Geoderma Regional 28 (2022) e00479

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

On the impact of grassland management on soil carbon stocks: a worldwide meta-analysis

K. Phukubye[a], M. Mutema[b], N. Buthelezi[a], P. Muchaonyerwa[a], C. Cerri[c], V. Chaplot[a,d,*]

[a] School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville 3209, Pietermaritzburg, South Africa
[b] Agricultural Research Council-Agricultural Engineering, Private Bag X519, Silverton 0127, Pretoria, South Africa
[c] Soil and Plant Nutrition, Luiz de Queiroz College of Agriculture, University of São Paulo, Avenida Pádua Dias, 11, Agronomia, Piracicaba, SP 13418-900, Brazil
[d] Institut de Recherche pour le Développement (IRD), Laboratoire d'Océanographie et du Climat: Expérimentations et approches numériques, UMR IRD-CNRS-MNHN-UPMC 7159, 5 place Jussieu, 75252 Paris Cedex 05, France

ARTICLE INFO

Keywords:
Soil organic carbon
Rehabilitation
Grazing
Multiple soil classes
Meta-analysis

ABSTRACT

Grasslands occupy 70% of whole agricultural land and hold significant amounts of carbon, a key element in the regulation of Earth's soils fertility, biomass production and climate. Previous work has shown that carbon stocks of grassland soils have been largely depleted worldwide due to missuse or mismanagement but that shifts in management could also potentially increase soil carbon stocks and mitigate against the degradation of natural ecosystems. However, the existing literature points to large discrepancies in the impact of grassland management practices on soil carbon, which the present study investigated. Here we considered 235 experimental sites in 18 countries across the world where shifts in grassland management involved different grazing strategies (free, F vs controlled, C; high, H vs low, L density grazers), grazers exclusion (E), mowing (M) and burning (B). The best performing practice was controlled grazing with high density of grazers (CHG) with an average soil organic carbon content (SOC_C) increase of 21% and with 100% of the studies pointing to a SOC_C increase. This was followed by E (14.9%; 60%) and FLG (13.3%; 80%). On average, burning grasslands, decreases SOC_C by 9.3% but 31% of the studies pointed to an increase, thus indicating discrepancies in the impact of grassland management. CLG and mowing did not significantly impact SOC_C. These results also indicated that B decreased SOC_C the most under moist to humid climates (−10.9% vs −1.7% under arid to semi-arid), while that E was only beneficial in arid to semi-arid grasslands. Adoption of rotational high-intensity grazing in place of free grazing grasslands, should be seriously considered by policy and decision makers to mitigate against climate change while fostering economic and social development.

1. Introduction

In 2015, 192 countries ratified the COP21 in Paris to keep global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit further increase of the temperature. At that occasion, transfer of atmospheric carbon (C) to soils, to increase the soil organic C stocks, was suggested as an effective and low cost means to meet the COP21 objective (Minasny et al., 2017). Spill over benefits such as improved soil health, soil fertility and reduced soil erosion will accrue to potentiate food production (Lal, 2015).

Grasslands, which are natural ecosystems with grass as the dominant vegetation, occupy about 40% of the earth's land surface area and 70%

Abbreviations: B, Burning; BD, Soil bulk density; C, Carbon; C/N, carbon to nitrogen ratio; CHG, Controlled high grazing; CLG, Controlled low grazing; CV, Coefficient of variation; N, Sample size; E, Grazer exclusion; FLG, Free grazing with low intensity; FHG, Free grazing with high intensity; LAT, Latitude (°); LONG, Longitude (°); M, Mowing with residues retained; MAP, Mean annual precipitation (mm $year^{-1}$); MAT, Mean annual air temperature (°C $year^{-1}$); Max, Maximum; Min, Minimum; PC, Principal Component; PCA, Principal Component Analyses; Quart, Quartile; SEM, Standard error of mean; SOC_C, Soil organic carbon content (%); SOC_S, Soil organic carbon stocks (kg C m^2); SON_C, Soil organic nitrogen content (%); Z, Altitude (masl); ΔSOC_C, Change in soil organic carbon content (%); $\Delta SOC_C >$ 0, Number of studies with positive change in soil organic carbon content (%); ΔSON_C, Change in soil organic nitrogen content (%); ΔBD, Change in bulk density (%); ΔC/N, Change in carbon to nitrogen ratio (%).

* Corresponding author at: School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville 3209, Pietermaritzburg, South Africa.

E-mail address: vincent.chaplot@ird.fr (V. Chaplot).

https://doi.org/10.1016/j.geodrs.2021.e00479
Received 12 February 2021; Received in revised form 5 August 2021; Accepted 24 December 2021
Available online 29 December 2021
2352-0094/

of all agricultural land (FAO, 2015). Despite being mostly found under the arid to semi-arid climates of Africa, Asia and America where net primary production is significantly lower than the worldwide average (Abdalla et al., 2016), grassland soils store about 10% of the global soil organic C (SOC) stocks, which is nearly 50% more than is stored in forests worldwide (FAO, 2015). Previous work established that grassland soil C stocks are sensitive to changes in land use and management. Guo and Gifford (2002) reported that converting grassland to cropland is detrimental to SOC stocks with a worldwide average loss of 59%. A comprehensive meta-analysis by Dlamini Chivenge and Chaplot (2016), using 628 soil profiles, revealed that grassland degradation further declines SOC stocks by a worldwide average of 9% and that this decline was associated with a loss of basal grass cover. Higher average SOC stock decline (−16%) was found under dry climates (<600 mm of rainfall per annum) than wet climates (−8% for >1000 mm yr^{-1} zone).

It was also learned from Abdalla et al. (2016) that when grazing intensity rises above carrying capacity, SOC stocks decrease at an average rate of −0.9% per year, which can be attributed to a net loss of grass and/or inability of frequently grazed plants to build root C reserves, thus unable to sustain atmospheric C allocation to soils (Savory and Parsons, 1980). On the other hand, Conant et al. (2017) reported that only 49% of worldwide studies on improved grassland management practices such as low stocking rates, exclusion of grazing livestock and planned rotational grazing enhanced SOC stocks, thus pointing to the absence of consensus on the grassland management strategies to promote for increasing SOC stocks. There is also no consensus on the impact of practices that do not involve livestock such as burning, which is a common practice for increasing fodder production and quality, whilst avoiding bush encroachments (Tainton, 1999). For instance, Abdalla et al. (2016) reported that SOC stocks increased from 1.4 to 1.6 kg C m^{-2} (i.e. by 14%) in the 0–0.2 m soil depth of a long-term (70 years) annual burning trial in sub-tropical humid South Africa. However, Granged et al. (2011) reported a decrease of 35% for a site in Spain, and Nardoto and Bustamante (2003) reported a 13% decline for another site in Brasil. Discrepancies on the impact of burning also exist within single ecosystems. For example, Snyman (2002) reported a decrease of −33% while Manson et al. (2007) reported an increase of +22% in SOC stocks of a grasslands subjected to burning in savannah climate of South Africa.

Previous studies that quantified consequences of grassland degradation (Dlamini et al., 2014), conversion of forest and/or cropland to grassland, burning, fertilization and reclamation of grass (Conant et al., 2001; Conant et al., 2017), grazing intensity (Abdalla et al., 2016) on grassland SOC demonstrated that SOC is very sensitive to changes in management practices. The studies also showed large discrepancies in the impacts of these practices on SOC changes. For instance, Conant et al. (2017) reported an average SOC increase of 0.28 Mg C ha^{-1} yr^{-1} following adoption of improved grazing but with changes in SOC stocks varying between −30% at one study site and 70% at another, which points to a need to understand the reasons behind such discrepancies before suggesting adoption of any given practice at large scale. Investigation of inconsistencies on the effects of a given practice to enhance grassland SOC stocks thus becomes an important objective. Therefore, the main purpose of the current paper was to investigate discrepancies in the effects of selected grassland management practices; burning, low and high intensity grazing (free or controlled), mowing and livestock exclusion, on SOC stocks.

2. Materials and methods

2.1. Database preparation

A comprehensive search was performed on the Web of Science to harvest published research papers on grassland management practices and their impacts on soil carbon stocks and other selected soil properties such as nitrogen content, bulk density and soil water content, between January and July 2017. The key words used for the search from title, abstracts and keywords included “grass” AND/OR “grassland” AND/OR “veld” AND/OR “burning of grass”, AND/OR “livestock exclosure” AND/OR “livestock exclusion” AND/OR “grazing, intensity” AND/OR “grazing density” AND/OR “soil carbon, nitrogen stocks”. All references in the papers found were also assessed in order to increase the search. The search process identified 342 papers. Only studies reporting on results based on grassland management trials longer than three years and including soil carbon concentration and stocks in their analyses were selected. Sixty-two papers met the acceptance criteria. The 62 papers reported on trials performed on 235 experimental sites in 18 countries across the world (Fig. 1). Table 1 shows a summarised version of the database. The studies had to compare management practices against free grazing as reference. Different management practices were considered from free grazing at high intensity (FHG) and controlled grazing at low or high intensity (CLG, CHG), burning (Burn), mowing (M) and cattle exclusion (E). The intervals between burning incidences varied with study site and were recorded in the same way as the duration of livestock exclosure, which also varied with experimental sites.

