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Long-term annual burning of grassland increases CO_2 emissions from soils

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ARTICLE INFO

ABSTRACT

Grasslands have potential to mitigate against climate change because of their large capacity to store soil organic carbon (SOC). However, the long-term impact of grassland management such as burning, which is still common in many areas of the world, on SOC is still a matter of debate. The objective of this study was to quantify the long-term effects of annual burning on CO_2 output from soils and SOC stocks. The study was performed on a 62 years old field trial comparing annual burning (AB) to no burning associated with tree encroachment (NB), and to annual mowing (AM) with all treatments laid out in randomized block design with three replicates per treatment. CO_2 emissions from soil were continuously measured over two years and were correlated to soil chemical and physical properties. AB and AM produced 30 and 34% greater CO_2 emissions from soil than NB (1.80 ± 0.13 vs. 2.34 ± 0.18 and 2.41 ± 0.17 g C-CO_2 m^{-2} d^{-1} for NB, AB and AM respectively). AB and AM also produced greater CO_2 emissions from soil and per gram of soil carbon (1.32 ± 0.1 and 1.35 ± 0.1 mg C-CO_2 g C^{-1} d^{-1}, respectively) than NB (1.05 ± 0.07 mg C-CO_2 g C^{-1} d^{-1}), which corresponded to significant differences of respectively 26% and 29%. Overall, CO_2 emissions from soil (per m^2) significantly increased with soil water content (r = 0.72) followed by SOC stocks (r = 0.59), SOC content (r = 0.50), soil bulk density (r = 0.49), soil temperature (r = 0.47), C:N ratio (r = 0.46) and mean weight diameter (r = 0.38). These findings suggest that long-term annual burning increases CO_2 output from soils. Additional greenhouse gases emissions from burning itself and alternative grassland management techniques were finally discussed.

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1. Introduction

Grasslands cover approximately 40% of the earth's terrestrial surface area and play an important role in the global carbon (C) cycle by storing about 10% of the global soil C stocks (Suttie et al., 2005). Additionally, in grasslands soil organic C (SOC) concentration is higher at the soil surface, which may turn the C to the external factors such as climate and land management. Fire is the most common anthropogenic grassland management practice, used since the early Holocene (Behling and Pillar, 2007), because of easy application in difficult terrains and on large areas. However, other practices like mowing, grazing and fertilization are also in use (Blüthgen et al., 2012; Peng et al., 2011). All these grassland management practices have potential to influence soil C stocks and eventually CO_2 emissions from the soil to the atmosphere (Peng et al., 2011; Granged et al., 2011; Jia et al., 2012).

Burning is a common practice used for increasing fodder production and quality, whilst avoiding bush encroachments (Tainton, 1999). It results in increased biomass growth period and biomass production (Ojima et al., 1994), while at the same time improving grass cover and biodiversity (Boakye et al., 2013). This grassland management practice can have negative consequences on soil chemical, physical and biological properties (Andersson et al., 2004; Granged et al., 2011). Burning causes a general decline of SOC through combustion of soil organic matter (SOM) in the upper soil layer (Granged et al., 2011). For example, Granged et al. (2011) reported a 35% reduction in SOM after three years of burning with significant changes in soil physical properties, leading to increased water repellence. In addition, the high soil temperature (ST) and low soil moisture content (SWC), during fires, causes a

sharp decrease in topsoil (0–0.05 m) biological biomass and its activity (Nardoto and Bustamante, 2003; D'Ascoli et al., 2005). Moreover, because of greater root and tuff density at the soil surface frequently-burned grasslands have the tendency to show detritus accumulation on the topsoil compared to non-burned shrubby grasslands and trees (Ansley et al., 2002). This, together with an enhanced mineralization of SOM (Singh et al., 1991), highly affects CO_2 effluxes from soil.

