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Potential of grassland rehabilitation through high density-short duration grazing to sequester atmospheric carbon

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ABSTRACT

According to the World Resources Institute (2000), a relative increase of carbon (C) stocks in world soils by 0.4% per year would be sufficient to compensate all anthropogenic greenhouse gas emissions. Several land management practices such as the suppression of tillage in agroecosystems and livestock exclusion in grasslands had initially been thought to store more carbon into the soil, but recent research puts this into question. In a context where finding effective C sequestration methods is urgent, the main objective of this study was to assess the ability of an innovative grassland management practice based on high density and short duration (HDSD) grazing to sequester atmospheric C into soils. The study was performed in a degraded communal rangeland in South Africa where soil organic C (SOC) depletion ranged from 5 to 95% depending on the degradation level, which varied from non-degraded (ND; with grass above ground coverage, Cov of 100%), degraded (D1; $50 < \text{Cov} < 75\%$), D2 ($25 < \text{Cov} < 50\%$) and HD (highly degraded: $\text{Cov} < 5\%$). The ability of HDSD (1200 cows ha^{-1} for 3 days a year) to replenish SOC stocks was compared to four commonly used strategies: (1) livestock exclosure (E); (2) livestock exclosure with topsoil tillage (ET); (3) livestock exclosure with NPK fertilization (2:3:3, 22 at 0.2 t ha^{-1}) (EF); (4) annual burning (AB); all treatments being compared to traditional free grazing control. A total of 540 soil samples were collected in the 0–0.05 m soil layer for all treatments and degradation intensities. After two years, topsoil SOC stocks were significantly increased under EF and HDSD, by an average of 33.4 ± 0.5 and 12.4 ± 2.1 g C m^2 y^{-1}, respectively. In contrast, AB reduced SOC stocks by 3.6 ± 3.0 g C m^2 y^{-1}, while the impact of E and ET was not significant at $P < 0.05$. HDSD replenished SOC stocks the most at D1 and D2 (6.7 and 7.4% y^{-1}) and this was explained by grass recovery, i.e. a significant increase in soil surface coverage by grass and grass production. HDSD is cost-effective, and thus has great potential to be widely adopted by smallholder farmers.

1. Introduction

Soils constitute the largest terrestrial carbon (C) pool, storing 2344 Pg C of soil organic C (SOC) in the top 3 m (Jobbagy and Jackson, 2000), which is more than three times the atmospheric pool of 720 Pg C. The SOC pool is thought to have been depleted by as much as 60% since the beginning of industrialization due to land use change, agriculture and land degradation (Houghton, 1995; FAO, 2010), with enormous release of greenhouse gases and associated impact on climate change. Replenishing the lost C is increasingly seen as a credible way for mitigating against climate change, while fostering other crucial soil functions such as food production, water supply, water quality, and biodiversity amongst many environmental benefits.

There are, however, still large uncertainties on the effectiveness of the measures taken to store atmospheric C in agricultural soils (Smith et al., 2008; Ciais et al., 2011). Because tillage is thought to be responsible for the historical decrease of SOC stocks from pre-deforestation levels (Lal, 2004), its abandonment has consequently been promoted to store back part or full of the lost SOC, which numerous scientific publications supported (e.g. Six et al., 2002). However, researchers such as Baker et al. (2007) and Luo et al. (2010) based on meta-data considering entire soil profiles vs the topsoil, showed that the abandonment of tillage does not lead to increased SOC stocks, with Dimassi et al. (2014) even pointing to a decrease in SOC stocks over the long term.

Grassland soils represent about 30% of the earth's land surface area, but because of poor management practices, their SOC stocks have been largely depleted over the last few decades, with overgrazing as the main cause (Lal, 2004; Conant et al., 2001). Indeed, large grazing populations reduce plant cover (Todd and Hoffman, 1999; Van Auken, 2000; Fuhlendorf et al., 2001; Rasmussen et al., 2001; Valone et al., 2002), with direct consequences on soil fertility and soil C erosion

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(Podwojewski et al., 2011; Mchunu and Chaplot, 2012). Trampling by animals is another direct consequence of overgrazing on soils, since it reduces pore space and associated soil infiltration by water (Abdel-Magid et al., 1987; Fleischner, 1994; Gamougoun et al., 1984; Schlesinger et al., 1990), which are all fostering soil erosion. Because several feedbacks exist between vegetation growth, soil compaction, soil infiltration by water, soil erosion and ultimately SOC stocks, overgrazing, which decreases biomass production and associated C inputs to the soil, also has the ability to lower SOC stocks. In support, Wu and Tiessen (2002) and Dong et al. (2012) in Chinese alpine grasslands reported that overgrazing and associated grassland degradation reduced SOC stocks by 33 to 90%. Martinsen et al. (2011) in Norway found that SOC stocks declined by 14% after 7 years of grazing, with 0.76 kg C m^{-2} in ungrazed compared to 0.64 kg C m^{-2} in heavily grazed grasslands. Steffens et al. (2008) found that grazing in semi-arid Mongolian grasslands resulted in a 45% decrease in SOC stocks (0.64 kg C m^{-2} on grazed vs 1.17 kg C m^{-2} on ungrazed grasslands). Franzluebbers and Stuedemann (2009) in the Southern Piedmont, USA, observed that 56% of the SOC stocks were lost after 12 years of grazing (0.051 kg C m^{-2} in heavily grazed vs 0.117 kg C m^{-2} under ungrazed) while Dlamini et al. (2014) in the highlands of KwaZulu-Natal, South Africa, reported a decrease in SOC stocks of up to 90%.