2.2. Data extraction

2.2.1. Variables of interest

Data on soil organic carbon content (SOC_C), soil organic nitrogen content (SOC_C), soil organic carbon stocks (SOC_S) and soil bulk density (BD) were collected from the papers. Here we used data from the shallowest available soil layer where most of soil carbon lies (Dlamini et al., 2014), mostly from the 0–0.05 m layer but when not available to 0.05 m the data came to the shallowest depth available to a maximum of 0.3 m ($n = 15$). In order to compare SOC_S from different thicknesses of the topsoil layer, the data were converted to soil carbon stocks per m^3 of soil using the depth of soil layer considered. Moreover, the data on soil organic matter content were converted to SOC_C using the 1.72 ratio (Pribyl, 2010), a conversion factor that assumes organic matter contains 58% organic carbon. Data for each management were subtracted from reference treatment (free grazing at low density) and expressed in gram or percent difference per year to remove the differences in length of trials. Finally data of carbon stocks were also reported per cubic metre of soil to improve the comparisons between layers of different thicknesses. When not available in the research papers, data of BD were estimated using values of SOC_C and SOC_S. The missing SOCc or SOC_S values were estimated in a similar way, and when not possible the data points had no information (see Table 2 for number of data points).

Here were considered the treatment means, the sample sizes (i.e. number of replications), and the standard deviation (SD) between replications. When not directly available these parameters were either estimated from the replicates or recalculated such as for SD that was in some cases obtained from standard error data [$SE = SD\ (n^{-1/2})$]. In case of the results were only presented in the format of figures, which occurred for two studies, the data were extracted through graph digitisation (use of “GetData Graph Digitizer 2.26”).

2.2.2. Secondary variables

The environmental factors were related to site location (LONG: longitude, LAT: latitude and Z: altitude), climate (MAP: mean annual precipitation, and MAT: mean annual air temperature), thickness of the entire soil profile and soil texture (clay, silt and sand content) of the upper layer. These variables were stratified into 3 classes (low, medium and high, Table 3). The soil order (WRB, 2015) at each data point was considered and the climates were defined following Mathew et al. (2017).

2.3. Statistical analysis

The first step of the statistical analysis was to calculate descriptive statistics for the selected variables (Tables 4 and 5). Meta-analysis was then applied to the data to quantify the significance of the impact of the

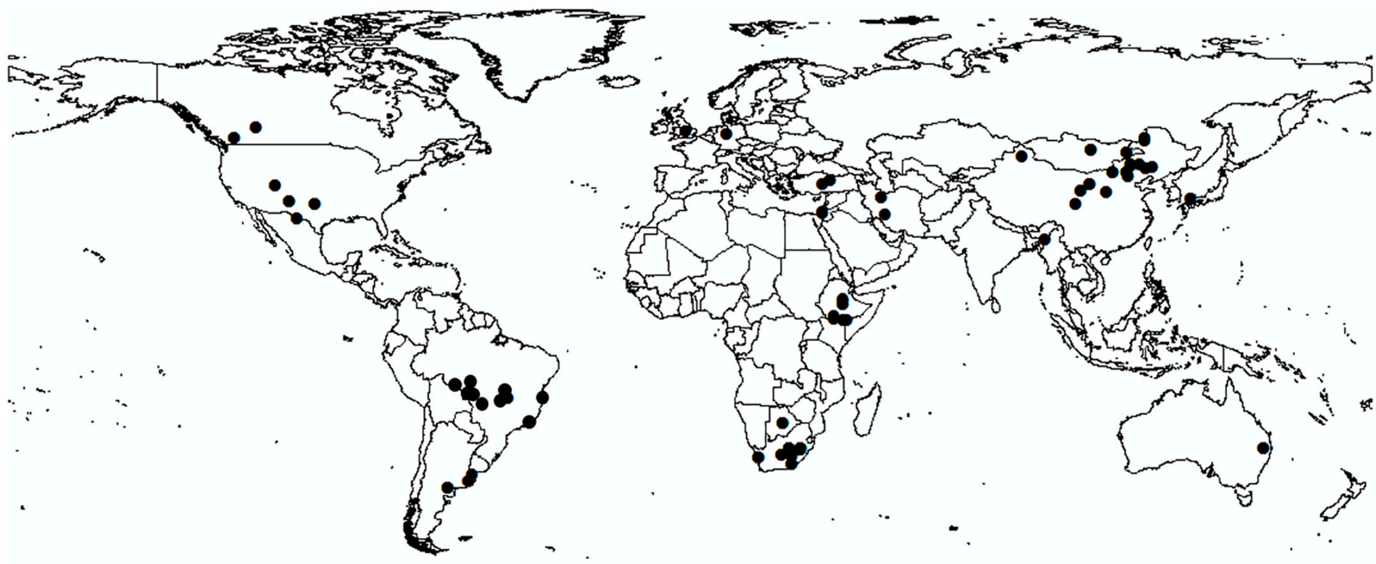

Fig. 1. Global distribution of the sites where data used in the analysis.

grassland management techniques under study on SOC_S. The MetaEasy software (v1.0.5, Kontopantelis and Reeves, 2009) was used to compute effect sizes (a quantitative measure of the magnitude of the relationship between two variables, the larger the effect size the stronger the correlation between the two variables) and standard errors (SE) from each technique. MetaEasy allows the standardisation of effect size according to eight possible methods based on the sample size and available information, and ultimately selects the method that minimises the biases (Kontopantelis and Reeves, 2009). Bootstrap resampling was used to assign confidence intervals (CI) at 95%.

The multiple correlations between grassland management techniques and soil and environmental conditions were further investigated using principal component analysis (PCA) (Fig. 3). PCAs convert nonlinearly correlated factors and variables into linear combinations called principal components (Jambu, 1991) and based on the assumption of normality, which was not necessarily true with the study due to the disparate nature of the data.

3. Results

3.1. Variations of soil and environmental conditions across the data set

Table 4 presents the descriptive statistics depicting variability of the environmental conditions across the data set. The mean annual precipitation (MAP) was 711 mm yr^{-1} with values ranging from 100 mm yr^{-1} in China (Rong et al., 2014) to 2326 mm yr^{-1} in Brazil (Conant et al., 2017). Mean MAT was 14.0 °C with data varying from −8.5 °C in Canada (Donkor et al., 2002) to 32 °C in Ethiopia (Kassahun et al., 2012). Altitude (mean of 956 m) ranged from 4 m in Brasil (Conant et al., 2017) to 3500 m in China (Li et al., 2011). Soil texture also varied greatly across sites with clay content (mean, 24.9%) varying from 3.0% in China (Pei et al., 2008) to 74% in Brazil (Nardoto and Bustamante, 2003).

3.2. Variations in soil carbon and nitrogen

Soil carbon and nitrogen varied greatly within the data set (Table 5). The average soil organic carbon content (SOC_C) computed from all reference treatments was 2.26% with a standard error mean of ±0.19% (Table 5). Values varied from 0.06% in the USA under Aridisols and 6% clay content (Neff et al., 2005) to 20.16% under gleyic andosols in Japan (Shimoda and Takahashi, 2009). The mean soil organic nitrogen (SON_C) at the reference sites was 0.19 ± 0.02 with values ranging from a minimum of 0.01% also found by Neff et al. (2005) to 1.17% under Mollisols with 10% clay content in Canada (Evans et al., 2012). The resultant average carbon to nitrogen (C/N) ratio at these sites was 11.52 ± 1.10.

Soil bulk density at reference sites averaged 1.22 ± 0.02 g cm^{-3} and soil organic carbon stocks (SOC_S) was 2.02 ± 0.08 kg C m^2 with values between 0.27 and 17.80 kg C m^2 (Table 5).

On average, changes in grassland management decreased BD by 0.40 ± 0.15% yr^{-1}, enhanced SOC_C by 0.71 ± 0.52% yr^{-1}, SON_C by 1.17 ± 0.84% yr^{-1} and SOC_S by 0.24 ± 0.54% yr^{-1} (Table 5). The change in SOC_C (ΔSOC_C) varied from a − 25.9% yr^{-1} under free grazing with high density grazers in Argentina (Abril, 1999) to 28.9% yr^{-1} at a livestock exclosure site in China (Yang et al., 2016).

3.3. Effects of grassland management practice on soil carbon

Soil carbon stocks were significantly affected by only one out of the six grassland managment techniques (Fig. 2A). Controlled grazing with high density grazers (CHG) significantly enhanced soil carbon stocks (SOC_S) with an effect size of 0.477 and a top-soil SOC_S increase by an average 5.9% yr^{-1} or 94.5 g m^{-3} yr^{-1} (Fig. 2A). In contrast, under the conditions of the study, the effect on SOC_S was neutral for exclosure (effect size = 0.004), mowing (0.009), high density free grazing (−0.013), burning (−0.002) and controlled grazing with low density grazers (−0.016).

Similarly, CHG was the only technique to significantly enhance soil carbon content (SOC_C) with an effect size of 0.70 and a mean percentage change of 6.6% yr^{-1} (Fig. 2B). Finally, for top-soil bulk density (BD) the effect of grassland management (Fig. 2C) was significant for burning (effect size of 0.071; 1.08% yr^{-1} increase) and controlled grazing at low density (0.074; 1.07% yr^{-1}).