Several studies have reported lower CO_2 emissions from soil in no burn (NB) than burned grasslands (e.g. Knapp et al., 1998; Rutigliano et al., 2007; Ward et al., 2007; Xu and Wan, 2008). For instance, Knapp et al. (1998) reported that annual burn (AB) for 17 years in eastern Kansas region, USA, resulted in 55% greater monthly CO_2 emission from the soil than in NB treatment. Similarly, Xu and Wan (2008) reported 23.8% more CO_2 emission in AB than NB on sandy soils of semiarid Northern China over two growing seasons, whereas Jia et al. (2012) reported in the same region 11% lower emissions with NB compared to AB but for only one growing season. Castaldi et al. (2012) also reported less CO_2 emissions from unburned compared to burned plots in central Africa.

Mowing is also regarded as an improved grassland management practice (Zhou et al., 2007; Hamilton et al., 2008), which can result in a decrease of the CO_2 emissions from soils (Bahn et al., 2006) by 20–50% compared to burning (Wan and Luo, 2003). However, the reasons for such a decrease are unclear. Wan and Luo (2003) explained it to be due to a decrease in photosynthetic C supply from aboveground biomass. Bahn et al. (2006) suggested that it could be a result of the depletion of easily available C substrates for the microflora. Nevertheless, others studies stated that mowing results precisely in an increase of rhizodeposition, soil microbial biomass and labile C (Zhou et al., 2007; Hamilton et al., 2008), which might suggest increased CO_2 emission from the soil. Therefore, the underlying reasons for mowing effect on CO_2 emissions from soils require further elucidations.

Both mowing and burning also impact the land cover evolution. Indeed, bushes often encroach into grasslands where neither burning nor mowing are applied (Trollope, 1980; Tainton, 1999; Montané et al., 2007). Montané et al. (2007) reported an increase of soil C stocks in the upper soil layers (top 15 cm depth) following shrubs encroachment into grasslands. Wang et al. (2013) also found an increase of soil C storage by shifting from grassland to woody plants.

While numerous studies exist on the impact of grasslands burning on CO_2 emissions from soil and soil C stocks, the existence of discrepancies between these limits decision making on grassland management. These studies show inherent limitations, related to their short duration, which long-term experiments might allow to overcome. In this study, 62-year annual burn and mow were compared against no burn treatment in an African Savanna. The no burn treatment was characterized by encroachment of large trees. Our main objective was to evaluate the impact of annual grassland burn management on SOC dynamics (C-stocks and CO_2 emissions from soils) and their factors of control.

2. Material and methods

2.1. Study area

The experiment was conducted at Ukulinga Farm, the training and research farm of the University of KwaZulu-Natal, Pietermaritzburg, South Africa (24° 24′E, 30° 24′S) (Fig. 1). The experimental site is located on top of a small sloping plateau ranging in altitude from 847 to 838 m (Fynn et al., 2004). Soil depths vary from 0.05 m in the upslope to 0.20 m in midslope and 0.6 m at the footslope, and were classified as Plinthic Acrisols (WRB-FAO, 2006). The parent material is colluvium shale with intrusions of dolerite. The soil is acidic with a pH (KCl) of 5.5 at the top-soil and its texture is silty clay loam (37% clay, 43% silt and 20% sand).

The climate is sub-tropical humid and characterized by warm and wet summers (October–April), and cool and dry winters (May–September). Long-term (30 years) mean annual temperature and precipitation at the farm were 16 °C and 694 mm, respectively.

The native vegetation of the study area is dominated by the southern tall grassveld, which produces dense vegetation with plant heights ranging between 0.5 and 0.75 m (Fynn et al., 2004). Depending on the grassland management, some scattered trees, for instance *Acacia sieberiana* and some grass species such as *Themeda triandra* and *Tristachya leucothrix* are also found (Fynn et al., 2004). The native grass species (e.g. *Themeda triandra* and *Tristachya leucothrix*) all use the C4 photosynthetic path (Fynn et al., 2005).

2.2. Experimental design

The experiment involved three treatments namely; no burn (NB), annual burning (AB) and annual mowing (AM). There has been neither burning nor mowing in the NB since 1950, and these plots are now encroached by densely spread trees of *Acacia sieberiana* species. Long-term annual burning (AB) involves the burning of grass in the 1st week of August every year since 1950. At the time of study, the AB plots were dominated by sparse *Themeda triandra* grass. In the AM treatment, the grass is cut at the same time as burning and the material is removed from the treatment plots. All treatments are replicated three times by slope position (upper, mid and footslope) in a randomized block design and the plots sizes are 18.3 × 13.7 m spaced by 4 m sidewalks. The three treatments (NB, AB and AM) were represented once in three slope positions (replicate 1: upslope; replicate 2: midslope and replicate 3: footslope). There was no grazing at the experimental site since it was established in 1950. More details about the experimental site and design can be found in Tainton et al. (1978).