Because grassland degradation is thought to have resulted in large C losses from soils, with a likely increase in recent years, grassland rehabilitation, the process by which grass basal cover and biomass production recover (SER, 2004), is thus posited as a credible strategy to sequester back the lost C and to improve ecosystem functioning as a whole (Bai et al., 2010; FAO, 2010). According to several authors (e.g. Conant et al., 2001; Ravindranath and Ostwald, 2008), the revegetation of degraded grasslands could offer a global greenhouse gas mitigation potential of as much as 300 Pg C.

Since overgrazing has been identified as a major cause of grassland degradation, livestock exclusion has thus been proposed to ensure grassland rehabilitation. The few available studies point, however, to contradictory results e.g. Steffens et al. (2008) in a semi-arid grassland of Mongolia showed a SOC stock increase of 82% following livestock exclusion for 25 years, while Li et al. (2013) in China found a 25% decrease. Seeding, fertilization and shifts in livestock management have also been proposed to rehabilitate degraded grasslands (Bruce et al., 1999; Conant et al., 2001; Rietkerk et al., 2000; Potthoff et al., 2005; Castellano and Valone, 2007; Smith et al., 2008; Bai et al., 2010; Feng et al., 2013). Nitrogen fertilization, for instance, enhances primary production (Conant et al., 2001), while inhibiting soil microbial respiration (Ramirez et al., 2010), with both mechanisms likely to foster increased C allocation in soils. Nitrogen additions have also been reported to significantly increase the decomposition of light soil C fractions over decadal turnover times, while it has also been shown to further stabilize soil C compounds in heavier mineral associated fractions (Neff et al., 2002). The application of appropriate grazing regimes in degraded grasslands is also seen to be a viable solution for their rehabilitation (Papanastasis, 2009), as grazing opens up swards and enables seeds to germinate in the gaps created between tuffs (Bullock et al., 1995; Kotanen, 1996; Bekker et al., 1997).

While many studies have considered different strategies to revegetate rangeland soils (Smith et al., 2000, 2002, 2003, 2008), only a few have reported their consequences on SOC stocks (De Deyn et al., 2011). Does grassland rehabilitation have the potential to fully replenish the lost soil C stocks? What might be the C sequestration rate? These are some of the important questions, which largely remain unanswered. Filling such research gaps is crucial not only to make informed decisions on agricultural practices for effective C sequestration in soils, but also to inform C models.

Smallholder farmers in South Africa and in many drylands are facing increased grassland degradation, with consequences on soil and soil C erosion (Dlamini et al., 2011; Mchunu and Chaplot, 2012), and associated depletion of SOC stocks by as much as 90% (Dlamini et al., 2014). This study investigated the extent at which a shift in cattle management involving short-duration, high-intensity grazing, as suggested by Savory and Parsons (1980), would yield grassland recovery and C sequestration into soils. This method aims at mimicking nature and the way large animal herds were used to move over large areas as packs, which flattened the grass and covered the soil surface with mulch and dung, thus allowing biological decay before the next growing season and the grassland to rest during long durations. The surficial tillage by animal hooves, which loosens the soil and increases water infiltration in soils is also hypothesized to stimulate seed germination and plant growth (Savory and Parsons, 1980; Savory, 1983; Fynn, 2008).

2. Materials and methods

2.1. Site description

The grassland rehabilitation experiment is located in the Potshini catchment, which is 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 temperate climate with cold dry winters and warm rainy summers, a mean annual precipitation of 684 mm, most of which falls in the summer months (October and March), 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 site is on a sandy loam soil derived from sandstone, mudstone and intruding dolerite boulders and is classified as Acrisols (WRB, 2006), with kaolinite as the dominant clay mineral. The soils are characterized by a dark brown (7.5YR 4/4) 0.25 m thick A horizon, with a weak sub-angular blocky structure. This horizon is underlain by a reddish (5YR 4/6) B-horizon 0.25–0.6 m. Underlying this horizon is the C horizon 0.6–1.2 m characterized by sandy saprolite. Soils are 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% (Table 1). The vegetation in the area is classified as a Moist Highland Sourveld (Camp, 1999). The dominant vegetation species include *Hyparrhenia hirta* and *Sporobolus africanus*.