3.4. Effect of soil and environmental conditions on the changes in soil carbon

Fig. 3 shows the variations in soil carbon stocks (ΔSOC_S) following the changes in management for different soil orders. The statistics for Mollisols were performed using 64 data points, Alfisols (60), Oxisols (43), Aridisols (24), Vertisols (17), Entisols (13), Ultisols (2) and with 14 data points with undetermined soil order. The median stock difference was with −10 gC m^{-3} y^{-1} the lowest for Oxisols, followed by Aridisols and Mollisols (2.1 and 3.2), Entisols (6.0), Alfisols (8.1), Vertisols (14.0)

Table 1
Compilation of references (authors and years), country of reference, investigated practices (B, burn; G, Grazing; E, exclosure), mean treatment duration and selected environmental factors (MAP, mean annual precipitation; MAT, mean annual temperature), soil type as provided by the authors and equivalent WRB (2015) soil order.

n	Authors	Soil type	Soil order	Countries	Practices	Duration	MAP	MAT
						y^{-1}	mm y^{-1}	°C y^{-1}
1	Abril and Bucher 1999	Aridic Haplustoll	Aridisols	Argentina	G	NA	550	23
2	Harris et al., 2007	Calciustolls	Mollisols	Argentina	E, B	25,2	400	16
3	Lavado et al., 1996	Typic Natraquoll	Mollisols	Argentina	G	38,8	950	15
4	Picone et al., 2003	Typic Natraquoll,	Mollisols	Argentina	B	4,0	1029	15
5	Sanjari et al., 2008	NA (clay to clay loam)	Alfisols	Australia	G, E	NA	645	15
6	Kgosikoma et al., 2015	NA laom to sand	Entisols	Botswana	G, B	25,0	426	22
7	Conant et al., 2017	NA	Oxisols	Brazil	G, E, B	16,0	1616	23
8	Nardoto and Bustamante, 2003	Oxisols	Oxisols	Brazil	B	NA	1350	21
9	Donkor et al., 2002	Luvisols	Alfisols	Canada	E	1,0	334	−8.5
10	Evans et al., 2012	Chernozems	Mollisols	Canada	E	0,5	270	15
11	Krzic et al., 2014	Chernozems	Mollisols	Canada	G	6,5	409	7.2
12	Cao et al., 2013	NA	Mollisols	China	G, E	NA	280	3.4
13	Chen and Tang, 2016	Calcic Chernozem,	Mollisols	China	G, E	1,3	279	2.4
14	Gao et al., 2009	Mat Cry-gelic Cambisol	Mollisols	China	G	NA	750	1.1
15	Jiao et al., 2016	“diluvial desert soil”	Aridisols	China	G	25,8	185	8.3
16	Liu et al., 2012	NA	Mollisols	China	G, E	13,0	308	2.1
17	Pei et al., 2008	Typic Calciorthid	Mollisols	China	E	13,5	134	9
18	Rong et al., 2014	Calciorthid	Mollisols	China	G, E	25,0	100	3.5
19	Steffens et al., 2008	Calcic Chernozems	Mollisols	China	G, E	17,0	343	0.7
20	Su et al., 2006	Sandy chestnut	Mollisols	China	G	5,0	366	6.5
21	Su et al., 2004	Sandy chestnut	Mollisols	China	E	25,0	366	6.5
22	Su et al., 2005	Sandy chestnut	Mollisols	China	E	10,0	366	6.5
23	Wang et al., 2016	Orthic Aridisol	Aridisols	China	G, E	NA	400	1.5
24	Li et al., 2011	sub-alpine meadow soil	Entisols	China	G	2,0	620	1.2
25	Wu et al., 2014	Chernozem/chestnut	Mollisols	China	G	25,0	339	−2.2
26	Xu et al., 2011	Calcic-orthic aridisol	Aridisols	China	G, E	25,0	400	1.2
27	Xu et al., 2014	Calcic-orthic aridisol	Aridisols	China	G, E	25,0	400	1.5
28	Yang et al., 2016	Chernozem	Mollisols	China	G	12,0	378	7.3
29	Zhao et al., 2007	Chernozium	Mollisols	China	G, E	21,3	343	0.7
30	Zhou et al., 2010	NA (“loess soils”)	Mollisols	China	G, E	7,0	505	8.8
31	Kassahun et al., 2012	Vertisols	Vertisols	Ethiopia	G	7,0	250	32
32	Yusuf et al., 2015	Chromic Cambisol	Mollisols	Ethiopia	G, E	3,0	550	20
33	Nüsse et al., 2017	Vertisol	Vertisols	Germany	G	25,0	879	8.2
34	Devi et al., 2014	NA (clayey loam)	Alfisols	India	G	30,6	1522	19
35	Zarekia et al., 2012	NA (sandy loam)	Entisols	Iran	G, E	25,0	200	19
36	Koyama et al., 2015	NA	Mollisols	Japan	B	30,0	232	0.2
37	Shimoda and Takahashi, 2009	Gleyic Andosols	Ultisols	Japan	G	26,0	1724	16
38	Barger et al., 2004	NA (coarse textured)	Mollisols	Mongolia	G	NA	399	0
39	Han et al., 2008	Chernozem	Mollisols	Mongolia	G	NA	400	−0.2
40	Niu et al., 2011	calcisols	Mollisols	Mongolia	G, E	21,8	210	8
41	Al-Seekh et al., 2009	Rendzinas	Entisols	Palestine	E	6,5	325	32
42	Abdalla et al., 2016	Westleigh	Alfisols	South Africa	B	42,5	694	16
43	Chaplot et al., 2016	Acrisols	Alfisols	South Africa	G, E	4,0	684	13
44	Manson et al., 2007	Hutton	Alfisols	South Africa	B	25,0	1380	25
45	Materechera et al., 1998	Glenrosa	Alfisols	South Africa	B	13,5	500	21
46	Oluwole et al., 2008	Glenrosa	Alfisols	South Africa	G, B	8,0	500	21
47	Snyman, 2002	Bloemdal	Alfisols	South Africa	B	1,0	560	25
48	Oğuz et al., 2015	NA	Aridisols	Turkey	G, E	4,0	306	9.4
49	Yalçın et al., 2016	Vertisol	Vertisols	Turkey	E	10,0	797	14
50	Ward et al., 2016	NA	Alfisols	UK	G	25,0	885	9.7
51	Bauer et al., 1987	Haploborolls	Mollisols	USA	E	9,0	412	6.3
52	Frank et al., 1995	Haplorborolls	Mollisols	USA	G, E	25,0	414	5.5
						NA		
53	Gardner, 1950	Whitehouse-Tucumcacori group	Entisols	USA	E	NA	431	11.6
54	Gill, 2007	Cryoborolls	Entisols	USA	E	NA	932	1.1
55	Manley et al., 1995	Ascalon/Altvan	Aridisols	USA	G	NA	405	7.6
56	Neff et al., 2005	Haplocambids	Aridisols	USA	G, E	25	207	12
57	Seitlheko et al., 1993	Aridic Ustochrepts/Calciusto,	Aridisols	USA	G	3	400	15
58	Schuman et al., 1999	Argiustolls	Mollisols	USA	G	8	387	8
59	Teague et al., 2010	Tilvern and Wichita series	Alfisols	USA	G, B	7,5	648	17
60	Weitz and Wood, 1986	Leeray clay	Vertisols	USA	G	25	361	9.9
						10		
61	Wood and Blackburn 1984	Leeray clay	Vertisols	USA	G	25	624	17.2
62	Nyamadzawo et al., 2014	Haplic Lixisols	Alfisols	Zimbabwe	G, B	25	750	19

and Ultisols (85.2), all these differences being not significant at $P < 0.05$ level.

As pointed out by Fig. 4, management duration did not have a significant impact ($P < 0.05$) on the changes of soil organic carbon stocks with average carbon gains of 30.43 gC m^{-3} y^{-1} for durations lower than 10 years, 5.59 gC m^{-3} y^{-1} for 10–20 years but −15.51 for 20–30 years and − 0.62gC m^{-3} y^{-1} for more than 30 years.

Fig. 5 shows the multiple correlations between the selected variables of interest (ΔSOC_C, ΔSOC_S, ΔSON_C, $\Delta C/N$, ΔBD) on one hand, and soil and environmental factors on the other hand. On Fig. 3A, focusing on all managment techniques, the first two axes of the PCA explained 94% of the data variability, with Axis 1 explaining 66% while Axis 2 accounted

Table 2
Definitions of the environmental factors and soil properties used in the data-analysis.

Environmental factors, soil properties and techniques	Symbols	Units	Definitions
Mean annual precipitation	MAP	mm year^{-1}	Long-term (at least 30 year) mean annual precipitation for the study location from the papers
Mean annual temperature	MAT	°C	Long-term (at least 30 year) mean annual air temperature for the study location from the papers
Longitude	LONG	°	Longitude of the midpoint of study site as given in paper
Latitude	LAT	°	Latitude of the midpoint of study site as give in paper
Altitude	Z	m	Average elevation above sea level of the study site given in the papers
Clay content	Clay	%	Average clay content
Sand	Sand	%	Average sand content

Table 3
List of controlling factor classes describing the environmental conditions used in the analyses.