2.3. Soil sampling and analysis

Soil samples for evaluation of SOC content (SOCc) and soil organic nitrogen content (SONc) were collected once (at the beginning of the second year) in each plot at three randomly selected pits (0–0.2 m deep). The samples were air-dried for 48 h, then gently ground and sieved through a 2 mm sieve. Total C and N were measured in the soil samples using LECO CNS-2000 Dumas dry matter combustion analyzer (LECO Corp., St. Joseph, MI). On the same day additional soil samples for bulk density (ρb) were also collected from each plot in the middle of the 0–0.2 m layer using 7.5 cm diameter metallic cylinder core with the height of 5 cm. Soil ρb was determined using the core method where the ratio of water content corrected mass to volume was computed (Grossman and Reinsch, 2002).

SOC stocks (SOCs) were calculated using the following equation (Batjes, 1996):

$$SOCs = SOCc \times \rho b \times T\left(1 - \frac{PF}{100}\right) b \qquad (1)$$

where SOC_S is SOC stock (kg C m^{-2}); SOC_C is soil organic carbon content in the ≤2 mm soil material (g C kg^{-1} soil); ρb is the bulk density of the soil (kg m^{-3}); T is the thickness of the soil layer (m); PF is the proportion of fragments of >2 mm in percent; and b is a constant equal to 0.001.

The nitrogen stocks (SONs) were calculated using the same equation (Batjes, 1996), replacing SOCc by the soil nitrogen content (SONc).

Water stable soil aggregates were separated using wet sieving methods described by Elliott (1986). Field moist soil samples were sieved through an 8 mm sieve and air-dried. A subsample of 80 g was placed on a 2 mm sieve and submerged in water for 5 mins followed by wet sieving for 2 mins. The wet sieving process involved moving the sieve up and down 50 times. The materials remaining on the 2 mm sieve were collected by backwashing the sieve into a pre-weighted drying pan. Eventually, four aggregate size classes were collected from each treatment (2, 0.25–2, 0.053–0.25, and >0.053 mm), by repeating the wet sieving procedure using 0.25 mm, and 0.053 mm
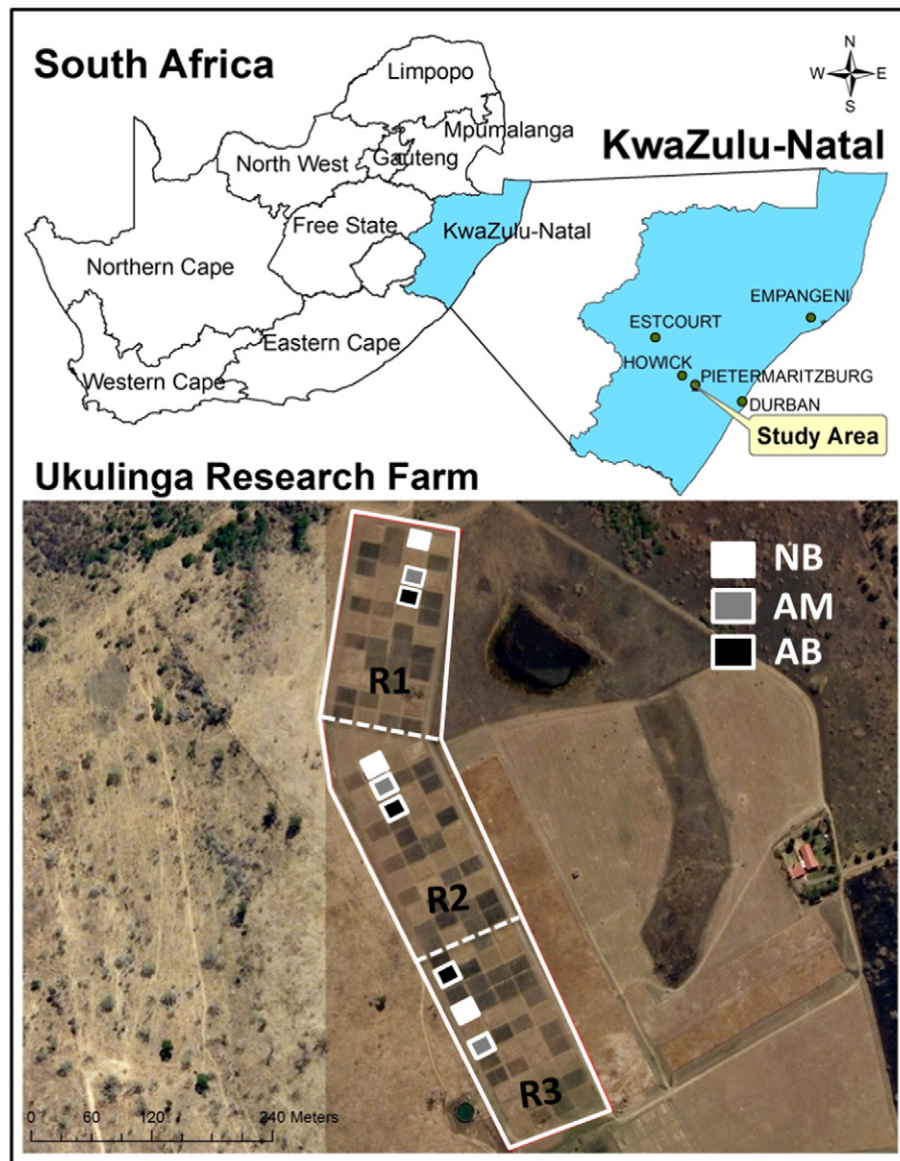
Fig. 1. Location of the study site in South Africa and selected treatments (NB; no-burning, AB; annual burning and AM; annual mowing) and their replicate (R) in each plot (R1: upslope, R2: midslope and R3: downslope position).

