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Land degradation impact on soil organic carbon and nitrogen stocks of sub-tropical humid grasslands in South Africa

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ABSTRACT

Land degradation is recognized as a main environmental problem that adversely depletes soil organic carbon (SOC) and nitrogen (SON) stocks, which in turn directly affects soils, their fertility, productivity and overall quality. While it is expanding worldwide at rapid pace, quantitative information on the impact of land degradation on the depletion of SOC and SON stocks remains largely unavailable, limiting the ability to predict the impacts of land management on the C losses to the atmosphere and associated global warming. The main objective of this study was to evaluate the consequences of a decrease in grass aerial cover on SOC and SON stocks. A degraded grassland showing an aerial cover gradient from 100% (Cov100, corresponding to a non-degraded grassland) to 50–75% (Cov75), 25–50% (Cov50) and 0–5% (Cov5, corresponding to a heavily degraded grassland), was selected in South Africa. Soil samples were collected in the 0.05 m soil layer at 48 locations along the aerial cover gradient and were subsequently separated into the clay + silt (2–20 μm) and sand (20–2000 μm) fractions, prior to total C and N analysis (n = 288). The decline in grass aerial cover from 100% to 0–5% had a significant ($P < 0.05$) impact on SOC and SON stocks, with losses by as much as 1.25 kg m^{-2} for SOC and 0.074 kg m^{-2} for SON, which corresponded to depletion rates of 89 and 76%, respectively. Furthermore, both the C:N ratio and the proportion of SOC and SON in the silt + clay fraction declined with grass aerial cover, which was indicative of a preferential loss of not easily decomposable organic matter. The staggering decline in SOC and SON stocks raises concerns about the ability of these acidic sandy loam soils to sustain their main ecosystem functions. The associated decrease in chemical elements (e.g., Ca by a maximum of 67%; Mn, 77%; Cu, 66%; and Zn, 82%) was finally used to discuss the mechanisms at stake in land degradation and the associated stock depletion of SOC and SON stocks, a prerequisite to land rehabilitation and stock replenishment.

1. Introduction

Grasslands occupy about 40% of world's land surface and store approximately 10% of the global soil carbon (C) stock of 1500 Gt (Suttie et al., 2005). Consequently, grasslands are considered to have greater potential to sequester SOC, depending on management strategies (Franzluebbers and Doraiswamy, 2007), making them an important component of the global C cycle. Additionally, grasslands provide key ecosystem goods and services by supporting biodiversity, and serving as rangelands for the production of forage to sustain the world's livestock (Asner et al., 2004; Bradford and Thurow, 2006; FAO, 2010; Suttie et al., 2005). However, land degradation severely impacts on the productivity of grasslands (UNEP, 2007).

Land degradation, defined here as the reduction in the capacity of grasslands to carry out their key ecosystem functions, is commonly attributed to disturbances including overgrazing, livestock trampling and soil erosion (Daily, 1995; UNEP, 2007). For instance, a recent study by Kotzé et al. (2013) investigated the impacts of rangeland management on the properties of clayey soils along grazing gradients in the semi-arid grassland biome of South Africa. They found that communal farms with continuous grazing were generally depleted of nutrient stocks, and nutrient depletion generally increased with increasing grazing intensity. Grassland management practices substantially influence the amount, distribution and turnover rate of soil organic matter and nutrients in soils (Blair et al., 1995). Moreover, because the larger proportion (ca 60–70%) of SOC and nutrient stocks in grassland soils is concentrated in the top 0.3 m (Gill et al., 1999), any external disturbance is likely to cause dramatic soil fertility and SOC depletion, which in turn will constrain grassland productivity, including biodiversity loss and forage production (Dong et al., 2012; Ruiz-Sinoga and Romero Diaz, 2010).