2.2. Experimental design

In this area characterized by large short-range soil variations (Dlamini et al., 2011), Dlamini et al. (2014) had selected a 30 × 50 m plot with homogeneous soils and soil properties but showing a gradient in the degradation of the grass cover from non-degraded grassland (ND) with grass above ground coverage (Cov) of 100% and located downslope, degraded grassland (D1) with 50 < Cov < 75%, D2 with 25 < Cov < 50%, middle slope, and highly degraded (HD) grassland with Cov < 5% upslope. This area was further sub-divided into six 5 × 50 m portions, each showing the whole range of intensities of grassland degradation. Each portion was subjected to different grassland management starting in June 2011: (1) high density short duration grazing (1200 cows ha^{-1} for 3 days; HDSD, Fig. 1) followed by livestock exclusion for 362 days; (2) livestock exclosure (E); (3) livestock exclosure with topsoil (0–0.02 m) tillage (ET); (4) livestock exclosure with NPK fertilization (2:3:3, 22 at 0.2 t ha^{-1}) (EF); (5) traditional free grazing with annual burning (AB); all treatments being compared to (6) traditional free grazing as a control. In the present study, 38 Nguni cattle from the local community were left overnight for 3 consecutive days during the dry season, in July 2011 and in July 2012. The E treatment consisted of full livestock exclusion throughout the same period. In the ET treatment, the excluded area was tilled by hand-hoeing to a depth of 0.02 m. The EF treatment included livestock exclusion and fertilization with nitrogen (N), phosphorus (P) and potassium (K) combined + NPK fertilizer (2:3:3, 22) at 0.2 t ha^{-1}. The AB treatment consisted of burning the grassland site once a year in June. Burning is an important management practice that is commonly used in African savanna by both livestock farmers and wildlife managers to regularly

Table 1
General soil characteristics of the experimental site prior to trial installation.

Depth	Sand	Silt	Clay	ρb	SOCc	SONc	SOCs	SONs	C/N	pH (KCl)	P	K	Ca	Mg
m	%			g cm^{-3}	g kg^{-1}		kg m^{-2}				g kg^{-1}			
0–0.05	66	15	20	1.49	9.5	1.0	0.71	0.06	9.5	3.84	4	115	138	70
0.05–0.25	67	16	17	1.45	4.4	0.4	0.95	0.09	11.0	3.86	1	49	38	18
0.25–0.45	66	17	17	1.40	3.0	0.4	0.84	0.11	7.5	3.84	1	39	26	17
0.45–0.6	67	17	16	1.38	1.7	0.2	0.35	0.04	8.5	3.81	1	39	27	23
0.6–0.9	64	21	14	1.52	1.8	0.3	0.82	0.14	6.0	3.85	1	25	31	22
0.9–1.2	58	24	18	1.59	2.5	0.4	1.19	0.19	6.3	3.78	1	30	46	28

control bush encroachment and to remove the dry and unpalatable vegetation before the next growing season (Tainton, 1999).

The study period received much less rain than the long term average with 295 mm in 2012, which corresponded to a 57% decrease and 344 mm in 2013, i.e. 50% less than the 30-years average of 684 mm.

2.3. Soil sampling

SOC stocks were assessed in June 2011, prior to trial installation (Dlamini et al., 2014), as a means to increase the level of confidence in the results on grassland management impact on soil C, such as suggested by Sanderman and Baldock (2010).

Three data points were randomly selected at each intensity of grassland degradation (ND, D1, D2, HD), resulting in 12 data points per grassland management. At each of the 12 points, three replicate topsoil (0–0.05 m) samples were collected 1-m apart in a radial basis sampling strategy, resulting in 36 soil samples per grassland management. At each of the 36 pits, two soil samples were collected using a 0.075 m diameter metallic cylinder, for the determination of SOC content and soil bulk density (Blake and Hartge, 1986). Identical sampling was performed in July 2013, i.e. two years after the onset of the trial to evaluate treatment impact on SOC stocks.

2.4. Evaluation of soil organic carbon stocks

The soil samples aimed at SOC determination were air-dried and sieved to pass through a 2 mm mesh. Total C and N were determined on air dried soil by complete combustion using a LECO CNS-2000 Dumas (LECO Corp., St. Joseph, MI). The soil samples aimed at bulk density estimation were oven-dried at 105 °C to determine dry weight.

The SOC stocks (SOCs) were then calculated using the following equation by Batjes (1996):

$$\mathrm{SOCs} = \mathrm{SOCc} \times \rho\mathrm{b} \times x_1 \left(1 - \frac{x_2}{100}\right) \times \mathrm{b} \tag{2}$$

where SOCc is the SOC concentration in the <2 mm soil material (g C kg^{-1}); ρb is the soil bulk density (kg m^{-3}); x_1 is the thickness of the soil layer (m); x_2 is the proportion of fragments of >2 mm in percent; and b is a constant equal to 0.001. SOCs were finally reported for equivalent soil mass following e.g. Dlamini et al. (2014). The SOCs changes over the duration of the experiment (2011 to 2013) were further estimated and expressed as percent of change from 2011 $\mathrm{SOC_S}$.

2.5. Evaluation of other soil characteristics

In order to characterize the soil type at the study site, selected soil properties were estimated at a single soil profile located at ND, from the soil surface to 1.2 m depth. Soil pH was measured in KCl using a Calimatic pHM766 pH meter, whereby a solution ratio of 1:2.5 was used (10 g soil: 25 mL solution). Soil texture was estimated using the pipette method. Exchangeable Ca, Mg and extractable 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 NH4HCO3, with detection by atomic absorption spectrometry (Manson and Roberts, 2000).