Environmental factors	Remarks	Class range	Name
Climate (MAP, mm year^{-1}; MAT, °C year^{-1})	Warm and dry	MAT: 3.5–31.9 MAP 100–300	Arid
	Cool and dry	MAT: −2.2-25.0 MAP:300–550	Semi-arid
	Cool and moist	MAT: 1.2–18.6 MAP: 550–700	Moist
	Warm and wet	MAT: 8.2–25.0 MAP:700–1350	Humid
	Warm and wet	MAT:15.6–18.9 MAP: >1350	Wet
Clay (%)	Average clay	0–20	Low
		20–40	Medium
		>40	High
Sand (%)	Average sand content	0–20	Low
		20–40	Medium
		>40	High
Grazing intensity: number of animal units stocked per unit area per year (AU ha^{-1} yr^{-1})	Light grazing	0.4–2.5	LG
	High density	>2.5	HG
Livestock exclosure: period of time a plot has been excluded from grazing and/or burning (years)		≤10	E ≤ 10
		10–20	E10–20
		20–30	E20–30
		≥30	E ≥ 30
Burning frequencies: number of years from one incidence of burning grass to the other (years)		1–2	B1–2
		3–5	B3–5
		>5	B > 5

Climate classes were adapted from Mathew et al. (2017); other factor classes were adapted from Mutema et al. (2015).

for 28%. In axis 1, ΔSOC_C, ΔSOC_S and ΔSON_C had positive coordinates while ΔBD had negative coordinates, indicating a tendency for soil C and N to increase concomitantly, and to be associated to a decrease in soil compaction. Fig. 3A also shows a positive correlation between ΔSOC_C and ΔSON_C on one hand and soil clay content on the other, meaning that changes in soil C and N were the greatest at higher soil clay content ($r = 0.67$, Table 6) but also warmer climatic conditions ($r = 0.58$ with MAT). Changes in the C/N ratio correlated the most with SOC_C, pointing to an increase in C relative to N as soil carbon content increases ($r = 0.62$, Table 6).

The PCA generated from the grazing treatments only (Fig. 4B) pointed to a correlation between MAT, MAP and clay content on the one hand and SOCc, SOC_N and SOCs in the other hand, thus showing a tendency for soil C and N to increase the most under high clay, temperature and rainfall conditions. From Table 7 we also learn that controlled grazing with high density grazers (CHG) had a singular behavior with the greatest SOC_S gains under arid to humid and low clay conditions. Controlled high grazing (CHG) enhanced SOC_S the most under moist-humid (233 g m^{-3} yr^{-1} or 8.9% yr^{-1}) and arid to semi-arid (15.6 g m^{-3} yr^{-1} or 1.9% yr^{-1}) and as compared to wet climates (0.5% yr^{-1}) and the increase was greater under low clay conditions (211.7 g m^{-3} yr^{-1} or 3.15% yr^{-1} at <20% clay) (Table 7). CHG thus appeared to induce highest SOC recovery under moist-humid and sandy soil conditions than under wet and clayey ones.

In contrast, controlled low grazing (CLG) only slightly increased SOCs under sandy and arid conditions but these differences were not significant. CLG enhanced SOC_S by 3.1% yr^{-1} under the wet climate (Table 7).

Finally, grass burning significantly decreased SOC_S from Arid to humid climates but not for wet ones (Table 8) and lessened SOC_S for all textures. The PCA of Fig. 5D showed that the impact of grazer exclusion (E) on soil C and N did not correlate with climate. However, Table 7 indicated SOC_S slight gains under arid to humid conditions and significant losses under wet climate (−2.1% yr^{-1}).

4. Discussion

4.1. The impact of grassland management on soil C and other selected soil properties

From our dataset, controlled grazing at high density (CHG) was the only grassland management technique that significantly increased topsoil organic carbon content (SOC_C) and stocks (SOC_S) as compared to controlled grazing at low density (CLG), free grazing at high density (FHG), grazer exclusion (E), mowing (M), and grass burning (B). CHG yielded the highest soil C increase in the study by Gao et al. (2009) in China finding a 48% SOC_C rise, Chaplot et al. (2016), in South Africa found a 35–45% increase, Li et al. (2000) in China (20%) and Manley et al. 1995 in the USA found 20%. From these studies we also learn that soil C recovery is likely to be due to increase in soil surface coverage by grass (Chaplot et al., 2016) that potentiates C inputs to the soil by plants. Greater soil coverage by grass also decreases soil C erosion during rainstorms (Mchunu and Chaplot, 2012). C increase may also be due to a greater proportion of N fixing grass species that helps building soil organic matter as indicated by Guo and Gifford (2002). CHG also

Table 4
Overall descriptive statistics of the controlling factors selected for this study. Data from 235 experimental sites worldwide.

	Mean	Median	Min	Max	Q1	Q3	CV	SEM	Skew	Kurt
MAP	711	494	100	2326	343	879	77	36,1	1.4	1.4
MAT	14.0	15.0	−8.5	32.0	6.7	20.8	69.6	0.6	0.0	0.0
Z	956	1012	4	3500	418	1375	67	44.8	0.7	0.6
Clay	24.9	23.0	3.0	74.0	11.0	33.0	68.7	1.5	1.0	1.0

Mean; Median, Min = minimum value; Max = maximum value; Q1 and Q3 = 25th and 75th percentiles; CV = coefficient of variation; SEM = standard error of mean; Skew = skewness; Kurt = kurtosis; MAP = mean annual precipitation (mm yr^{-1}); MAT = mean annual air temperature (°C); Z = altitude (m); Clay = clay content (%).

Table 5
Overall descriptive statistics of the selected variables. Soil organic carbon content (SOC_C, %); soil organic nitrogen content (SON_C, %), Soil organic carbon stocks (SOC_S, kg C m^3); soil bulk density (BD in g cm^{-3}); variation in SOC_C, SON_C, SOC_S and BD (ΔSOC_C, ΔSON_C, ΔSOC_S and ΔBD in percentage difference per year from the reference (Ref) and the considered treatment (Treat), C/N ratio.

	n	Mean	median	min	max	Q1	Q3	CV	SEM	Skew	Kurt
SOC_C Ref	446	2.26	1.44	0.06	20.16	0.96	2.83	116	0.19	3.87	3.84
SOC_C Treat	446	2.34	1.42	0.12	26.04	0.95	2.53	135	0.22	4.75	4.72
ΔSOC_C	446	0.71	0.34	−38.7	42.9	−0.85	1.69	933	0.52	0.37	0.38
SON_C Ref	301	0.19	0.15	0.01	1.17	0.11	0.21	104	0.02	3.29	3.24
SON_C Treat	301	0.19	0.15	0.01	1.16	0.09	0.21	92	0.02	2,98	2.93
ΔSON_C	301	1.17	0.02	−25.9	28.9	−1.58	2.08	715	0.84	0.76	0.75
SOC_s Ref	367	3,02	1,93	0,08	12,70	1,34	4,27	86,96	0,17	1,72	1,71
SOC_sTreat	367	3,04	1,95	0,15	14,50	1,33	4,44	91,74	0,18	1,93	1,91
ΔSOC_s	367	0.24	0.089	−40.6	41.3	−1.05	0.98	748	0.54	0.08	0.08
C/N Ref	301	11.52	10.42	0.00	102	8.81	13.59	91	1.10	7.34	7.22
C/N Treat	301	11.72	10.10	0.00	103	8.26	14.37	92	1.14	6.78	6.67
ΔC/N	301	−0.43	−0.07	−56	87	−8.87	7.36	433	1.98	0.96	0.94
BD Ref	386	1.22	1.17	0.63	1.77	1.03	1.43	20	0.02	0.09	0.09
BD Treat	386	1.25	1.22	0.53	2.11	1.07	1.42	20	0.02	−0.04	−0.03
ΔBD	386	−0.40	−0,25	−10,71	13,91	−0,76	0,01	559	0,15	0,24	0,23

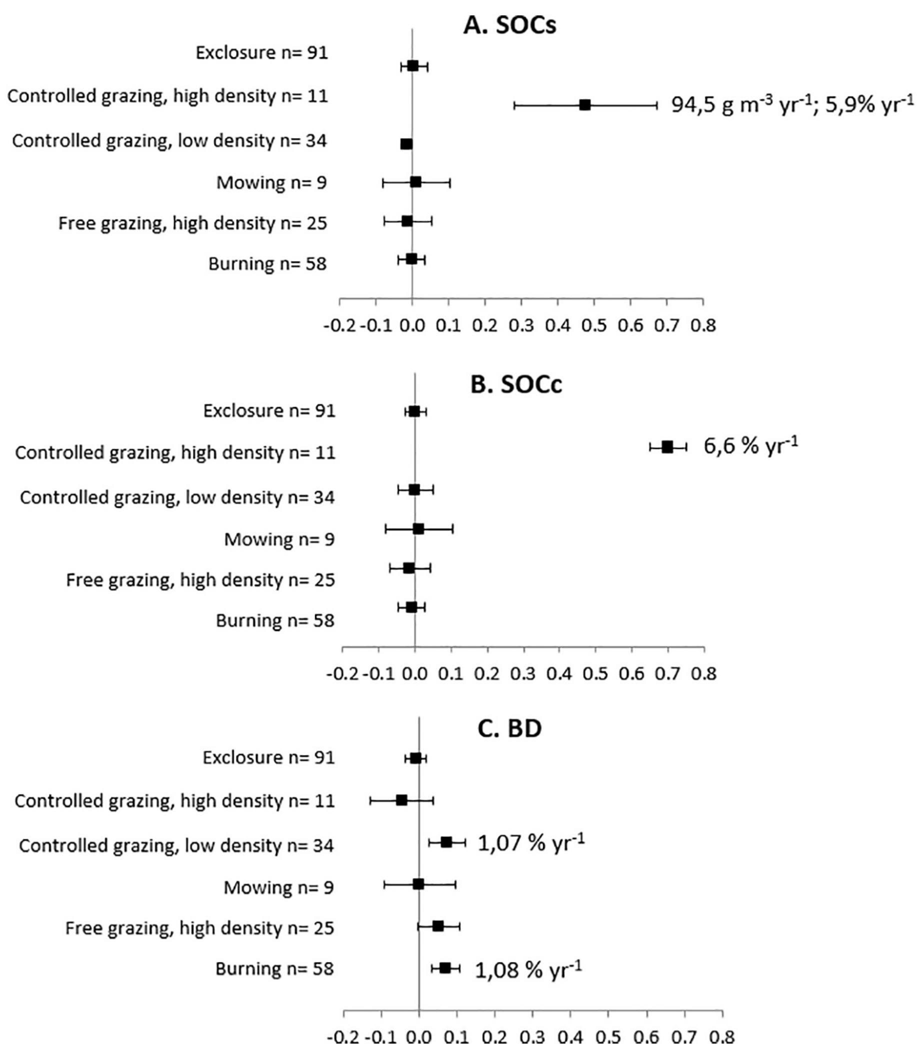

Fig. 2. Soil response to selected grassland management practices as compared to free grazing at low density as control. A: Soil organic carbon stocks; B: Soil organic carbon content; C: soil bulk density. Error bars are effect size means ±95% bootstrap CIs. Where the CIs do not overlap the vertical x = 0 line, the effect size for a practice is significant. *n* is the number of studies and the percentage corresponding to the bar indicates the mean percentage changes per year when changes are significant. Data for the surface soil layer are considered here.

