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Re-aggregation dynamics of degraded cropland soils with prolonged secondary pasture management in the South African Highveld

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Prolonged arable cropping of subtropical sandy grassland soils resulted in substantial losses of water-stable aggregates. The objective of this study was to evaluate how rapidly and to which degree soil aggregates may be restored when degraded cropland soils are converted to secondary pasture lands. Hence, chronosequences of degraded cropland soils (more than 20 years of arable cropping) were sampled that had been converted to secondary pastures between 1 and 52 years ago in three agro-ecosystems of the South African Highveld. Primary grasslands as well as sites under long-term cropping served as references. The surface soils (Plinthusthalfs; 0–10 cm) were fractionated to aggregates of different sizes by wet sieving (8000–2800 μm, 2800–2000 μm, 2000–500 μm, 500–250 μm, 250–53 μm and<53 μm). All fractions were analyzed for their respective content of soil organic carbon and total nitrogen and corrected for sand content. The results showed that reconversion of cropland into secondary pasture restored the soil structure after 9.5–18 years of pasture management almost completely: the amount of sand-corrected large macroaggregates (>2000 μm) approached 85–94% of the levels of the primary grasslands. The stocks of organic matter bound to large macroaggregates recovered more slowly and reached only 50% of that of the primary grassland, which, however, exhibited also a slightly elevated clay content. The carbon concentration in the aggregates did not change significantly. Thus, the increase in C stocks in the secondary pasture soils was mainly due to a rebuilding of large macroaggregates, which contained more C than the smaller-sized aggregate classes, but not more C than the respective aggregates in the degraded cropland. We conclude that only the amount of large macroaggregates was restored upon land conversion, while their protective capacity was obviously not restored and thus not strong enough to account for a full sequestration of soil organic matter.

1. Introduction

Restoration of degraded soils is an important development strategy to combat desertification and to reduce soil erosion in sub-Saharan Africa (Vågen et al., 2005) and other semi-arid and arid parts of the world. These dry regions cover 41% of the Earth's land surface and are very vulnerable to soil degradation (Millennium Ecosystem Assessment, 2005). Soil restoration in such ecosystems usually implies recovery of soil organic matter (SOM) levels depleted by cropping (Obi and Ebo, 1995). Generally, to regain SOM levels, a change in land use practice is required (Conant et al., 2001; DeGryze et al., 2004; Post and Kwon, 2000). To be successful in sequestering C, it may be required to restore soil functions involved in the stabilization of SOM.

Arable cropping of the land, especially tillage, has a strong influence on soil structure. Thus, several studies investigated the effects of arable cropping, usually involving continuous or different tillage practices, on soil structure and SOM dynamics (e.g., Beare et al., 1994; Bhattacharyya et al., 2009; Six et al., 1999; Wright and Hons, 2005). Prolonged cropping resulted in rapid losses of SOM when aggregates were disrupted due to ploughing (Bronick and Lal, 2005; Six et al., 1998), and such effects were particularly pronounced for the sandy soils of the South African Highveld (Lobe et al., 2001, 2011). To revert this process, any land use change that is designed to restore the soils must assure that soil structure is rebuilt effectively and rapidly.

One strategy to enhance soil fertility and to reduce soil erosion may be the conversion of cropland into permanent secondary grassland for use as a pasture, because this practice enhances the accrual of SOM (e.g., Conant et al., 2001; DeGryze et al., 2004; Studies: Knops and Tilman, 2000; Lane and BassiriRad, 2005; McLauchlan et al., 2006; Post and Kwon, 2000; Zach et al., 2006). The example in the South African Highveld shows that this practice can be economical as it is initiated by farmers (Preger et al., 2010). Yet, only a few studies investigated the accumulation of SOM following the conversion of cropland to pasture in the semi-arid tropics and subtropics (e.g. Chevallier et al., 2000; Preger et al., 2010). Most of the available studies found an increase of SOM stocks after conversion of cropland

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into permanent pasture (Bruce et al., 1999), though frequently restricted to the upper 5 or 10 cm of soil (Guo and Gifford, 2002; Knops and Tilman, 2000; Potter et al., 1999). A few studies in other parts of the world, however, indicated that when converting cropland into pastures it is at least possible that soils re-aggregate to the level of comparable primary grassland (DeGryze et al., 2004; Jastrow, 1987, 1996; Li and Shao, 2006). Particularly macroaggregates might be rapidly reformed, in arable soils frequently even showing seasonal dynamics (Plante et al., 2002; Six et al., 2004).

In the South African Highveld, the secondary pasture soils accumulated SOM in the upper 0–10 cm, but in individual fractions like the sand-size ones which contain mainly particulate organic matter (POM), the recovery of SOM was incomplete (Preger et al., 2010). The turnover rates of these recent plant inputs or POM are considerably affected by the physical protection inside aggregates (e.g., Angers and Chenu, 1998; Baldock and Skjemstad, 2000; Christensen, 1996; Puget et al., 2000; Six et al., 2002a). Yet, less is known about how the re-formation of soil aggregates in secondary grassland soils affects SOM dynamics (Blanco-Canqui and Lal, 2004), and we are not aware of any study that could be representative for sandy soils of the subtropics. Due to low clay contents, sandy soils usually have a limited potential for stabilization of organic matter through interactions between organic and mineral particles (Sollins et al., 1996; Von Lützow et al., 2006), but there may be a close connection between the SOM contents and the stability of aggregates in West African sandy soils (Dutartre et al., 1993). Hence, to understand the dynamics of aggregates and the interaction between aggregates and organic matter in secondary pastures it should be of particular importance to reveal the regeneration dynamics of organic matter in the aggregates of the sandy soils of the South African Highveld.

