Chapter 4

The Impact of Land Degradation on the Quality of Soils in a South African Communal Rangeland

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Additional information is available at the end of the chapter

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Abstract

Grassland productivity of communal rangelands is limited by land degradation, which leads to nutrient depletion, soil fertility decline and overall soil quality. However, little is known as to what the soil quality threshold is for different degradation intensities. To address this, we selected a 0.05 m surface soil layer of a communal rangeland site in Drakensburg, South Africa, exhibiting a degradation gradient varying from heavily degraded (0–5%, grass aerial cover), moderately degraded (25–50%) and non-degraded (75–100%) grasslands, to evaluate the effects of land degradation on soil aggregate stability, compaction, bulk density and texture. Results indicate that land degradation decreased soil aggregate stability by 47%, increased soil compaction by 42% and increased soil bulk density by 12%, and these were accompanied by a pattern of lower sand and almost two times greater clay content in heavily degraded grassland compared with non-degraded grassland. Ultimately, this decline in the soil quality of the communal rangeland has serious implications for the ecosystem services and functions it provides, such as storing water, carbon sequestration and nutrient cycling. We recommend the protection and improvement of grass vegetation because of its dense sward characteristics, which intercept raindrop energy, slow surface runoff and increase the structural stability of the soil to minimize and prevent degradation in rangelands.

Keywords: land degradation, rangeland, soil quality, grass cover, smallholder

1. Introduction

Rangelands, including grasslands, scrublands and tundra, cover approximately 50% of the world's land surface [1]. The Land Degradation Assessment in Drylands (LADA) estimates that 16% of rangelands are currently undergoing degradation, with 20–25%

of the total land area being degraded, ultimately affecting the livelihoods of about 1.5 billion people worldwide [2]. Notably, this soil degradation is occurring in addition to historic degradation.

The degradation of rangelands is a consequence of several key activities, including overgrazing, livestock trampling and soil erosion [3, 4]. The widespread occurrence of soil degradation is also due to the mismanagement of marginal lands (semiarid, steep, shallow soils) in harsh and highly variable climates [5, 6]. With increasing population densities and the associated pressures on land, soil degradation is intensifying [7, 8].

Land degradation adversely depletes soil nutrients, which in turn directly affects their fertility, productivity and overall soil quality [9]. According to Vanlauwe et al. [8], soil fertility decline is directly linked to low productivity and food insecurity and is at the heart of rural poverty. Because soils are one of the largest stores of carbon that are in direct exchange with the atmosphere, soil degradation also negatively affects society through climate change feedbacks [10].

Because soil fertility depletion is one of the major threats to the sustainability of rangelands, precise determination of changes in soil quality is important in understanding the role of soils in the global cycle [11, 12]. A better understanding of the mechanisms of land degradation is crucial, not only to limit its consequences but also for mitigation and sustainable soil management [13]. While environmental degradation is expanding globally at an alarming rate, there is a major gap in our knowledge on the extent, severity and intensity of land degradation [14].

For many smallholder farmers in Sub-Saharan Africa (SSA), communal rangelands are grazed by livestock, which provide rural people with meat and dairy products and a source of income. However, one of the greatest challenges is that the rangelands are in a state of degradation due to an increase in human activities on marginal lands, misuse and mismanagement (overgrazing) and the associated problems of soil erosion [7, 9, 15, 16]. Soil fertility depletion and soil quality decline are major threats to the sustainability of these communal rangelands, partly because fertilizer inputs are not available or affordable in sufficient quantities [12].

Little is known on the impact of different intensities of land degradation on soil quality, with the most pertinent key issue being the threshold at which the effect of degradation will lead to a decline in soil quality. The main objective of this study was to evaluate the impact of a decrease in grass aerial cover as a consequence of land degradation on the quality of soil in a communal rangeland in the uplands of the Drakensburg region, KwaZulu-Natal Province, South Africa, that is managed by smallholder farmers. Grass cover was used as an indicator of land degradation, and quantification of such a land degradation indicator was done to help identify areas under threat and provide a basis for developing effective land management and rehabilitation options to improve the quality of communal rangeland soils [17, 18].