resulted in higher soil compaction than all reference treatments, which might be attributed to soil trampling by livestock hooves. The associated decrease in soil porosity lessens oxygen and CO_2 exchanges between the atmosphere and soils, thus limiting organic matter decomposition and C fluxes out of soils as pointed out by previous studies such as these by Chaplot et al. (2016).

Using data from many sites across the world Dlamini et al. (2014) showed that CHG perform best in terms of SOCc under dry and sandy soil conditions, which may be another reason for discrepancies. In fact, under these conditions that C losses due to degradation were also highest (−16% for dry climates vs −8% for wet; −10% for sandy vs −1% for clayey) due to a combination of harsh climate and low aggregate

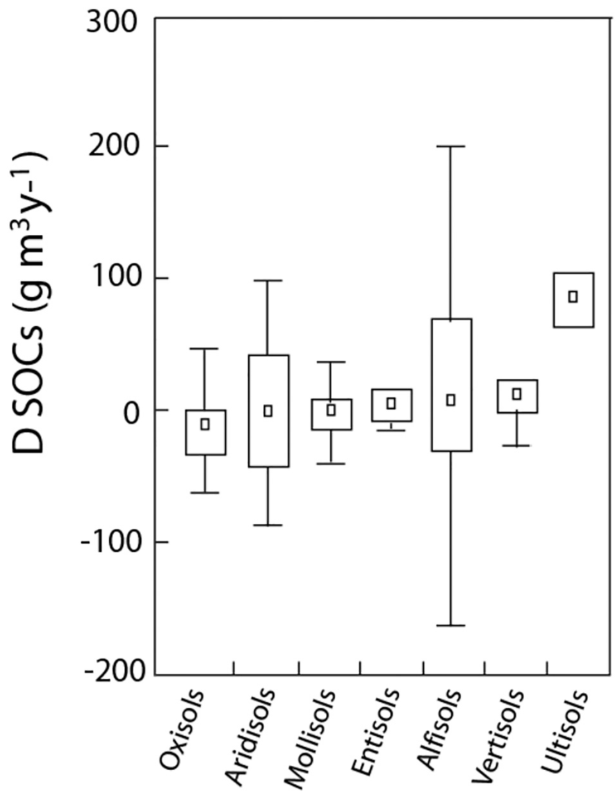

Fig. 3. Impact of soil orders (WRB, 2015) on the changes of soil organic carbon stocks following rehabilitation. The general statistics are median, 1st and 3rd quartile, non-outlier minimum and maximum.

stability, which subsequently result in poor soil organic matter protection. In addition to SOC_C, CHG also enhanced SON_C and increased C/N ratios.

Grazer exclusion (E) had an insignificant impact on soil carbon stocks under arid to semi-arid and moist to humid climates (Table 7) as well under coarse textured soils, but was detrimental to soil C under wet climate and clayey soils. A possible explanation for the latter is likely to be the low number of data points for E under wet climates ($n = 4$) and clayey soils (n = 4).

Additionally, E tended to enhance soil nitrogen content but its impacts on the C/N ratio and on soil bulk density were insignificant. Such results can be attributed to dominancy by nitrogen-fixing grass species that help building soil C or the presence of C3 or C4 grass species of different C behavior (Ritchie and Raina, 2016; Mahaney et al., 2008).

In general, fire had detrimental effects on SOC, irrespective of climate and soil texture (except for moist-humid climate with a 3.7% increase), but the differences with free grazing were not significant. The loss of soil C can be explained by high C losses in gaseous forms during combustion of organic matter (Oluwole et al., 2008) and through preferential erosion of black carbon formed during burning of the grass (Rumpel Chaplot et al., 2014). The loss of soil C lessens the stability of soil structure (Heydari et al., 2017), which in turn increases soil C losses to the atmosphere as gases from organic matter decomposition and/or via erosion by water. Burning can also decrease soil basal cover and thus lessen C inputs to soils. The gains could be explained by removal of low productivity grass species and/or trees of lower soil C input capacity.

4.2. Recommendations for appropriate grassland management

The study pointed to controlled grazing at high intensity for short duration as the best performing grassland management practice worldwide with, however, greater benefits in Arid to humid climates

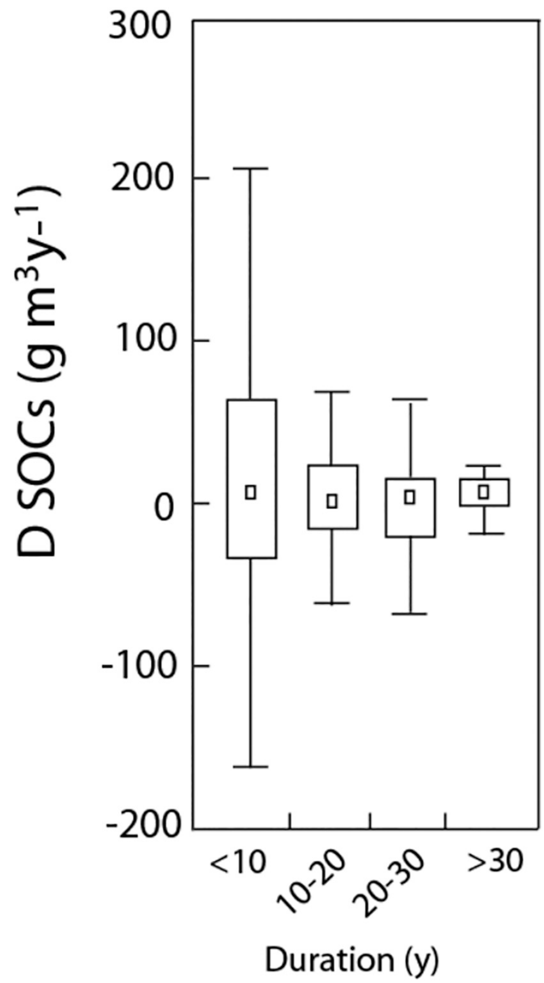

Fig. 4. Impact of management duration (years) on the changes of soil organic carbon stocks following rehabilitation. The general statistics are median, 1st and 3rd quartile, non-outlier minimum and maximum.

than in the wet regions of the world. This practice was first suggested by Voisin (2001) following his work under temperate climate and reworked as holistic grassland management by Savory and Parsons (1980) in the dry southern Africa. Controlled high density grazing (CHG) proved to be more efficient than free grazing or rotational grazing for forage production (higher quality and quantity) and for rehabilitation of degraded grasslands where quasi-bare soils are a common feature (Savory and Parsons, 1980). In his work Voisin (2001) demonstrated that grass grazed at 3-leaf stage was not only of higher nutritional value but also recovered faster as enough energy was accumulated in its stem and roots. Grazing at the 3-leaf stage allows more grass to be produced as flowering is prevented, which helps keeping their rooting systems and their associated water and nutrient supply functions during droughts for long, thus potentially explaining the higher increase in C content and stocks in high intensity short duration grazing. Voisin (2001) also demonstrated in Western Europe that a grazing period of two to three days every 21 days in spring during when grass growth rate is faster and every 35 days afterward was optimal. This is probably due to development of higher rooting systems that allocate C to soils for a longer period as exudates. The fact that more forage is harvested by cows under CHG practices and further transformed into dung which has high potential to become soil organic matter is another potential process for building soil C.