Yet, contradictory results have been reported on the impact of land degradation on SOC stocks with some studies showing a decrease in SOC with overgrazing (Martinsen et al., 2011; Steffens et al., 2008),

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some no change (Dormaar et al., 1977; Johnston et al., 1971) whereas some show an increase (Derner et al., 1997; Smoliak et al., 1972).

For instance, SOC stocks declined by 15% after seven years of grazing in Norway, with 0.76 kg C m^{-2} in ungrazed compared to 0.64 kg C m^{-2} in heavily grazed grasslands (Martinsen et al., 2011). Steffens et al. (2008) found that 30 years of overgrazing in a semi-arid Chinese grassland resulted in 50% decrease in SOC stocks, with 0.64 kg C m^{-2} in grazed compared to 1.17 kg C m^{-2} in ungrazed grasslands. A similar depletion rate was found in the USA, where Franzluebbers and Stuedemann (2009) observed that heavy grazing reduced SOC stocks to 0.051 kg C m^{-2} after 12 years of grazing, compared with 0.117 kg C m^{-2} on ungrazed grasslands. Wu and Tiessen (2002) reported that land degradation reduced SOC and N by 33% and 28%, respectively in a degraded Chinese alpine grassland. Finally, Dong et al. (2012) found an extreme SOC depletion rate of 90% in a degraded Chinese grassland.

In contrast, grazing increased SOC stocks under several environments (Bauer et al., 1987; Derner et al., 1997; Frank et al., 1995; Smoliak et al., 1972), by rates ranging from 14% to 91%. However, in the latter, moderate grazing is reported to be beneficial to grassland soils rather than contributing to their degradation.

While the studies focusing on land degradation have reported associated losses in SOC, little is known on the impact of different degradation intensities on SOC stocks, with the underlying research question being at what threshold of land degradation do SOC stocks dramatically decrease?

To further improve the understanding of land degradation impact on SOC losses from soils, more work needs to be done on the mechanisms controlling organic matter destabilization. As such, the changes in organic matter quality as a consequence of land degradation could be early indicators of SOC stock depletion in both natural and agricultural ecosystems, as suggested by Christensen (2001). Furthermore, a better understanding of the rates of SOC and SON depletion and the associated destabilization mechanisms is expected to enhance efforts to circumvent land degradation and accelerate the recovery of degraded soils (Schmidt et al., 2011), while maintaining a viable forage production for livestock and supporting biodiversity (Lal, 2004).

For many smallholder farmers in Africa, grasslands make a significant contribution to food security by providing part of the feed requirements of livestock used for meat and milk production (O'Mara, 2012). However, many of the grasslands are in poor condition and showing signs of degradation due to an increase in anthropogenic pressures on marginal lands, overgrazing and the associated problems of soil erosion (Suttie et al., 2005). As a consequence, this is jeopardizing both the environment and the economical development of rural livelihoods.

In this study of a communal rangeland in the uplands of the Drakensburg region, KwaZulu-Natal Province, South Africa managed by smallholder farmers, our main objective was to evaluate the consequences of a decrease in grass aerial cover on SOC and N depletion rates and the associated organic matter quality. Grass aerial cover was used as an indicator of land degradation.

2. Materials and methods

2.1. Site description

The study area is located in the Potshini catchment, 10 km north of the Bergville district in the KwaZulu-Natal Province of South Africa (Long: 29° 21′; Lat: −28° 48′). This area has a sub-tropical humid climate, characterized by cold dry winters and warm rainy summers (October to March), with a mean annual precipitation of 684 mm, a mean annual potential evaporation of 1600 mm and a mean annual temperature of 13 °C (Schulze, 1997). The altitude ranges from 1080 to 1455 m.a.s.l and the average slope gradient is 8%. The underlying geology is sandstone and mudstone, and the soils are classified as Acrisols (WRB, 2006). The vegetation in this area is dominated by Moist Highveld Sourveld (Camp and Hardy, 1999). The dominant vegetation species of the Moist Highveld Sourveld include *Hyparrhenia hirta* and *Sporobolus africanus*.