Based on the analytical data, the soil was classified as Acrisols. Soil horizons were sandy (sand content >64% in the top 0.9 m of the soil) and acidic (pH < 3.9). The top 0.05 m of the soil was dark-brown (10YR4/3), well structured (granular structure of few mm to 1 cm)

Fig. 1. Picture showing the study degraded grassland and its successful rehabilitation by high density-short duration (HDSD) grazing.

and enriched in organic C compared to the horizons below (9.5 g kg^{-1} vs 4.4 g kg^{-1} for the 0.1–0.25 layer). This layer showed a high density of fine roots from the grass and higher content in nutrients and cations than the underlying layers (Table 1).

2.6. Changes in grassland cover

Changes in soil surface coverage by grass, grass basal cover and plant aboveground biomass were quantified across all intensities of grassland degradation and grassland management practices. Surface coverage by grass and basal cover were determined using the method of Hardy and Tainton (1993), with 100-point observations per m^2. Three observations per combination between degradation intensity and grassland management were made using 0.5 × 0.5 m metallic quadrats placed on the soil surface, at the same location once a year, in June. The aboveground biomass was harvested within the quadrats by clipping all shoot material above the soil surface to the crown. All grassland treatments were considered with the exception of the control and AB, which were freely grazed. Grass samples were oven-dried at 60 °C and weighed.

2.7. Statistical analysis

T-test was applied to the data to test the level of significance between the management treatments under study. The data were also subjected to an analysis of variance using the PROC MIXED procedure of SAS software (SAS Institute, 2003). These variables were considered as fixed effects, whereas degradation intensities, year and grassland treatments were considered as random effects. Differences between means were tested with the DIFF option of LSMEANS statement with a significance level of $P < 0.05$.

Because the treatments were not truly replicated, statistical tests could not be in theory directly used to infer the results to other unstudied plots, unless we assume the mechanisms leading to the changes in soil carbon stocks are generalizable, a hypothesis we retained.

3. Results

3.1. Grassland management impact on grass cover

Grassland management had a significant impact on aboveground biomass. The biomass harvested at the enclosures in June 2012, i.e. 12 months after implementation of treatments (Fig. 2A) did not significantly differ between HDSD (337 g m^{-2} with a standard error of ±52 g m^{-2}), E (164 ± 35 g m^{-2}) and ET (192 ± 52 g m^{-2}), while the biomass was significantly greater at EF (1073 ± 113 g m^{-2}). Twenty four months after trial implementation, the above ground biomass was significantly higher for HDSD (977 ± 141 g m^{-2}) and EF (1184 ± 71 g m^{-2}) than for the other treatments (Fig. 2B).

The changes in biomass production translated into changes in grass basal cover (Fig. 3). From an average of 10.6 ± 1.5% in the control, basal cover increased at HDSD (12.6 ± 2.9%) and EF (12.6 ± 2.6%), but these differences were not significant at $P < 0.05$. In contrast, basal cover decreased at AB (3.8 ± 1.2%), which was significant at the $P < 0.05$ level compared to the control. Fig. 3 also indicated that E and ET basal covers did not significantly differ from the control.

The changes in biomass production significantly differed between the different grassland degradation intensities (Fig. 4A). Twenty four months after trial implementation, grassland biomass production at HDSD had increased by a maximum of 371 ± 241% at D2, followed by 231 ± 640% at ND, 113 ± 101% at D1 and 48 ± 57% at HD. In case of EF, biomass production increased the most at HD (544 ± 340%). Finally, biomass production significantly increased for AB, but only at the ND treatment (Fig. 4A).

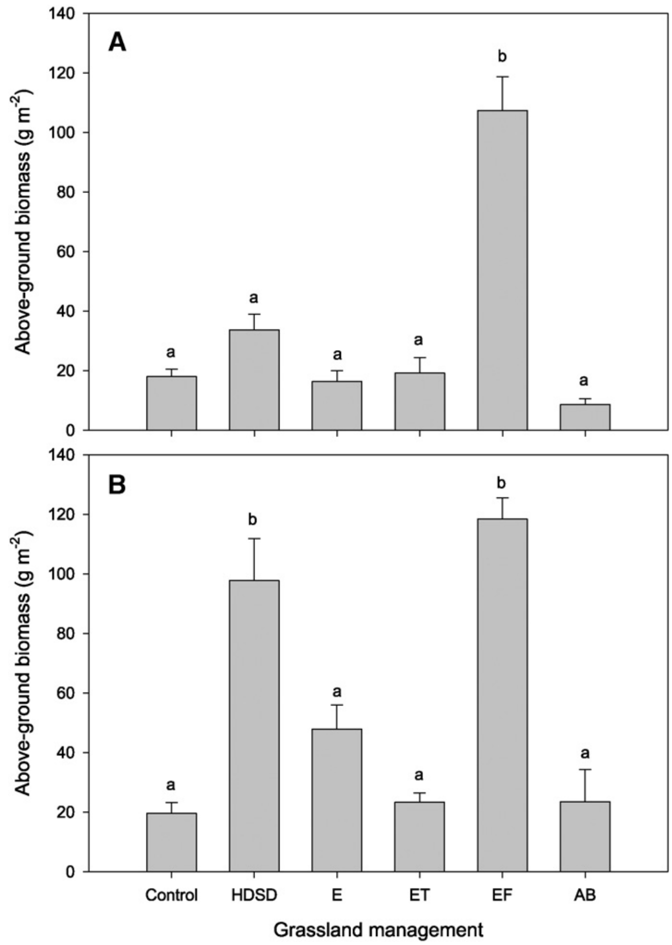

Fig. 2. Effects of grassland management on above-ground biomass in June 2012 (i.e. one year after trial installation) (A) and June 2013 (i.e. 24 months after) (B). HDSD: high density-short duration grazing; E: livestock exclosure; ET: livestock exclosure with topsoil tillage; EF: livestock exclosure with NPK fertilization (2:3:3. 22 at 0.2 t ha^{-1}); AB: annual burning. Different letters indicate statistically significant difference from Control. n = 12.