This study showed the benefits of CHG were higher for dry and sandy environments where vegetative growth is low because of scarce rains and high temperatures. Improving grazing management in these areas is

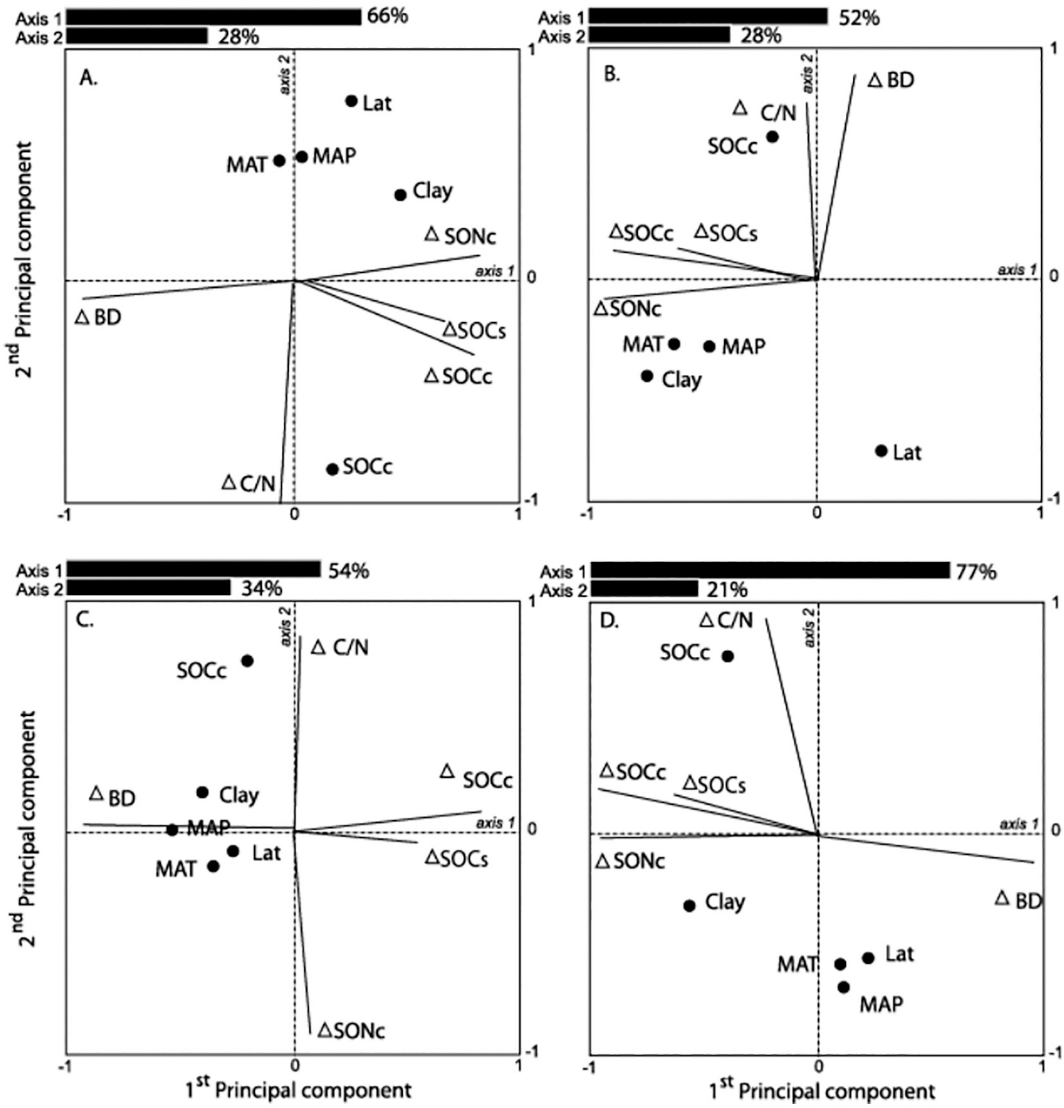

Fig. 5. Principal component analysis for selected grassland management practices (all treatments, A; grazing treatments, B; Fire treatments; C Exclosure treatments, D) and showing the correlation between the changes in selected soil properties and soil and environmental variables.

Table 6
Spearman rank correlation coefficients between environmental factors and the soil properties under different types of change in grassland management: grazing intensity, grazer exclusion (E), grass burning (B).

	Grazing				B				E			
	ΔSOC_C	ΔSON_C	ΔC/N	ΔBD	ΔSOC_C	ΔSON_C	ΔC/N	ΔBD	ΔSOC_C	ΔSON_C	ΔC/N	ΔBD
MAP	0.27*	−0.39*	0.12	−0.49*	0.15	−0.14	0.53*	−0.33*	0.14	−0.07	0.23*	0.13
MAT	0.58*	0.54*	0.37*	−0.41*	0.02	−0.33*	0.02	−1.00*	−0.18	0.03	0.04	0.08
LAT	−0.20	0.31*	−0.04	0.27*	−0.17	−0.36*	0.21*	−0.33*	0.26*	0.18	0.04	−0.38*
Z	−0.06	−0.19	0.35*	0.04	0.02	−0.02	0.29*	−0.33*	−0.15	−0.12	0.03	0.31*
CLAY	0.67*	0.33*	0.47*	0.37*	−0.74*	−0.62*	0.24*	nd	0.10	0.43*	−0.45*	−0.32*
SOC_C ref	−0.05	−0.11	0.62*	0.23*	0.29*	−0.30*	0.41*	−1.00*	−0.26*	−0.18	0,08	−0.18
BD	0.52*	0.29*	−0.72*	−0.39*	0.74*	0.32*	0.32*	0.33*	−0.05	0.04	−0.05	0.20

nd not determined due lack of adequate data.
MAP = mean annual precipitation (mm yr^{-1}); MAT = mean annual air temperature (°C); LAT = latitude (°); Z = altitude above sea level (m); Clay = clay content (%); reference organic carbon content (SOC_C ref); soil bulk density (BD, g cm^{-3}).
* Significant correlations at $p < 0.05$.

not only important to mitigate against climate change but also to ensure food security in already highly vulnerable regions. However, CHG implies a drastic shift in livestock management from traditional free grazing as it requires subdivisions of entire grassing areas into paddocks of similar size which need to be fenced and supplied with water. Since CHG requires more labour and investment for paddock construction, accurate estimation of grass stages and biomass over time for grazing planning, and moving the grazers from paddock to paddock the practice has mostly been applied to highly degraded grasslands. Rehabilitation of degraded grasslands using livestock requires extreme care to avoid

Table 7
Climate and soil clay content impact on the change in soil organic carbon stocks (**ΔSOC$_S$**).

	CLG			CHG			E			Burn		
	g m^{-3} yr^{-1}	% yr^{-1}	n	g m^{-3} yr^{-1}	% yr^{-1}	n	g m^{-3} yr^{-1}	% yr^{-1}	n	g m^{-3} yr^{-1}	% yr^{-1}	n
Climate												
Arid/semi-arid	25.4	1.25	23	15.6*	1.9*	6	1.86	0.98	46	−819.2*	−15.3*	14
Moist/humid	65.3	1.98	26	233*	8.9*	3	38.7	3.8	20	−143.8*	−9.1*	13
Wet	47.9	3.12	245	6.2	0.5	1	−34.4*	−2.1*	4	63.73	0.24	31
Clay content												
0–20	43.1	2.77	148	211.7*	3.15*	6	53.35	4.81	13	−6.07	−1.51	13
20–40	166.3*	4.79*	61	nd	nd	4	−10.6	−2.44	12	−93.22	−6.35	17
>40	7.0	1.18	69	43.5	0.65	2	−51.71	−1.87	4	−17.71	−0.20	9

* Significant correlations at $p < 0.05$.

unintended consequences such as increased soil bulk density and reduced water infiltration, especially nearby watering points.

The study results further suggests the lack of impact of Soil Order on soil C recovery, which was surprising, probably owing to the that different soil orders may exhibit similar soil properties. Finally, fire as a method for managing grasslands did not appear to be beneficial for building soil C stocks, irrespective of the soil and environmental conditions. The fact that burning is less detrimental under dry and sandy conditions than under clayey and wet ones is probably due to the fact that the soils are already highly C depleted.

5. Conclusions

The main conclusions from the current study performed using 235 grassland experimental sites from 18 countries across the world were that (i) grassland soil C and N was confirmed to be significantly affected by grassland management practice but that large discrepancies in such effect existed from site to site; (ii) sandy soils in grasslands of arid to semi-arid and moist-humid climates have greater potential for C and N recovery following changes in management practices as than clayey soils of the tropics; (iii) the best performing grassland management practice was controlled rotational grazing with high density grazers and short duration which gave rise to average soil C stock increase of 5.9% yr^{-1} (iv) excluding grazers or burning grasslands were not beneficial for soil C with exclosure being highly detrimental under wet and clayey soils. The current widespread use of these practices needs to be reassessed.

These results improve our knowledge on the impact of grassland management on soil C and the links to climate change and soil texture. Adoption of rotational high-density grazing for short duration in place of free grazing grasslands, especially on degraded grasslands, should be seriously considered by policy and decision makers to mitigate against climate change while fostering economic and social development. This study benefitted from the existence of numerous publications that could assist decision and policy makers on determining proper grassland management techniques for rehabilitating grasslands across the world. However, most of the studies only reported on soil carbon content, little on N content and even less on C and N stocks. In addition, only 11 studies assessed the impact of controlled high density grazing thus pointing to the need to coordinate research on key soil variables and on this very promising practice across different environmental conditions in order to ascertain its underlying mechanisms and associated ecosystem functions of food and water security. The research to come should thus consider critical variables and routinely use consistent standards and inform on durations of experiments.

Finally, the fact that none of the study techniques was truly beneficial in terms of soil C and N in the wet climate points to the need to test other alternatives.

Declaration of Competing Interest

None.

Acknowledgements

The research received financial support from the Water Research Commission of the Republic of South Africa (WRC K5/2266).