2. Materials and methods

2.1. Study site description

The study was carried out at the Potshini catchment, which is 10 km north of the Bergville District in the KwaZulu-Natal Province of South Africa (longitude: 29° 21′; latitude: –28° 48′). The site has a mean annual precipitation of 684 mm, the majority of which falls during the summer months (October and March), a mean annual potential evaporation of 1600 mm and a mean annual temperature of 13°C [19]. The altitude ranges from 1080 to 1455 m.a.s.l. The site is on a dark brown sandy loam soil (15% clay) derived from sandstone, mudstone and intruding dolerite boulders and classified as Acrisol [20], with the dominant clay mineral being kaolinite. The soil is moderately deep and well-drained and has an undulating slope of 6–8%. It is acidic (pH 3.78–3.86), with an effective cation exchange capacity (ECEC) ranging between 1.86 and 5.86 $cmol_c\ kg^{-1}$ and an acid saturation ranging between 48 and 80%. The vegetation in the area is classified as Moist Highland Sourveld [21], and the dominant vegetation species include *Hyparrhenia hirta* and *Sporobolus africanus*.

2.2. Soil sampling and preparation

A degraded communal rangeland site with homogeneous soil type and grazed extensively by livestock, a common and widespread land use practice in SSA [22], in the uplands of the Drakensburg region of South Africa (**Figure 1**) was selected because it exhibited a degradation

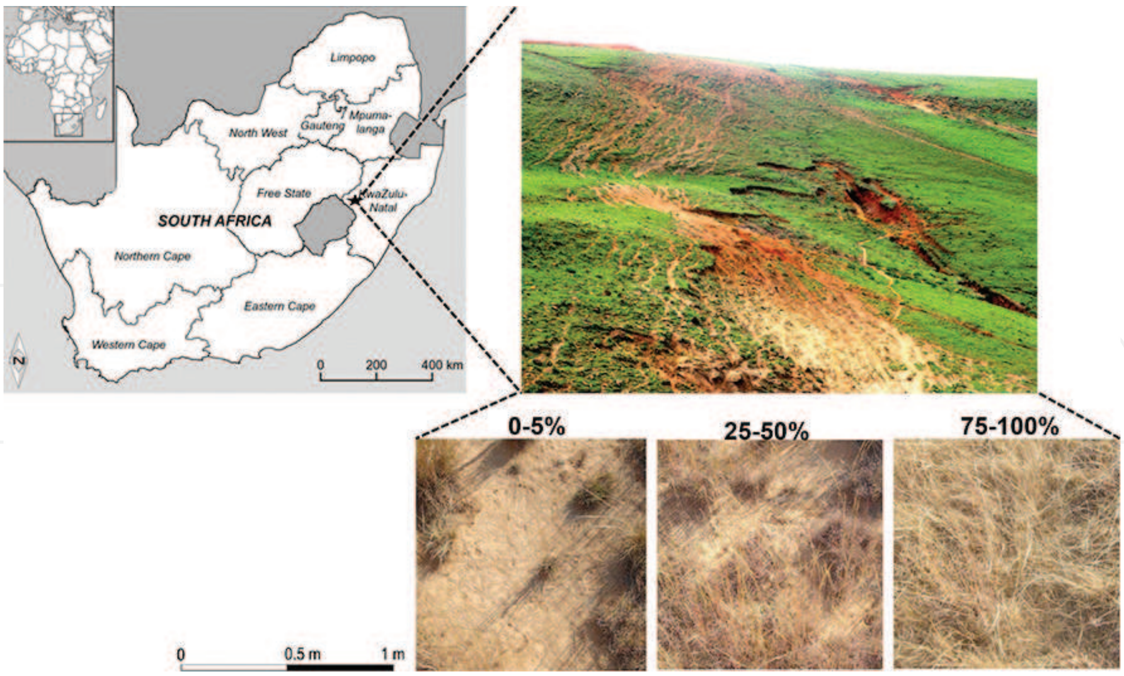

Figure 1. Location of the study area in the Drakensburg uplands of South Africa. Shown are images of soil surface coverage by vegetation for the different land degradation intensities or grass aerial cover from 0 to 5% (heavily degraded), 25 to 50% (moderately degraded) and 75 to 100% (non-degraded).

gradient varying from heavily degraded grassland with visible bare soils in the north to non-degraded grassland in the south. Such a state of degradation is a common feature of many communal rangelands in this part of South Africa.