For AB, there was a tendency for SOCs to decrease as biomass production increased ($r^2 = 0.84$) (Fig. 5), while SOCs increased with increasing biomass at HDSD ($r^2 = 0.92$).

3.2. Grassland degradation impact on soil organic carbon

Grassland degradation impact on soil organic carbon was observed prior to trial implementation, i.e. in 2011. The highly degraded (HD) grasslands were characterized by the lowest soil organic carbon contents (SOCc) but higher bulk densities (ρb). The average SOCc at HD was 0.15% (Table 2). SOCc ranged between 0.11% (for Control, HDSD, E) and 0.25% for EF, through 0.16% for ET and 0.18 for AB. ρb was between 1.55 and 1.60 g cm^{-3}. SOCc increased to an average of 0.59% (0.45 < SOCc < 0.73%) for D2, to 1.03% (0.77–1.18%) for D1 and to 1.55% (1.02–2.09%) for the non-degraded (ND) situation, while ρb decreased to an average of 1.53 g cm^{-3} at D2, 1.42 g cm^{-3} at D1 and to 1.41 g cm^{-3} at ND (Table 2). All the differences in SOCc and ρb between the different grassland degradations were significant at $P < 0.05$.

3.3. Grassland management impact on soil organic carbon stocks

Two years after trial implementation, EF had increased SOC stocks (SOCs) by an average of 33.42 ± 0.49 g C m^2 y^{-1} or 4.01 ± 0.30% and HDSD had increased SOC stocks (SOCs) by an average of 12.36 ±

2.12 g C m^2 y^{-1} or 3.63 ± 0.68% (Table 3), which was in both cases significant at $P < 0.05$, while SOCs changes for E, ET, AB were not significant (Table 3). Overall, grassland management had a significant impact on SOCs with an F value of 150 and a P level <0.001.

The changes in SOCs for HDSD and EF significantly differed amongst the investigated intensities of grassland degradation (Table 3, Fig. 4C). At HDSD, SOCc increased the most at D1 (24.89 ± 3.15 g C m^2 y^{-1}) as compared with ND (−0.45 ± 0.07 g C m^2 y^{-1}). The increase in SOCs of 7.4 ± 1.9% y^{-1} was highest at D1 and decreased to 6.7 ± 0.6% y^{-1} at D2 and carbon sequestration rates were close to zero for HD and ND. In case of EF, a maximum of 101.69 ± 1.70 g C m^2 y^{-1} (i.e. 11.72% y^{-1}) occurred at HD followed by D2 (35.28 ± 1.00 g C m^2 y^{-1} or 5.75% y^{-1}), while D1 and ND did not experience any significant SOCs alteration at $P < 0.05$. The AB treatment lost an average of 3.64 ± 3.01 g C m^2 y^{-1} or 1.3 ± 0.63% y^{-1}, with the greatest losses occurring at ND (Table 3, Fig. 4C).

4. Discussion

4.1. Link between grass recovery and C sequestration in soils

This study by pointing to a significant increase of SOC stocks with increasing grass biomass and grass cover (Fig. 5) with rates of as much as about 12% y^{-1}, confirms the potential role of grassland rehabilitation in climate change mitigation. In other words, the study shows that the grassland management practices that did not yield C sequestration were those having made no difference in terms of grass recovery. Amongst the proposed explanations are increased root biomass production (Steinbess et al., 2008), greater soil aggregate stability (An et al., 2013) and associated greater organic matter protection from decomposers (Chaplot and Cooper, 2015).

4.2. Impact of annual burning on the increase of grass production but decrease in soil C stocks

Increased grass production under the annual burn treatment is likely to be due to the enhanced availability of key nutrients in the soil (Fynn et al., 2003). While the increase in grass production and grass coverage was accompanied by an increase in SOC stocks at the high density short duration and fertilized treatments. Such an increase at the non-degraded grass treatment submitted to annual burning resulted in lower SOC stocks. Several studies have similarly shown that burning reduces total SOC stocks (Fynn et al., 2003; Novara et al., 2013). While SOC reduction is often attributed to a decrease of organic matter inputs to soils, this hypothesis cannot be retained for the present study as biomass production under annual burning was significantly enhanced. Another explanation lies into the increased rate of soil organic matter mineralization as soil temperature increases (Mills and Fey, 2004). In addition, burning by decreasing soil surface coverage is likely to unprotect the soil surface from raindrops, thus potentiating soil organic carbon losses by water erosion (Mchunu and Chaplot, 2012).