References

Abdalla, K., Chivenge, P., Everson, C., Mathieu, O., Thevenot, M., Chaplot, V., 2016. Long-term annual burning of grassland increases CO_2 emissions from soils. Geoderma 282, 80–86.
Abril, A., 1999. The effects of overgrazing on soil microbial community and fertility in the Chaco dry savannas of Argentina. Appl. Soil Ecol. 12, 159–167.
Al-Seekh, S.H., Mohammad, A.G., Amro, Y.A., 2009. Effect of grazing on soil properties at southern part of West Bank Rangeland. Hebron Univ. Res. J. 1, 35–53.
Barger, N.N., Ojima, D.S., Belnap, J., Shiping, W., Yanfen, W., Chens, Z., 2004. Changes in plant functional groups, litter quality, and soil Carbon and Nitrogen mineralization with sheep grazing in an Inner Mongolian Grassland. J. Range Manag. 57 (6), 613–619.
Bauer, A., Cole, C.V., Black, A.L., 1987. Soil property comparison in virgin grasslands between grazed and nongrazed management systems Soil. Sci. Soc. Am. J. 51, 176–182.
Cao, J., Wang, X., Sun, X., Zhang, L., Tian, Y., 2013. Effects of grazing intensity on soil labile organic carbon fractions in a desert steppe area in Inner Mongolia. SpringerPlus 2 (1). https://doi.org/10.1186/2193-1801-2-S1-S1.
Chaplot, V., Dlamini, P., Chivenge, P., 2016. Potential of grassland rehabilitation through high density-short duration grazing to sequester atmospheric carbon. Geoderma 271, 10–17.
Chen, J., Tang, H., 2016. Effect of grazing exclusion on vegetation characteristics and soil organic carbon of Leymus chinensis grassland in northern China. Sustainability 8. https://doi.org/10.3390/su8010056.
Conant, R.T., Paustian, K., Elliot, E.T., 2001. Grassland management and conversion into grasslands: Effects on soil carbon. Ecol. Appl. 11, 343–355.
Conant, R.T., Cerri, C.E.P., Osborne, B.B., Paustian, K., 2017. Grassland management impacts on soil carbon stocks: a new synthesis. Ecol. Appl. 27 (2), 662–668.
Devi, T.I., Yadava, P.S., Garkoti, S.C., 2014. Cattle grazing influences soil microbial biomass in sub-tropical grassland ecosystems at Nambol, Manipur, northeast India. Trop. Ecol. 55 (2), 195–206.
Dlamini Chivenge, P.P., Chaplot, V., 2016. Overgrazing decreases soil organic carbon stocks the most under dry climates and low soil pH: A meta-analysis shows. Agric. Ecosyst. Environ. 221, 258–269.
Dlamini, P., Chivenge, P., Manson, A., Chaplot, V., 2014. Land degradation impact on soil organic carbon and nitrogen stocks. Geoderma 235, 372–381.
Donkor, N.T., Gedir, J.V., Hudson, R.J., Bork, E.W., Chanasyk, D.S., Naeth, M.A., 2002. Impacts of grazing systems on soil compaction and pasture production in Alberta. Can. J. Soil Sci. 82, 1–8.
Evans, C.R.W., Krzic, M., Broersma, K., Thompson, D.J., 2012. Long-term grazing effects on grassland soil properties in southern British Columbia. Can. J. Soil Sci. 92, 685–693.
Gao, Y., Schumann, M., Chen, H., Wu, N., Luo, P., 2009. Impacts of grazing intensity on soil carbon and nitrogen in an alpine meadow on the eastern Tibetan Plateau. J. Food Agric. Environ. 7, 749–754.
Gardner, L., 1950. Effects of Thirty Years of Protection from Grazing in Desert Grassland Author(s). J. Ecology 31 (1), 44–50.
Gill, R.A., 2007. Influence of 90 Years of Protection From Grazing on Plant and Soil Processes in the Subalpine of the Wasatch Plateau, USA. Rangeland Ecol. Manage. 60, 88–98.
Granged, A.J.P., Zavala, L.M., Jordán, A., Bárcenas-Moreno, G., 2011. Post-fire evolution of soil properties and vegetation cover in a Mediterranean heathland after experimental burning: a 3-year study. Geoderma 164, 85–94.
Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change. Glob. Chang. Biol. 8, 345–360.
Han, G, Hao, X., Zhao, M., Wang, M., Ellert, B.H., Willms, W.M. Wang., 2008. Effect of grazing intensity on carbon and nitrogen in soil and vegetation in a meadow steppe in inner Mongolia. Agric. Ecosyst. Environ. 125, 21–32.

Harris, W.N., Moretto, A.S., Distel, R.A., Bouttona, T.W., Boo, R.M., 2007. Fire and grazing in grasslands of the Argentine Caldenal: Effects on plant and soil carbon and nitrogen. Acta Oecol. 32, 207–214.

Heydari, M., Rostamy, A., Najafi, F., Dey, D., 2017. Effect of fire severity on physical and biochemical soil properties in Zagros oak (Quercus brantii Lindl.) forests in Iran. J. For. Res. 28, 95–104.

Jambu, M., 1991. Exploratory and Multivariate Data Analysis. Academic, Orlando, FL.

Jiao, T., Nie, Z., Zhao, G., Cao, W., 2016. Changes in soil physical, chemical and biological characteristics of a temperate desert steppe under different grazing regimes in Northern China. Commun. Soil Sci. Plant Anal. 47, 338–347.

Kassahun, A., Tegegne, A., Aberra, D., 2012. Impacts of rangeland degradation on soil physical, chemical and seed bank properties along a gradient in three rangeland vegetation types in Somali Region, Eastern Ethiopia. Ethiop. J. Agric. Sci. 22, 84–101.

Kgosikoma, O.E., Mojeremane, W., Harvie, B., 2015. The impact of livestock grazing management systems on soil and vegetation characteristics across savanna ecosystems in Botswana. Afr. J. Range Forage Sci. 32 (4), 271–278.

Kontopantelis and Reeves, 2009. Metaeasy: a meta-analysis add-in for microsoft excel. J. Stat. Softw. 30, 1–25.

Koyama, A., Kubo, D., Yoshihara, Y., Jamsran, U., Okuro, T., 2015. Response of degraded vegetation to introduction of prescribed burning or mowing management in a Mongolian steppe. Grassl. Sci. 62, 37–44.

Krzic, M., Lamagna, S.F., Newman, R.F., Bradfield, G., Wallace, B.M., 2014. Long-term grazing effects on rough fescue grassland soils in southern British Columbia. Can. J. Soil Sci. 94, 337–345.

Lal, R., 2015. Soil erosion and carbon dynamics. Soil Till. Res. 8, 137–142.

Lavado, R.S., Sierra, J.O., Hashimoto, P.N., 1996. Impact of grazing on soil nutrients in a Pampean grassland. J. Range Manag. 49, 452–457.

Li, S.G., Harazono, Y., Oikawa, T., Zhao, H.L., He, Z.Y., Chang, X.L., 2000. Grassland desertification by grazing and the resulting micrometeorological changes in Inner Mongolia. Agric. For. Meteorol. 102 (2–3), 125–137.

Li, W., Huang, H.-Z., Zhang, Z.-N., Wu, G.-L., 2011. Effects of grazing on the soil properties and C and N storage in relation to biomass allocation in an alpine meadow. J. Soil Sci. Plant Nutr. 11 (4), 27–39.

Liu, N., Zhang, Y., Chang, S., Kan, H., Lin, L., 2012. Impact of grazing on soil carbon and microbial biomass in typical steppe and desert steppe of Inner Mongolia. PLoS One 7 (5). https://doi.org/10.1371/journal.pone.0036434.

Mahaney, W.M., Smemo, K.A., Gross, K.L., 2008. Impacts of C 4 grass introductions on soil carbon and nitrogen cycling in C 3-dominated successional systems. Oecologia 157, 295–305.

Manley, J.T., Schuman, G.E., Reeder, J.D.R.H., 1995. HartRangeland soil carbon and nitrogen responses to grazing. J. Soil Water Conserv. 50, 294–298.

Manson, A.D., Jewitt, D., Short, A.D., 2007. Effects of season and frequency of burning on soils and landscape functioning in moist montane grassland. Afr. J. Range Forage Sci. 24, 9–18.

Materechera, S.A., Mandriringana, O.T., Mbokodi, P.M., Nyamapfene, K., 1998. Organic matter, pH and nutrient distribution in soil layer of a savannah thornveld subjected to different burning frequencies at Alice, in the Eastern Cape. South Afr. J. Plant Soil 15 (3), 109–115.

Mathew, I., Shimelis, H., Mutema, M., Chaplot, V., 2017. What crop type for atmospheric carbon sequestration: Results from a global data analysis. Agric. Ecosyst. Environ. 243, 34–46.

Mchunu, C., Chaplot, V., 2012. Land degradation impact on soil carbon losses through water erosion and CO_2 emissions. Geoderma 177-178, 72–79.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Zueng-Sang Chen, Kun, Cheng, BhabaniDas, S., DamienField, J., Alessandro, Gimona, Carolyn, B. Hedley, Suk Young, Hong, Biswapati, Mandal, BenMarchant, P., Manuel, Martin, BrianMcConkey, G., Vera Leatitia, Mulder, Sharon, O'Rourke, AnneRicher-de-Forges, C., Odeh, Inakwu, Jose, Padarian, Keith, Paustian, Pan, Genxing, Laura, Poggio, Savin, Igor, Stolbovoy, Vladimir, Uta, Stockmann, Yiyi, Sulaeman, Chun-Chih, Tsui, Tor-Gunnar, Vagen, Bas van, Wesemael, Leigh, Winowiecki, 2017. Soil carbon 4 per mille. Geoderma 292, 59–86.

