preferential erosion are created as a consequence of the complex interactions between biotic and abiotic processes.

A conceptual model of landscape change

The results of this study contribute to a growing body of knowledge about ecogeomorphic processes in drylands. In the context of the debate about land degradation consequent upon grassland to shrubland transitions it provides insights into the mechanisms of landscape change. We have used these insights, in conjunction with the existing literature, to develop a conceptual model, figure 3, which summarises the processes, patterns and interactions that we consider significant in semi-arid land degradation.

This conceptual model suggests that two scenarios can occur following bush encroachment: 1. the cycle of plant - soil property interactions can continue in a relatively stable fashion; the spatial heterogeneity becomes more defined in the shrublands, but badlands do not develop. 2. the cycle of plant-soil interactions can continue until the extent of spatial heterogeneity is such that the conditions that inhibit plant growth are predominant in the landscape and badlands develop, as seen in the Karoo. However, the soil type and local conditions determine the areas that are sensitive to further degradation rather than the presumption that all intershrub areas will continue to degrade to this extent. The decrease in mean contents of organic matter and soil moisture and the increase in shear strength and bulk density seen in the Karoo badlands compared to the shrublands demonstrate how the soil properties are adversely affected by loss of vegetation. However, it is the soil type that determines whether a concrete-like crust develops. The crust itself creates a dense soil structure that will not only reduce the infiltration capability and increase surface runoff but also makes it difficult for plants to become re-established. These factors all contribute to the increase in erosion evident in badland landscapes.

Conclusions

This study shows that the spatial structures of both physical and chemical properties of soil are complex in semi-arid landscapes. At a scale that is representative of grassland communities, our results show that some soil parameters, particularly physical parameters, are spatially autocorrelated. These results reflect the 'patchy' nature of semi-arid grasslands. In the study region pure grasslands are rare, shrubs are often interspersed and bare patches are a common characteristic. The plot most representative of 'pure' grassland had ranges of spatial autocorrelation that were greater than the more mixed grassland plot suggesting that the spatial patterns of soil parameters are largely controlled by the structure of vegetation associated with it, even in grassland. Overall, soil parameters in grassland landscapes can be classed as having a relatively uniform distribution, reflecting the more homogeneous nature of grassland cover. Where spatial autocorrelation was detected, the ranges from the 'pure' plot nearly always exceeded 10m, suggesting abiotic factors are more likely to be the controlling mechanisms of these soil patterns.

The spatial patterns evident in the shrubland landscapes demonstrate that the self-perpetuating nature of semi-arid shrubs causes a redistribution of soil properties. In the cases where clear spatial autocorrelation was evident, both physical and chemical soil parameters demonstrated significantly smaller ranges of spatial autocorrelation than those derived from the grassland plots. As the ranges are greater than the mean diameters of the shrubs themselves, they are most likely to represent the intershrub areas in the landscape. Although a significant number of semi-variograms were best represented by pure nugget models, which under normal circumstances would indicate that no significant spatial patterns exist, periodicity was identified in the majority of the datasets. This pattern represents the variation of the shrub and intershrub zones across the landscape and is therefore a function of scale. The geostatistical results indicate that at a scale more representative of vegetation communities, fine-scale patterns may be insignificant. However, if the results of both this study and the work of Schlesinger *et al*. (1996), for example, are considered together, they demonstrate that the spatial patterns in semi-arid landscapes occur at multiple-scales.

The changing spatial patterns of soil parameters may be used to link vegetation change with the degradation of semi-arid landscapes. The soil with the most stable structure, demonstrated through the higher organic matter, lower bulk density and high shear strength, was found to be in the grasslands. The uniform plant cover and rootmats increase the stability of this environment, reflected in the relatively homogenous patterns of the soil parameters. The shrublands, in contrast, demonstrate a decrease in structural stability. Increased heterogeneity in plant cover, rootmats and thus organic matter are thought to significantly influence the structure of the soil. These factors act as a catalyst, inducing changes in other soil parameters. The spatial patterns demonstrate that there are areas of stronger soil structure adjacent to areas of poorer soil structure; these areas represent the shrub and inter-shrub areas, respectively. Low organic matter and high bulk densities characterise the inter-shrub areas, which result in poorer infiltration capabilities and an increase in susceptibility to the erosive power of overland flow.