4.3. Impact of high density cattle grazing on SOC stocks

Significant increases on the rate of SOC accumulation in soils were achieved through high density-short duration grazing and fertilization of exclosed grasslands, with rates of 12.36 ± 2.12 and 33.42 ± 0.49 g C m^2 y^{-1} respectively. This was relatively close to the values reported by Steinbess et al. (2008) in Germany (49 g C m^{-2} y^{-1}) following conversion of agricultural land into grassland, by Fornara et al. (2013) using NPK and Mg additions to permanent grasslands in UK (58 kg C m^{-2} y^{-1}), and Janssens et al. (2005) for European grasslands (60 g C m^{-2} y^{-1}). Steinbess et al. (2008) specifically showed that increasing grass species' diversity was beneficial for soil carbon because of increased root biomass production.

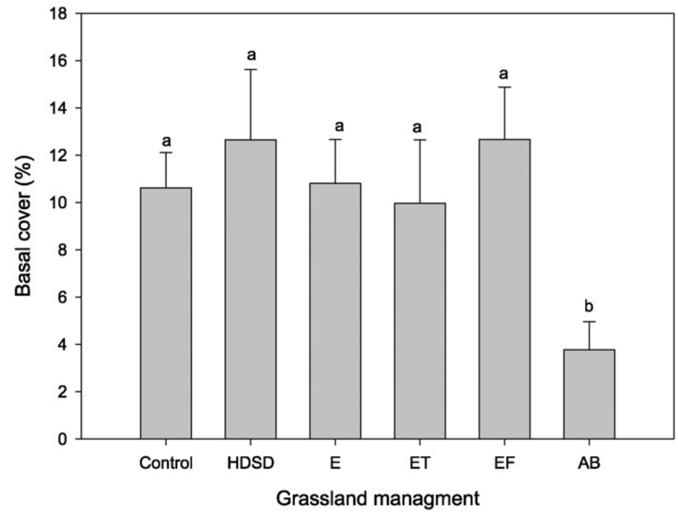

Fig. 3. Effects of grassland management on grass basal cover in June 2013, i.e. 24 months after trial installation. Different letters indicate statistically significant difference from Control at $P < 0.05$. $n = 12$.

In contrast, the rates obtained at the present study were much lower than the observations made by De Deyn et al. (2011) in UK grasslands and using fertilizer application and plant seeding with sequestration rates of as much as 317 g C m^{-2} y^{-1}.

The increase in SOC stocks under HDSD and fertilized grassland may be attributed to the addition of nutrients (N, P, K) to the soils in either organic (in case of HDSD) or inorganic form (EF), as pointed by Bardgett et al. (1998) in the case of sheep dung, which foster below ground carbon dynamics (Liu and Greaver, 2010). Such inputs increase biomass production and root activity, with both resulting in greater C inputs to the soil, which in turn enhances carbon sequestration.

The ability of HDSD to rehabilitate degraded grasslands is often attributed to a series of mechanisms. Intense cattle grazing opened up the sward canopy, which allowed sunlight to penetrate to low-growing grasses and forbs (Savory, 1983; Menke, 1992; Fynn, 2008). In addition, cattle exclusion for long periods of time is likely to allow the grass to rest. Finally, livestock 'hoofs' action' in HDSD grazing flattens the grass thus putting dead material in contact with decomposer bacteria and invertebrates in the soil which speeds nutrient recycling and litter turnover (Menke, 1992). Additionally, the treading action of cattle hooves break up impermeable crusts often found in bare soil surface conditions (Dlamini et al., 2011). The present study; showed no significant change in grass characteristics and SOC under the grass management treatments involving cattle exclosure only and surficial tillage, but only when exclosure is associated with fertilization. This suggests that the fertilization of the soil by the cattle is the most likely determinant of grass recovery under HDSD grazing.

C sequestration through HDSD grazing appeared to be the greatest for intermediate grassland degradation intensities, while limited C sequestration occurred at the non-degraded and highly degraded grasslands. The low C sequestration at the non-degraded and highly degraded grasslands can be explained in both cases by non-significant changes in grass production, while the significant changes in grass production at the intermediate degradation intensities directly translated into more C allocation into soils.

An interesting result was, however, the ability of fertilization to enhance grass production and SOC stocks at the highly degraded soils, which HDSD did not succeed to achieve. Such a result might be explained by the tendency of the cattle to aggregate and spend a large amount of time grazing and walking in highly vegetated areas and avoiding compacted bare soils, a phenomenon confirmed by our field observations.