The objectives of this study were, therefore, to investigate (i) how rapidly and to what extent the conversion of degraded cropland into secondary pasture affects the re-aggregation of soil, (ii) how the duration of pasture management influences the C contents in the different aggregate fractions, and (iii) how the duration of pasture management influences the contribution of the respective C stocks in the different aggregate fractions to the C stock of the bulk soil. To answer these questions, we investigated different aggregate fractions and their soil C data from chronosequences of secondary pastures established on degraded cropland in the semi-arid Highveld of South Africa.

2. Materials and methods

2.1. Site selection

For this study, we sampled soil in the South African Highveld in the Free State Province (Fig. 1). To obtain three independent replications of our chronosequence, we sampled three comparable agro-ecosystems close to the towns of Harrismith, Kroonstad, and Tweespruit. Du Preez and Du Toit (1995) defined an agro-ecosystem as a region with homogeneous environmental factors such as climate, topography and soil, which influence biomass yield. These agro-ecosystems had previously also been studied by, e.g., Lobe et al. (2001, 2011), and Preger et al. (2010). In each of the three agro-ecosystems, grassland sites were selected which had formerly been cropped and were now continuously used as pastures for a known number of years (1 to 52 years; information about land use history was taken from written farm records of the South African farmers). As a reference, adjacent long-term cropland and native primary grassland used as pasture were also sampled. The altitude of the sites ranged between 1350 and 1830 m above sea level. All three agro-ecosystems lie in a summer-rainfall region and in the so-called grassland biome (Harrismith: Moist Cold Highveld Grassland; Kroonstad: Dry Sandy Highveld Grassland; Tweespruit: Moist Cool Highveld Grassland; Bredenkamp et al., 1996). The secondary pastures contained both commercially seeded (pasture) grass-species (e.g. *Digitaria smutsii (Stent)* and *Eragrostis curvula (Schrad.)(Nees)*) and native grasses that invaded secondary pastures (e.g. *Eragrostis* sp., *Themeda triandra (Forssk)* and *Hyparrhenia hirta (L.) (Stapf)*). The major crops before conversion were wheat, maize, and occasionally sunflower (Lobe et al., 2005). In the time of cropping, the fields had been ploughed regularly to a depth of 20 to 30 cm and mineral fertilizer had been applied regularly, with a tendency towards deeper ploughing in the more recent past (information provided by farmers). The crop rotation cycle had included fallow periods (Lobe et al., 2001). We only included secondary grassland sites that had been used for cropping for at least 20 years before being reconverted into pastures; most of the sampled pastures had been cropped for even longer periods of time. After 20 years of cropping, soil organic carbon (SOC) contents of the degraded fields deviated by less than 10% from the steady state SOC content reached after prolonged cropping (derived from Lobe et al., 2001). The soils were Plinthustalfs (Soil Survey Staff, 1998), equivalent to Westleigh or Avalon soil forms in the South African soil classification system (Soil Classification Working Group, 1991). The respective WRB soil types are Plinthic Lixisols (World Reference Base for Soil Resources, 2006). Variations in soil texture were kept within a narrow range (Table 1).

Both secondary pasture and primary grassland sites were grazed by cattle and, at some places, by sheep. The stocking density for pastures in the three agro-ecosystems ranged between 0.25 and 0.65 livestock units ha^{-1} $year^{-1}$. At a few sites, the secondary pastures had also been used occasionally for hay production (~2 t DM (dry matter) ha^{-1} $year^{-1}$; information provided by farmers). The sites were never irrigated nor organically fertilized. The primary grasslands were not fertilized in any of the three agro-ecosystems. The seeded secondary pastures received either a fertilizer mixture or single fertilizers like super phosphate and limestone ammonium nitrate to promote pasture establishment, amounting to 0–56 kg N ha^{-1} and 0–33 kg P ha^{-1}. Afterwards, in Harrismith and Kroonstad only a few secondary pasture sites were fertilized every two to three years with inorganic fertilizer (0–50 kg N ha^{-1} $year^{-1}$). However, in Tweespruit all pastures (except the 8, 18 and 52 years old pastures) were fertilized periodically every year (40–50 kg N ha^{-1} $year^{-1}$) after establishment.

At some places, shrub or tree encroachment from slangbos (*Stoebe vulgaris*, *Levyns*) or *Acacia* sp. was observed. Sampling was then conducted in zones free of bushes and trees. In Harrismith, pastures were burnt as is commonly practised about every fifth year to eliminate old grass with poor feed value (Tainton, 1999). In Tweespruit and Kroonstad, farmers did not burn secondary pastures as a management practice. Weed control has been applied to some pastures in Tweespruit and only within the first year after establishment. We only sampled secondary pastures that had not been ploughed or ripped since conversion.

At most younger sites, the sown grass species still dominated the vegetation cover at sampling. At older secondary pastures, diversity of plant species tended to be a bit greater. Apart from one two-year-old site, all pastures had an estimated vegetation ground cover exceeding 50% at the time of sampling. The pastures were level to gently sloped, inclination was 10% at most. Rainfall and temperature data were obtained from the South African Weather Service. The climatic data were compiled for 1960 to 2005. When available, we also used farm records of climatic variables. The age of the secondary grassland sites mentioned here indicated the time span between seeding of the pasture and the time of sampling in September to November 2005.

2.2. Site sampling

At each site, composite samples (n = 5) were taken in a radial sampling scheme (Wilding, 1985) with a core sampler (diameter 5 cm) from three different soil depths (0–5, 5–10 and 10–20 cm) for analysis of C and N in bulk soil (Preger et al., 2010). This sampling was different to the sampling of the aggregates. For the latter purpose, undisturbed soil blocks (~10 cm × 10 cm × 10 cm in size) were carefully excavated