In badland landscapes abiotic processes take over as the mechanisms of spatial reorganisation of soil parameters. The significance of the development of badlands in relation to vegetation change is therefore presented not through the spatial patterns themselves but through the differences in responses between the shrublands and badlands. Both the mean values and spatial patterns suggest that badland landscapes represent an extension of the redistribution of soil parameters seen in shrublands. This implies that if the correct conditions exist, shrubland landscapes can continue to degrade until the intershrub regions become the dominant landform; the landscape becomes inhospitable to plants and through various hydrological processes leads to conditions that propagate rills and gullies. Once the landscape has reached this level of degradation, natural re-vegetation and recovery of badlands would potentially take many decades, whereas short-term recovery would require significant intervention efforts. The results from this study suggest that further badland development in dryland environments could be reduced by improving land management practices and maintaining adequate vegetation cover in shrubland landscapes.

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Figure Underlines

Figure 1: Location of the research area within South Africa (A) and plot locations and type (B)

Figure 2: An example of the nested sampling strategy

Figure 3: Conceptual model of processes, patterns and interactions connecting vegetation change to the susceptibility of soil to erosion in semi-arid environments

Tables

Table 1: Vegetation cover (%) and the mean diameter (in metres) and standard deviation of shrubs and grass tussocks for both the total and individual plots († n=147, ††n=94).

Plot	**Plot type**	**Vegetation cover (%)**	**Mean diameter (metres) & St. Dev.**	
			Shrub	**Grass tussocks**
1	Mixed	62	0.44±0.28	0.52±0.23
2	Grassland	63	0.32±0.17	0.53±0.22
3	Shrubland	70	0.49±0.29	0.32±0.15
4	Badland	18	0.30±0.13	0.37±0.13
5	Shrubland	44	0.60±0.27	0.20±0.14
6	Badland	26	0.41±0.24	0.25±0.13
7	Badland	14	0.48±0.43	0.26±0.16
	Mean diameter (m)		0.45±0.28†	0.34±0.21††

Table 2: Means and coefficients of variation [(SD ÷ mean) x 100] of all the soil parameters from the combined grassland, shrubland and badlands plots([†] n=216, [††]n=215, [†††]n=214, badlands n= 322)

	Grassland		**Shrubland**		**Badlands**	
Soil Parameter	Mean	CoV	Mean	CoV	Mean	CoV
Organic matter (%)	3.42[†]	30.12	2.57[††]	28.02	2.44	18.44
Bulk density (g/cm3)	1.18[†]	17.8	1.24[††]	17.7	1.3	10.77
Soil moisture (%)	8.24[†]	55.1	3.01[††]	60.8	2.22	39.64
Shear strength (KPa)	24.53[†]	58.62	14.36[††]	56.62	26.97	70.71
pH	6.08[†]	8.06	6.27[††]	10.69	6.89	7.69
Conductivity (dS/m)	0.20[†]	36.25	0.15[††]	40	0.14	65.81
Avail. calcium (ppm of soil)	1818.7[†††]	49.06	2914[†]	76.97	2434.5	40.08
Avail. potassium (ppm of soil)	302.34[†††]	32.96	282.15[†]	42.64	199.71	39.67
Avail. magnesium (ppm of soil)	992.4[†††]	38.24	995.6[†]	41.21	2043.4	29.36
Avail. sodium (ppm of soil)	75.8[†††]	79.97	96.46[†]	33.95	103.63	92.38
Avail. phosphorus (ppm of soil)	38.52[†††]	36.68	31.65[†]	38.61	16.96	67.51

Table 3: Mann-Whitney results for differences between vegetation states (results, non-significant at the 0.05 level, are presented in bold).