Three categories of grass aerial cover were identified from surface soils across a degradation gradient of the communal rangeland site. A direct assessment was conducted based on vegetation cover [23], specifically grass aerial cover, which is the area of the ground covered by the vertical projection of the aerial portion of plants [24], to determine whether the land was degraded or not. Aerial cover was assessed by placing a 1 m×1 m plot frame at fixed intervals along each corresponding aerial cover category, while aerial cover of the plants in the plot was recorded as an estimate of the percentage of the total area [25]. The following grass aerial cover categories were established: 75–100% (Cov_{100}), corresponding to non-degraded grassland; 25–50% (Cov_{50}), corresponding to moderately degraded grassland; and 0–5% (Cov_5), corresponding to heavily degraded grassland. At each grass cover category, three sampling points were randomly selected, resulting in nine equidistant sampling locations along the degradation gradient. Four replicate soil samples 1 m apart at each sampling point were collected in a radial basis sampling strategy from a 0.05 m surface layer, giving a total of 12 samples per grass cover category and 36 soil samples along the degradation gradient. The surface layer was intensively sampled because the effects of land degradation on the quality of soil have been shown to be more pronounced in this soil layer [9, 26, 27]. In addition to these samples, triplicate core samples were also collected for bulk density using a 0.075 m diameter metallic cylindrical core (height=0.05 m) following a similar sampling strategy. Soil samples for bulk density were taken directly from the field to the laboratory and immediately oven-dried at 105°C to determine the oven-dry weight using the gravimetric method [28].

Once in the laboratory, field moist samples for soil aggregate stability were passed through an 8 mm sieve by gently breaking the soil along planes of weakness, air-dried and stored at room temperature before soil analyses. The remaining air-dried soils were ground to pass through a 2 mm sieve for further soil physical and chemical analyses.

2.3. Penetration resistance

In the field, penetration resistance (PR) was evaluated by randomly selecting 15 positions in each grass aerial cover category, and PR readings were taken in the topsoil surface layer. The PR of the soil, which is a proxy for soil compaction, was determined using a handheld cone penetrometer [29]. Notably, PR measurements were taken before the soil surface was disturbed for soil sample collection.

2.4. Determination of chemical and physical properties

Particle size distribution was determined by the sieve and pipette method [30]. Soil pH was determined in a 1:2.5 solution ratio in both deionized water and 1 M KCl suspension using a Calimatic M766 pH meter. The exchangeable cations Ca and Mg were determined by extraction in 1 M KCl, while P, K, Zn, Mn and Cu were determined by extraction in an Ambic 2 extract containing 0.25 M NH_4HCO_3 [31], with detection by inductively coupled plasma optical emission spectrometry (ICP-OES) using an Optima 7300DV spectrometer (Perkin Elmer, Inc., Shelton, CT). Effective cation exchange capacity (ECEC) was calculated as the sum of extractable cations, with base saturation calculated as the proportion (%) of the ECEC accounted for by exchangeable bases (Ca, Mg, K and Na).

2.5. Determination of soil aggregate stability

After field sampling, moist soil samples were taken to the laboratory and air-dried at room temperature. During this period, large soil aggregates were periodically broken down by hand along lines of weakness to obtain maximum millimeter-sized aggregates. Soil samples were then sieved to isolate 3–5 mm aggregates for aggregate stability testing. Soil aggregate stability was determined on the 3–5 mm aggregates following the ISO standard method (ISO/DIS 10930:2012) outlined by Le Bissonnais [32]. The aggregates were subjected to rapid wetting by immersion into water, slow wetting by capillarity and mechanical disaggregation by shaking after wetting with ethanol, which correspond to different aggregate breakdown mechanisms, *viz*. slaking, differential clay swelling and mechanical breakdown, respectively. For the rapid wetting test, 10 g of 3–5 mm aggregates was submerged in 50 ml of distilled water in a beaker for 10 minutes, resulting in slaking of the soil. For the slow wetting test, 10 g of 3–5 mm aggregates was spread on top of a foam soaked in water. Thereafter, aggregates were allowed to wet through capillarity for 60 minutes. For the mechanical disaggregation test, 10 g of 3–5 mm aggregates was first immersed in a beaker with ethanol and then transferred to a beaker with distilled water to rest for 30 minutes. The aggregates were then transferred to an Erlenmeyer flask using distilled water and gently shaken up and down by hand 10 times. The weights of the aggregates collected on each sieve size (2, 1, 0.5, 0.2, 0.1 and 0.05 mm) were measured and expressed as the percentage of the initial dry mass sample. The mean weight diameter (MWD) for each disaggregation mechanism was calculated using the following equation:

$$\mathrm{MWD} = \frac{\sum (x_i w_i)}{100}, \tag{1}$$

where x is the mean inter-sieve size and w_i is the percentage of fragments retained by the sieve i. The greater the MWD, the more resistant the soil aggregates are to the aggregate breakdown mechanisms.

2.6. Statistical analysis

Results are presented as standard error (SE) of the means for each grass cover along the degradation gradient and, where specified, subjected to one-way analysis of variance using GenStat (VSN International, Hemel Hempstead, UK). Differences between means were tested using Duncan's multiple range test at P<0.05.

3. Results and discussion

In this study, land degradation reduced rangeland soil quality through a linear decrease in grass cover. Consequently, soil aggregate stability in the topsoil layer decreased from an average of 1.35 mm in non-degraded grassland to 0.71 mm in heavily degraded grassland, corresponding to a decline of 47% (**Figure 2**). The decline in the protective grass cover induced by degradation led to soil structural alteration, disruption of soil aggregates, increasing susceptibility of degraded soil to soil crusting and compaction. The less structural stability of the degraded soil may in turn increase soil erodibility — the inherent susceptibility of soil to detachment and transport by rainsplash and runoff [32].

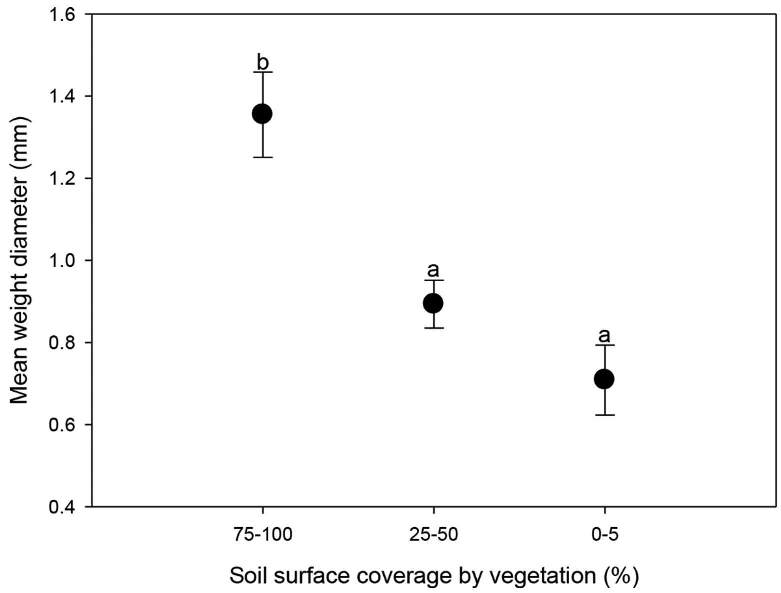

Figure 2. Relationship between soil aggregate stability and soil surface coverage by vegetation. Data are presented as mean±SE (n=12) per soil surface coverage by vegetation, and bars with different letters are significantly different at the $P<0.05$ level.

Penetrometer resistance, an important mechanical property used as an indicator of soil compaction [33], increased with decreasing grass cover from an average of 11.3 kg cm^{-2} in non-degraded grassland to 19.5 kg cm^{-2} in heavily degraded grassland, corresponding to an increase of 42% (**Figure 3A**). In agreement with our study, Snyman and du Preez [26] found that rangeland degradation decreased soil compaction by 65% from 18.3 kg cm^{-2} in non-degraded fine sandy loam soil to 6.4 kg cm^{-2} in heavily degraded fine sandy loam soil in a semiarid region in Bloemfontein, South Africa. One of the profound effects of soil compaction is the reduction in pore space and macroporosity, which is associated with increased bulk density [34, 35]. Such was the case in the present study, as soil bulk density increased by 12% from an average of 1.43 g cm^{-3} in non-degraded grassland to 1.61 g cm^{-3} in heavily degraded grassland, indicating increasing compaction (**Figure 3B**). Similarly, Hiltbrunner et al. [36] observed a 20% increase in soil bulk density on degraded grassland in a Swiss subalpine grassland, and this led to changes in biomass production.