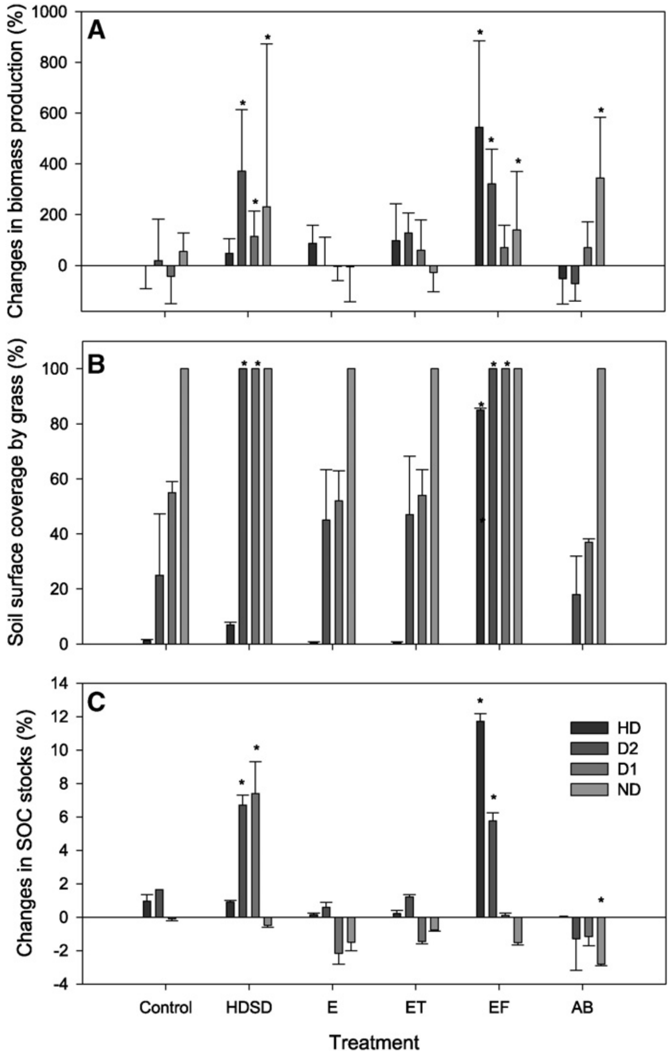

Fig. 4. Effects of rehabilitation treatments on the changes in biomass production (A), soil surface coverage by grass (B) and SOC stocks (C). Mean and standard error. A and C display the changes between June 2012 and June 2013; B shows the proportion of the soil surface covered by the grass in June 2013 only. Data are reported for different grassland degradation intensities as observed in June 2011: ND (non-degraded with grass above ground coverage. Cov of 100%). D1 (degraded: 50 < Cov < 75%). D2 (25 < Cov < 50%) and HD (highly degraded: Cov < 5%). A star indicates statistically significant difference from Control.

4.4. On the lack of SOC recovery consecutive to grazer exclusion only

This study shows that excluding the grazers per se did not improve the grassland, both in terms of soil coverage by grass and grass diversity, with associated lack of C sequestration in soils. From this result, we can conclude that fencing is not enough, an observation already made by Spooner et al. (2002) for grass recovery. While livestock removal from grasslands has long been hypothesized to regenerate degraded grassland, several recent studies such as those by Yan and Lu (2015) pointed to an increase in grass height and biomass at non-grazed sites rather than a recovery in grass basal cover and soil surface coverage. Marty (2015) in the study of grasslands of the central valley of California, even pointed to a loss of biodiversity and hydrologic function over 10 years of livestock grazing removal. This adds further arguments to the hypothesis that grazers, rather than being a cause of grassland degradation, may be in several environments, a means for improved grassland functioning provided, however, proper management is applied.

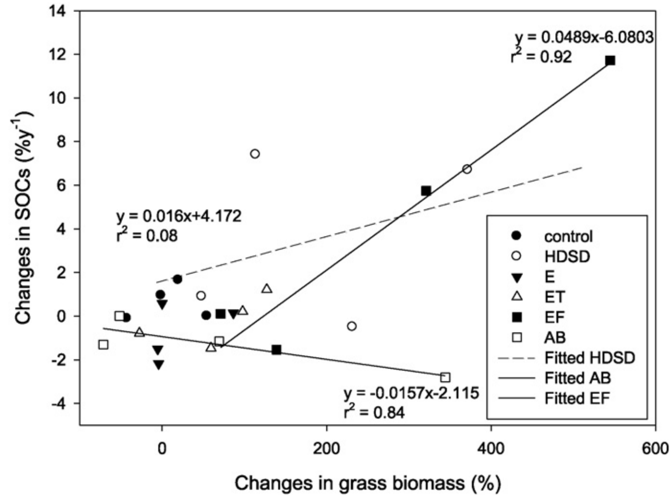

Fig. 5. Variations in soil organic carbon stocks (SOCs) as function of changes in grass biomass for study grassland managements.

5. Conclusions

Three main conclusions can be drawn from this study on grassland rehabilitation impact on soil organic carbon stocks.

The first conclusion is that two years after a shift in grassland management from free grazing by cattle to high density (1200 cows ha^{-1}) and short duration (5 h for 3 days y^{-1}) grass production was significantly increased to a maximum of 900% and soil surface coverage rose to 100% in situations where it initially was at minimum of 25%. The second conclusion was that over the duration of the study, the removal of

Table 2
Mean ρb and SOC content in the topsoil (0–0.05 m) for the study intensities of grassland degradation and treatments for 2011 and 2013. n = 12 for each grassland degradation intensity; n = 48 for the mean of degradation intensities.