sized sieves. The mean weight diameter (MWD) for the water stable aggregate for each treatment was calculated using the following equation (Kemper and Rosenau, 1986):

$$MWD = \sum_{i=1}^{n} Xi\, Wi \qquad (2)$$

where Xi is the mean diameter for each fraction size, Wi is the proportional weight the fraction from the total dry weight of soil used, and n is the number of aggregate classes separated.

2.4. Measurements of CO_2 emissions from soil

CO_2 emissions from soil were measured once a month from March 2013 to March 2015 with ten measurements per plot using LI-COR 6400 gas exchange system (LI-COR, Lincoln, NE, U.S.A) fitted with the LI-COR 6400–09 soil respiration chamber. The closed chamber system has an internal volume of 991 cm^3 and soil area of 71.6 cm^2 (Healy et

al., 1996). We evaluated the sample size necessary to estimate CO_2 emissions measurement points within the plot with a standard error of $\pm 10\%$ of the mean as in Eq. (3) below:

$$n = (CV/10)^2 \qquad (3)$$

where n is the sample size and CV is the average coefficient of variation within the plot.

The samples size was found to be 10 points within each plot, which was randomly selected between grass and trees.

All the measurements were carried out during daylight hours, starting at 10:00 and finishing around 13:00 h. This time period was determined by a pre-experiment, which compared CO_2 emissions from soil during the day and found that emission between 10:00 and 13:00 closely represented the average daily CO_2 emissions from soil. CO_2 fluxes from soil were expressed in two units: (1) in g CO_2-C in unit of surface per day (g CO_2-C m^{-2} day^{-1}) to evaluate the CO_2 emission from soil to the atmosphere and (2) in g CO_2-C per gram of soil C per

day (g CO_2-C g C^{-1} day^{-1}) as a mean to evaluate the stability of C in the soil. The CO_2 emissions measured from soil do not include the emissions resulting from burning of plant residues.