Mutema, M., Chaplot, V., Jewitt, G., Chivenge, P., Blöschl, G., 2015. Annual water, sediment, nutrient, and organic carbon fluxes in river basins: A global meta-analysis as a function of scale. Water Resour. Res. 51, 8949–8972.

Nardoto, G.B., Bustamante, M.M.C.B., 2003. Effects of fire on soil nitrogen dynamics and microbial biomass in savannas of Central Brazil. Pesq. Agrop. Brasileira 38, 955–962.

Neff, J.C., Reynolds, R.L., Belnap, J., Lamothe, P., 2005. Multi-decadal impacts of grazing on soil physical and biogeochemical properties in southeast Utah. Ecol. Appl. 15 (1), 87–95.

Niu, D., Hall, S.J., Fu, H., Kang, J., Qin, Y., Else, J.J., 2011. Grazing exclusion alters ecosystem carbon pools in Alxa desert steppe. N. Z. J. Agric. Res. 54 (3), 127–142.

Nüsse, A., Linsler, D., Kaiser, M., Ebeling, D., Tonn, B., Isselstein, J., Ludwig, B., 2017. Effect of grazing intensity and soil characteristics on soil organic carbon and nitrogen stocks in a temperate long-term grassland. Arch. Agron. Soil Sci. 1476–3567.

Nyamadzawo, G., Wuta, M., Nyamangara, J., Nyamugafata, P., Tendayi, T., 2014. Burning, biomass removal and tillage effects on soil organic carbon and nutrients in seasonal wetlands (Dambos) of Chiota smallholder farming area, Zimbabwe. Arch. Agron. Soil Sci. 60 (10), 1411–1427.

Oğuz, İ., Koçyiğit, R., Erşahin, S., 2015. The effect of range management on soil carbon content in degraded soil. J. Agric. Facul. Gaziosmanpasa 32 (3), 133–137.

Oluwole, F.A., Sambo, J.M., Sikhalazo, D., 2008. Long-term effects of different burning frequencies on the dry savannah grassland in South Africa. Afr. J. Agric. Res. 3, 147–153.

Pei, S., Fu, H., 2008. Changes in soil properties and vegetation following exclosure and grazing in degraded Alxa desert steppe of Inner MongoliaChina. Agric. Ecosyst. Environ. 124, 33–39.

Picone, L.I., Quaglia, G., García, F.O., 2003. Biological and chemical response of a grassland soil to burning. J. Range Manag. 56, 291–297.

Pribyl, D.W., 2010. A critical review of the conventional SOC to SOM conversion factor. Geoderma 156, 75–83.

Ritchie, M.E., Raina, R., 2016. Effects of herbivores on nitrogen fixation by grass endophytes, legume symbionts and free-living soil surface bacteria in the Serengeti. Pedobiologia 59, 233–241.

Rong, Y., Yuan, F., Ma, L., 2014. Effectiveness of exclosures for restoring soils and vegetation degraded by overgrazing in the Junggar Basin, China. Grassl. Sci. 60, 118–124.

Rumpel Chaplot, C., Ciais, V., Chabbi, P., Bouahom, A., Valentin, B.C., 2014. Composition of eroded carbon during its journey through a tropical watershed: a clue to the question whether it is source or sink of CO_2. Biogeosci. Discuss. 10, 18175–18192. https://doi.org/10.5194/bgd-10-18175-2013.

Sanjari, G., Ghadiri, H., Ciesiolka, C.A.A., Yu, B., 2008. Comparing the effects of continuous and time-controlled grazing systems on soil characteristics in Southeast Queensland. Aust. J. Soil Res. 46, 348–358.

Savory, A., Parsons, S.D., 1980. The Savory grazing method. Rangelands 2, 234–237.

Schuman, GE, Reeder, JD, Manley, JT, Hart, RH, Manley, WA, 1999. Impact of grazing management on the carbon and nitrogen balance of a mixedgrass rangeland. Ecol. Appl. 9, 65–71.

Seitlheko, E.M., Allen, B.L., Wester, D.B., 1993. Effect of three grazing intensities on selected soil properties in semi-arid west Texas. Afr. J. Range Forage Sci. 10 (2), 82–85.

Shimoda, S., Takahashi, Y., 2009. Differences in soil carbon storage due to mowing, burning and uncontrolled management practices of grassland at the foot of Mount Sanbe, Japan. Grassl. Sci. 55, 175–180.

Snyman, H.A., 2002. Fire and the dynamics of a semi-arid grassland influence on soil characteristics. Afr. J. Range Forage Sci. 19, 137–145.

Steffens, M., Kölbl, A., Totsche, K.U., Kögel-Knabner, I., 2008. Grazing effects on soil chemical and physical properties in a semiarid steppe of Inner Mongolia (P.R. China). Geoderma 143, 63–72.

Su, Y.Z., Zhao, H.L., Zhang, T.H., Zhao, X.Y., 2004. Soil properties following cultivation and non-grazing of a semi-arid sandy grassland in northern China. Soil Tillage Res. 75 (1), 27–36.

Su, Y.Z., Li, Y.L., Cui, H.Y., Zhao, W.Z., 2005. Influences of continuous grazing and livestock exclusion on soil properties in a degraded sandy grassland, Inner Mongolia, northern China. Catena 59 (3), 267–278.

Su, Y.Z., Li, L.Y., Zhao, H.L., 2006. Soil properties and their spatial pattern in a degraded sandy grassland under post-grazing restoration, Inner Mongolia, northern China. Biogeochemistry 79, 297–314.

Tainton, N.M., 1999. The ecology of the main grazing lands of South Africa. In: Tainton, NM (Ed.), Veld Management in South Africa. University of Natal Press, Pietermaritzburg, pp. 23–53.

Teague, W.R., Dowhower, S.L., Baker, S.A., Ansley, R.J., Kreuter, U.P., Conover, D.M., Waggoner, J.A., 2010. Soil and herbaceous plant responses to summer patch burns under continuous and rotational grazing. Agric. Ecosyst. Environ. 137, 113–123.

Voisin, A., 2001. La productivité de l'herbe. In: France Agricole, 2nd ed. Paris.

Wang, Z., Johnson, D.A., Rong, Y., Wang, K., 2016. Grazing effects on soil characteristics and vegetation of grassland in northern China. Solid Earth 7, 55–65.

Ward, S.E., Smart, S.M., Quirk, H., Tallowin, J.R.B., Mortimer, S.R., Shiel, R.S., Wilby, A., Bardgett, R.D., 2016. Legacy effects of grassland management on soil carbon to depth. Glob. Chang. Biol. 22, 2929–2938.

Weitz, M., Wood, M.K., 1986. Short duration grazing in Central New Mexico: Effects on infiltration rates. J. Range Manag. 39, 365–368.

WRB, 2015. World reference base for soil resources 2014, update 2015. In: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps World Soil Resources Reports No. 106. FAO, Rome.

Wu, X., Li, Z., Fu, B., Lu, F., Wang, D., Liu, H., Liu, G., 2014. Effects of grazing exclusion on soil carbon and nitrogen storage in semi-arid grassland in Inner Mongolia, China. Chin. Geogr. Sci. 24 (4), 479–487.

Xu, M.-Y., Wang, K., Xie, F., 2011. Effects of grassland management on soil organic carbon density in agro-pastoral zone of northern China. Afr. J. Biotechnol. 10, 4844–4850.

Xu, M.-Y., Xie, F., Wang, K., 2014. Response of vegetation and soil carbon and nitrogen storage to grazing Intensity in semi-arid grasslands in the agro-pastoral zone of Northern China. PLoS One 9 (5). https://doi.org/10.1371/journal.pone.0096604.

Yalçın, E., Doğan, A., Akçin, A., 2016. Effects of grazing on soil parameters in Meadow ecosystems. Hacettepe J. Biol. Chem. 44 (2), 161–171.

Yang, J., Kang, Y., Sakurai, K., Ohnishi, K., Siriguleng., 2016. Change of soil microbial biomass, C, N between long-time free grazing and exclosure pastures in semiarid grassland ecosystem in Tongliao and Chifeng of Inner Mongolia. J. Bioremed. Biodegrad. 7 (3) https://doi.org/10.4172/2155-6199.1000347.

Yusuf, H.M., Treydte, A.C., Sauerborn, J., 2015. Managing semi-arid rangelands for Carbon storage: grazing and woody encroachment effects on soil carbon and nitrogen. PLoS One 10 (10). https://doi.org/10.1371/journal.pone.0109063.

Zarekia, S., Jafari, M., Arzani, H., Javadi, S.A., Jafari, A.A., 2012. Grazing effects on some of the physical and chemical properties of soil. World Appl. Sci. J. 20 (2), 205–212.

Zhao, Y., Peth, S., Krummelbeina, J., Horn, R., Wang, Z., Steffens, M., Hoffmann, C., Peng, X., 2007. Spatial variability of soil properties affected by grazing intensity in Inner Mongolia grassland. Ecol. Model. 205, 241–254.

Zhou, Z.C., Gan, Z.T., Shangguan, Z.P., Dong, Z.B., 2010. Effects of grazing soil physical properties and soil erodibility in semiarid grassland of the Northern Loess Plateau (China). Catena 82, 87–91.

Frank, A.B., D.L. Tan&, L. Hofmann, and RF. Follett. 1995. Soil carbon and nitrogen of Northterm gazing. J. Range Manage. 48, 470-474.

FAO. 2015. FAOSTAT Database. Online at: http://faostat3.fao.org/home/E, accessed 02 Sep 2015.