Some studies have shown that soil compaction decreases the infiltration capacity of the soil [35, 37]. At our study site, Podwojewski et al. [38] found using rainfall simulation on runoff plots that land degradation decreased the soil infiltration rate by 72% from 21.6 mm h^{-1} in non-degraded grassland to 6 mm h^{-1} in heavily degraded grassland. While in South West England, the authors [38] found that the infiltration capacity was reduced by 80% and surface runoff volumes were increased by nearly 12 times on heavily degraded grassland compared with non-degraded grassland. The decrease in the infiltration capacity of soils with increasing degradation intensity may be explained by several reasons. First, a decline in protective grass cover and associated dense sward characteristics by land degradation leads to reduced intercepted raindrops and water movement through the soil. Second, a decline in the protective cover offered by grass decreases surface roughness, leading to decreased detention storage [38]. Although not investigated here, some studies have shown that soil compaction and the reduction in pore space also decrease the hydraulic conductivity of soil [34, 39].

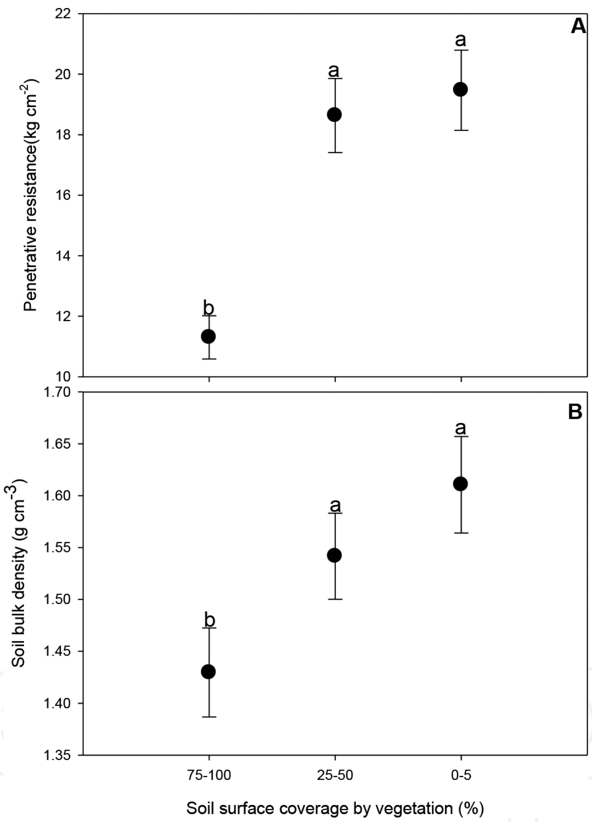

Figure 3. Mean±SE values of (A) penetrative resistance, a proxy for soil compaction (*n*=15), and (B) soil bulk density (*n*=12) per soil surface coverage by vegetation, and bars with different letters are significantly different at the *P*<0.05 level.

In this study, a pattern of lower sand (49%) was observed in heavily degraded grassland, compared with 72% in moderately degraded and 73% in non-degraded grassland. The depletion in sand was so marked that the mean clay content was almost two times (34%) greater in heavily degraded grassland compared with 14% in non-degraded grassland, while the distribution of silt content was similar along the degradation gradient (**Figure 4**). Indeed, intensification of degradation can induce shifts in the distribution of texture, as indicated in the study by Dong et al. [27] in the Qinghai-Tibetan Plateau in China, which found that grassland degradation led to a shift in soil texture from loamy toward sandy loamy soils. This phenomenon was corroborated by Fullen et al. [40], whose study compared the textures of grassland and degraded sandy soils from Shropshire, UK, and concluded that degradation changed mean soil texture from a very slightly stony loamy sand to a slightly stony sandy loam. The authors also found that the degraded soil was particularly deficient in sand, especially medium and coarse sands, and the depletion in sand was so marked that the degraded bare soil had significantly greater mean percentage clay content than non-degraded grassland soil. A recent meta-analysis by Dlamini et al. [41] concluded that grassland degradation has a significantly negative effect on coarser textured soils than fine textured soils due to the lack of physical protection of organic matter and weak aggregation in sandy soils.