Soil Parameter	**Grass & shrubs**	**Grass & badlands**	**Shrub & badlands**
Organic matter (%)	<0.005	<0.005	**0.3477**
Bulk density (g/cm^3)	0.0113	<0.005	0.002
Soil moisture (%)	<0.005	<0.005	0.001
Shear strength (KPa)	<0.005	**0.97**	<0.005
pH	0.0003	<0.005	<0.005
Conductivity (dS/m)	<0.005	<0.005	<0.005
Avail. calcium (ppm of soil)	0.0049	<0.005	**0.6686**
Avail. potassium (ppm of soil)	0.0102	<0.005	<0.005
Avail. magnesium (ppm of soil)	**0.5998**	<0.005	<0.005
Avail. sodium (ppm of soil)	<0.005	<0.005	**0.7375**
Avail. phosphorus (ppm of soil)	<0.005	<0.005	<0.005

Table 4: Parameters showing strong correlations (>0.5) from Spearman's Rank correlation coefficient analyses in the grasslands and shrublands

Soil Parameter Correlations		Grasslands	Shrublands
Organic matter	Bulk density	-0.626	-0.571
	pH	-0.516	*
	Conductivity	*	0.505
Bulk density	Conductivity	-0.546	*
	Water content	*	-0.642
Water content	Conductivity	0.533	*
	Magnesium	*	-0.522
	Calcium	*	-0.685
	pH	*	-0.632
pH	Magnesium	*	0.587
	Calcium	*	0.698
Calcium	Magnesium	0.76	0.766
	Sodium	0.546	*
	Potassium	0.551	*
Sodium	Potassium	0.502	*
Potassium	Magnesium	0.519	*
	Phosphorus	0.658	0.531

In all cases the p-value indicated that the correlation was different from zero.

Table 5: Ranges of spatial autocorrelation (in metres) derived from semi-variograms for all grassland, shrubland and badland plots in the Karoo.

	Grasslands		**Shrublands**		**Badlands**		
Soil parameter	Plot 1	Plot 2	Plot 3	Plot 5	Plot 4	Plot 6	Plot 7
Organic matter (%)	5.98	21.09	4.5*	*na*	*na**	7.2	*7.48*
Bulk density (g/cm3)	8.6	11.55	*na*	6.82	na*	*na*	*na**
Soil moisture (%)	16.17	19.47	6.6	15.84	na	*na*	*na*
Shear strength (KPa)	8.51	9.24	*Nugget*	Expo	16.62	Nugget	*14.03*
pH	*Nugget*	*Nugget*	15.54	5.89	*na*	*na*	na
Conductivity (dS/m)	Nugget	19.47	Nugget	Nugget	*na*	*na**	8.54
Av Ca (ppm of soil)	Nugget	10.5	*na*	Nugget	*na*	4.8	*27.45*
Av K (ppm of soil)	Nugget	Nugget	*na**	31.44	*na**	*na*	*na*
Av Mg (ppm of soil)	16.12	Nugget*	21.43	8.68	*28.2*	*7.2*	*32.64*
Av Na (ppm of soil)	*na**	*Nugget**	*Nugget*	*na**	*na*	*na**	*na**
Av P (ppm of soil)	Nugget	19.61	8.37	5.27	*na*	*na*	*na*

Values in italics exhibit periodicity in their semi-variograms
* Semi-variogram displays a decrease in variance with an increase in lag distance
na: no fit to any model

Table 6: A comparison of the spatial autocorrelation values (in metres) of nutrients in semi-arid grasslands.

Ranges of spatial autocorrelation for grassland plots				
Nutrient	**Karoo** Plot 1:	**Karoo** Plot 2:	**Sevilleta** (Schlesinger et al., 1996)	**Jornada Basin (two sites)** (Schlesinger et al., 1996)
Ca	na	10.5	1.40	0.72, 1.26
K	na	na	1.21	1.37, 1.25
Mg	16.12	na	3.29	1.10, 1.89
Na	na	na	6.05	1.16, 3.19
P	na	19.61	na †	2.42, 0.48 †

† Measurements of PO_4

na: random variance i.e. no spatial patterns evident.

Table 7: A comparison of the spatial autocorrelation values (in metres) of nutrients in semi-arid shrublands.

Ranges of spatial autocorrelation for shrubland plots				
Nutrient	**Karoo** Plot 3:	**Karoo** Plot 5:	**Sevilleta** (Schlesinger et al., 1996)	**Jornada Basin (two sites)** (Schlesinger et al., 1996)
Ca	nd	na	>7.00	1.22, >7.00
K	na	31.44	na	2.13, 2.49
Mg	21.43	8.68	1.49	1.14, 2.22
Na	na	nd	0.46	na, >7.00
P	8.37	5.27	$1.25^{\dagger}$	>7.00, $3.49^{\dagger}$

† Measurements of PO_4

na: random variance i.e. no spatial patterns evident.

nd: not determined