2.5. Soil temperature and water content

Soil temperature (ST) and soil water content (SWC) were determined in conjunction with CO_2 effluxes at the 10 data points per plot. ST was evaluated by a sensor connected to the soil chamber (LI-COR 6400-09) by inserting the thermocouple close to the measurement points of CO_2 emissions at a depth of 0–0.05 m. SWC was measured for one season at the closest point to the CO_2 chamber using a Hydrosense soil moisture meter (Campbell Scientific, Inc., USA), calibrated by measurement of the meter responses at saturated soil.

2.6. Statistical analysis

Summary statistics were done for CO_2-C emissions from soil under NB, AB and AM during the whole study period, and summer and winter periods were separated (Table 2). A coefficient of variation was carried out using all the data together. The CO_2 emissions and soil properties data were analyzed as a complete randomized block design using the GENSTAT 14th Edition software. Since CO_2 emissions from soil were measured 24 times during the study period repeated analysis of variance was performed. There were systematic differences between slope positions, which however were considered in the analysis of variance as a block factor. Treatment means were compared using Tukey corrections for multiple comparisons, with significant differences defined at $P < 0.05$, unless specified otherwise. Finally, the study period and seasonal cumulative CO_2 emissions from soil for the treatment were compared. The CO_2 emissions from soil data were analyzed with regard to the season (winter/summer) and also to the position in the slope, the later having high contribution to the overall variability in data.

3. Results

3.1. Impact of treatments on soil properties

The mean $\pm$ SE of the soil bulk density (ρb), SOC content (SOCc), SON content (SONc), SOC stocks (SOCs), SON stocks (SONs), C:N ratio and mean weight diameter (MWD) in the top-soil (0–20 cm) for no burning (NB), annual burning (AB) and annual mowing (AM) are reported in Table 1. Annual mowing had the greatest ρb, while NB had the least. AB soils were with 1.1 ± 0.0 g cm^{-3}, 7% denser than NB soils, while AM was 13% denser than NB soils. SOCc was 19% greater in AB than NB, while AM was intermediate with average value of 27.2 g kg^{-1}. SOCs show the same trend with 13% greater SOCs in AB than NB. SONc was greatest in AB, followed by AM and least in NB. Finally, soil aggregates stability, as measured by MWD, was highest in NB and lowest in AM. All these differences were not significant at p < 0.05.

3.2. Precipitation, air and soil temperature during the study period

The precipitation, average monthly air temperature and ST for the study period (March 2013 to March 2015) are presented in Fig. 2. The total annual precipitations were 631 mm in 2013 and 480 mm in 2014, with about 90% of the precipitation occurring in summer
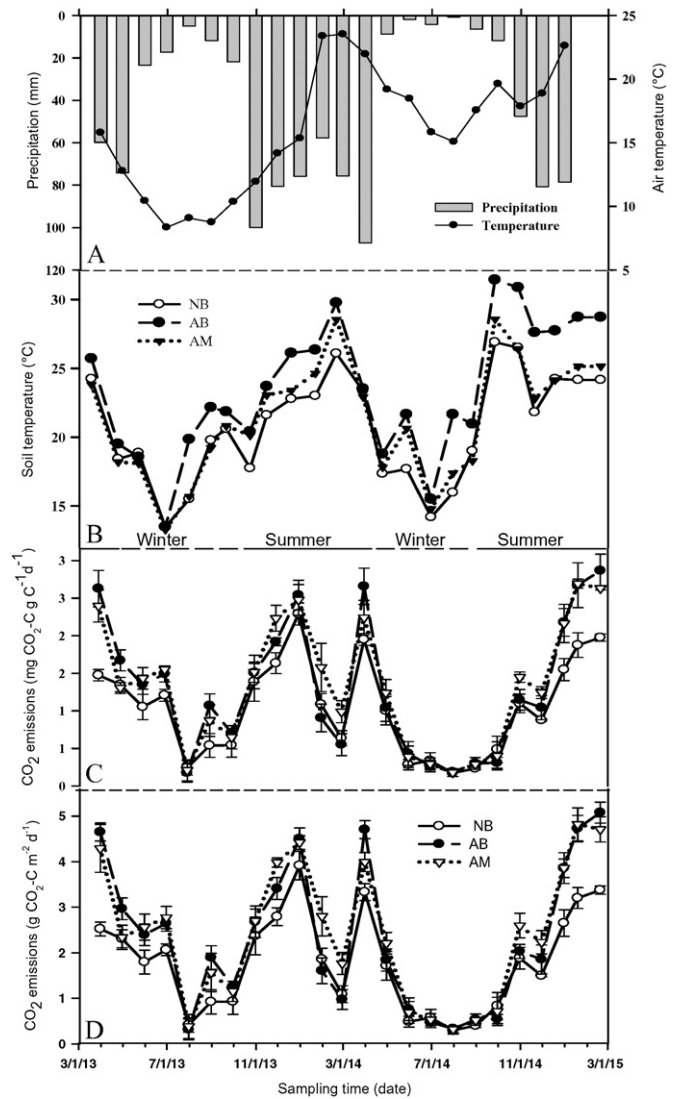