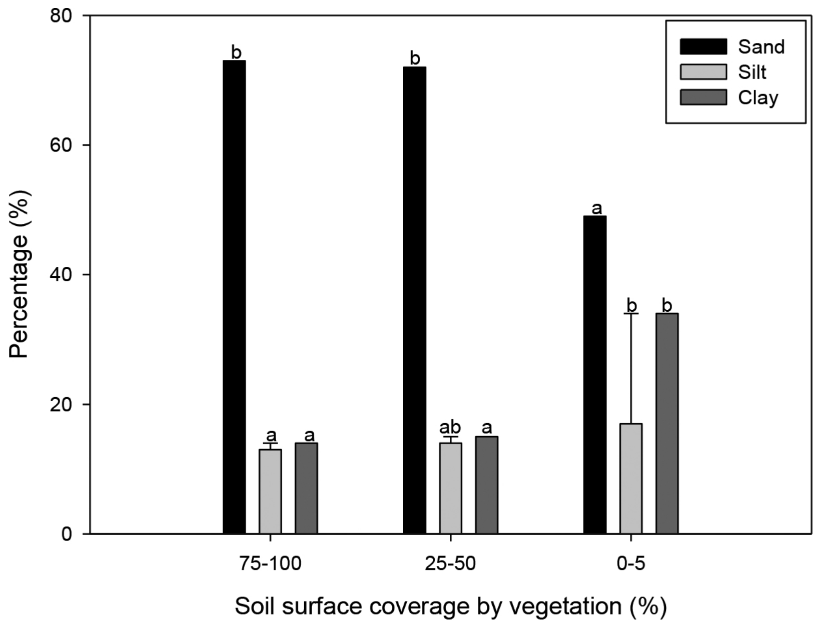

Figure 4. Relationship between sand, silt, clay and soil surface coverage by vegetation. Data are presented as mean±SE (n=12) per soil surface coverage by vegetation, and bars with different letters are significantly different at the P<0.05 level.

Land degradation results in the reduction of vegetation cover, which is unfavourable to soil protection. Degraded soils generated through the loss of vegetation cover are exposed to raindrop impact, which may lead to crust formation and a reduction in the infiltration capacity of the soil [42]. Such effects may lead to bare soil being more susceptible to surface runoff generation as drainage becomes impeded. These changes to soil hydrology have implications for runoff from degraded land, potentially modifying not only the quantity but also the quality of runoff, in terms of sediment and nutrient loads transported over and through the soil [37]. Vegetation cover by intercepting raindrops and enhancing infiltration protects the soil surface from the erosional effects of rainsplash and surface runoff, and this in turn helps preserve the water quality in surface waters of rangelands.

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4. Conclusion

The reduction in grass cover induced by degradation in the communal rangeland resulted in a decrease in soil aggregate stability. The reduced soil structure or aggregation was concomitant with an increase in soil compaction and bulk density as well as a shift in soil texture associated with decreasing sand content and increasing clay content in the soil surface layers. Soil structure and texture are soil quality parameters crucial to the provision of ecosystem services and desirable for functioning of rangelands. Land degradation by adversely altering the quality of these soil properties negatively affects the services they provide, such as storing water, carbon and nutrients, which affect grassland productivity when lost. For many smallholder farmers, the grass vegetation of communal rangelands is essential to livestock production by providing forage for grazing animals, meat, dairy products and income to the people. As such, quantitative data on the effects of degradation on the quality of rangeland soils and the processes involved are crucial for developing effective land management and rehabilitation options, with the goal of improving rangeland productivity. Soil quality in degraded rangelands can be enhanced by adopting focused initiatives, such as the UN Convention to Combat Desertification. Improvement of rangelands can involve various grassland management options — from fertilization, soil tillage, livestock exclusion, burning and appropriate grazing regimes, which can lead to more sustainable rangelands. More work of this nature needs to be carried out on different soil types under diverse rangeland environments.

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