Treatment	Year	HD	D2	D1	ND	Mean
ρb (g cm^{-3})						
Control	2011	1.59	1.48	1.40	1.40	1.47
	2013	1.52	1.49	1.45	1.26	1.43
HDSD	2011	1.59	1.55	1.41	1.40	1.49
	2013	1.50	1.43	1.23	1.23	1.35
E	2011	1.59	1.55	1.41	1.40	1.49
	2013	1.48	1.45	1.45	1.30	1.42
ET	2011	1.57	1.53	1.52	1.53	1.54
	2013	1.48	1.37	1.42	1.28	1.39
EF	2011	1.55	1.52	1.43	1.37	1.47
	2013	1.49	1.31	1.32	1.29	1.35
AB	2011	1.60	1.52	1.36	1.37	1.46
	2013	1.55	1.45	1.42	1.15	1.39
SOCc (%)						
Control	2011	0.11	0.65	0.77	1.31	0.71
	2013	0.11	0.65	0.74	1.46	0.74
HDSD	2011	0.11	0.45	1.18	2.09	0.96
	2013	0.12	0.49	1.35	2.38	1.08
E	2011	0.11	0.45	1.18	2.09	0.96
	2013	0.14	0.49	1.15	2.25	1.01
ET	2011	0.16	0.67	0.84	1.03	0.68
	2013	0.17	0.75	0.90	1.23	0.76
EF	2011	0.25	0.73	1.10	1.42	0.88
	2013	0.26	0.85	1.19	1.51	0.95
AB	2011	0.18	0.60	1.10	1.38	0.82
	2013	0.19	0.63	1.05	1.64	0.88

Grassland degradation intensities from ND (non-degraded with grass above ground coverage. Cov of 100%). D1 (degraded: 50 < Cov < 75%). D2 (25 < Cov < 50%) and HD (highly degraded: Cov < 5%). Rehabilitation treatments from "Control": free grazing; HDSD: high density. Short duration grazing; E: livestock exclosure; ET: livestock exclosure with topsoil tillage; EF: livestock exclosure with NPK fertilization (2:3:3. 22 at 0.2 t ha^{-1}), AB: free grazing and annual burning.

Table 3
Changes in SOC stocks in the topsoil (0–0.05 m) from 2011 to 2013 for the grassland degradation intensities and rehabilitation treatments. n = 12 for each treatment and grassland degradation intensity.

Treatment	HD		D2		D1		ND			
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
	$g\ C\ m^2\ y^{-1}$									
Control	7.41	1.63	8.44	1.20	−0.10	0.18	0.00	0.00	3.94	0.75
HDSD	13.74	2.00	24.89	3.15	11.28	3.25	−0.45	0.07	12.36	2.12
E	6.52	0.50	2.98	1.95	−2.14	0.90	−1.18	0.20	1.55	0.89
ET	2.11	0.67	7.62	0.20	−4.37	0.50	−1.51	0.30	0.96	0.42
EF	101.69	1.70	35.28	1.00	0.32	0.05	−3.60	0.20	33.42	0.49
AB	1.13	4.13	−6.17	4.17	−3.15	3.68	−6.38	0.07	−3.64	3.01
			$\%\ y^{-1}$							
Control	0.95	0.40	1.65	0.00	−0.10	0.12	0.00	0.00	0.62	0.13
HDSD	0.90	0.10	6.70	0.60	7.40	1.90	−0.50	0.10	3.63	0.68
E	0.15	0.10	0.59	0.30	−2.17	0.65	−1.50	0.50	−0.73	0.39
ET	0.21	0.20	1.22	0.13	−1.47	0.13	−0.78	0.07	−0.20	0.13
EF	11.72	0.45	5.75	0.50	0.11	0.13	−1.54	0.12	4.01	0.30
AB	0.07	0.00	−1.30	1.87	−1.16	0.54	−2.81	0.10	−1.30	0.63

Italic values indicate significance at $p < 0.05$.

grazers from grasslands did not result in grassland rehabilitation, both in terms of surface coverage and grass production, which tended to show that grazers are unlikely to be the only factor responsible for the decrease in grass density and grassland degradation for savannah grasslands at the study site. Since grassland rehabilitation was achieved by adding nutrients into soils, nutrient availability into soils appears as a key factor in grassland rehabilitation and most likely in grassland degradation. The third conclusion was the immediate recovery of the study grass characteristics directly translated into gains in soil carbon stocks of as much as 6.7 to 11.7% per year of the 0–0.05 m soil stock (or 12 to 33 $g\ C\ m^2\ y^{-1}$), depending on the rehabilitation technique and the initial degradation status.

Grasslands cover about 30% of the world's land surface and store approximately 10% of the global soil organic carbon (SOC) stock of 1500 Gt. For illustrative purposes, if we apply the 12 to 33 $g\ C\ m^2\ y^{-1}$ sequestration rate to the 59,320,000 km^2 of grassland soils, the yearly C sequestration rate could be as much as 0.70 to 1.95 Gt C y^{-1}. Extrapolated to the first meter of the soil and using a logarithmic decrease, C sequestration could increase to 2.13–5.87 Gt C y^{-1}. Moreover, assuming soils have lost about 2/3 of their carbon from the middle age (Lal, 2004) with 300 Gt lost from grasslands soils, replenishing this stock at the rate defined above could take a minimum of 50 years.

High density-short duration grazing is cost-effective, and thus has great potential to be widely adopted by smallholder farmers.

More is to be expected from this research trial: (1) on C storage from topsoil to bedrock; (2) on the quality of the stabilized organic matter and on the longer-term carbon sequestration. Research studies to come also have to consider truly replicated treatments and a set of ecosystem functions from food production to biodiversity through water quality and availability, from plot to river basins and oceans with feedbacks to the atmosphere.

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