2.2. Experimental design and sampling strategy

A degraded grassland site with a surface area of 1500 m^2 (30 m × 50 m) and homogeneous soils was selected in the uplands of the Drakensburg region of South Africa (Fig. 1). This site was selected because it exhibited a land degradation gradient varying from highly degraded areas with bare soils in the north to areas fully covered by grass in the south. Such areas are a common feature of many communal rangelands in this part of South Africa. For soil sampling, four categories of grass aerial cover were identified and evaluated in the site, i.e. 75–100% (Cov100, corresponding to non-degraded land), 50–75% (Cov75), 25–50% (Cov50), and 0–5% (Cov5, corresponding to heavily degraded land). In this study, grass aerial cover is defined as the area of the ground covered by the vertical projection of the aerial portion of the plants (USDA, 1996). Aerial cover was measured by placing a 1 m × 1 m plot frame at fixed intervals along each corresponding aerial cover category, while the aerial cover of the plants in the plot was recorded as an estimate of the % of total area (Daubenmire, 1959). At each cover category, three sampling points were randomly selected. For each selected sampling position, four replicate soil samples were collected in the 0–0.05 m soil layer 1 m apart in a radial basis sampling strategy to yield twelve samples per category. The sampling resulted in a total of 48 soil samples. Furthermore, for each category, additional soil samples for bulk density were sampled using a 0.075 m diameter metallic cylindrical core (height, 0.05 m) following similar sampling strategy. The surface layer was intensively sampled because the effects of land degradation on SOC and nutrient stocks have been shown to be more pronounced in this soil layer (Dong et al., 2012; Snyman and du Preez, 2005). For the analysis of SOC and N stocks, with depth in each grass cover category, additional soil samples were collected by horizon at depth increments of 0–0.05 m, 0.05–0.15 m, then every 0.15 m down to 1.2 m using a hand shovel from the face of a 1 m × 1 m × 1.2 m soil pit. Triplicate soil bulk density samples were also collected in the different depth increments of the soil profiles using 220.89 cm^{-3} metal cylindrical cores (height 0.05 m, diameter 0.75 m). Soil samples for bulk density were taken to the laboratory, immediately oven-dried at 105 °C to determine the oven dry weight using the gravimetric method (Blake and Hartge, 1986). Once in the laboratory, the field moist samples were passed through an 8-mm sieve by gently breaking apart the soil. The remaining soil samples were air-dried and ground to pass through a 2-mm sieve for further soil analysis.

2.3. Soil physical and chemical analysis

The particle size distribution was determined by the sieve and pipette method (Gee and Bauder, 1986). The penetration resistance (PR) of the soil, a proxy for soil compaction was measured in the field using a hand-held cone penetrometer (Herrick and Jones, 2002). The PR was evaluated by randomly selecting fifteen positions in each grass aerial cover category for penetration readings of the soil surface. The PR measurements were taken before the soil surface was disturbed for soil sample collection from a 0.05 m soil layer. The soil pH was measured in a 1:2.5 (10 g) to 1 M KCl (25 ml) suspension using a Calimatic pHM766 pH meter. Exchangeable Ca, Mg and acidity were determined by extraction in 1 M KCl while P, K, Zn, Mn and Cu were determined by extraction in Ambic 2-extract containing 0.25 M NH_4HCO_3, with detection by atomic absorption spectrometry (Manson and Roberts, 2000). The concentration of P and K was determined by inductively-coupled plasma optical emission spectrometry (ICP-OES).

Effective cation exchange capacity (ECEC) was calculated as the sum of extractable cations, with the percentage acid saturation calculated as the exchangeable acidity × 100 / (Ca + Mg + K + exchangeable acidity). Total C and N were measured in the bulk soil using LECO CNS-2000 Dumas dry matter combustion analyzer (LECO Corp., St. Joseph, MI).