Fig. 2. Monthly rainfall and average monthly air temperature (A), soil temperature (n = 30) at 0–5 cm depth (B), CO_2 emissions (Mean $\pm$ SE) from soil expressed as C-CO_2 g $C^{-1}d^{-1}$ (C) and g C-CO_2 m^{-2} d^{-1} (D) form no burn (NB), annual burn (AB) and annual mow (AM) treatments N = 30.

(Fig. 2A). The highest mean air temperature of 23 °C was recorded in January and December 2014 and lowest (8 °C) in July 2013. Average ST in AB of 23.4 °C was significantly higher than AM (21.4 °C) and NB (20.7 °C) (Fig. 2B). Overall, the average summer ST of 24 °C was significantly higher than that of winter which was 19 °C. While all treatments had similar ST in winters, the summer period ST was significantly higher in AB with average of 25.5 °C compared to NB with 22.5 °C, which was not significantly different from that of AM (23.3 °C).

3.3. Seasonal variation in fluxes and cumulative CO_2-C emissions from soil

Table 2 shows summary statistics of CO_2-C emissions per m^2 and gram of C in the soil for the study period, broken down into summer and winter

Table 1
Selected properties of top-soils (0–20 cm) under grassland and subjected to no burn (NB), annual burn (AB) and annual mowing (AM) treatments. The values are means (n = 3) $\pm$ SE.

Treatments	ρb (g cm^{-3})	SOCc (g kg^{-1})	SONc (g kg^{-1})	SOCs (kg m^{-2})	SONs (kg m^{-2})	C:N ratio	MWD (mm)
No burn (NB)	1.00 ± 0.2	25.7 ± 2.2	1.9 ± 0.1	1.4 ± 0.2	0.1 ± 0.0	13.7 ± 1.1	2.5 ± 0.3
Annual burn (AB)	1.07 ± 0.0	30.5 ± 0.9	2.1 ± 0.1	1.6 ± 0.1	0.1 ± 0.0	14.4 ± 0.8	2.3 ± 0.3
Annual mow (AM)	1.15 ± 0.0	27.2 ± 1.1	1.9 ± 0.1	1.1 ± 0.5	0.1 ± 0.0	14.2 ± 0.5	1.8 ± 0.8

Table 2

Summary statistics of CO_2-C emissions from soil per m^2 and gram of carbon in the soil form no burn (NB) annual burn, (AN) and annual mow (AM) treatments during the whole study period, summer and winter. N = 24.

	CO_2-C					
	g CO_2-C m^{-2} d^{-1}			mg CO_2-C g C^{-1} d^{-1}		
	NB	AB	AM	NB	AB	AM
All seasons						
Mean	1.80[b]	2.34[a]	2.41[a]	1.05[b]	1.32[a]	1.35[a]
SD	1.08	1.57	1.48	0.63	0.89	0.83
Min	0.25	0.08	0.09	0.15	0.05	0.05
Median	1.84	2.11	2.41	1.07	1.19	1.31
Max	4.15	5.27	5.22	2.40	3.04	2.73
SE	0.13	0.19	0.17	0.07	0.11	0.10
CV	0.60	0.67	0.61	0.60	0.68	0.61
Summer						
Mean	2.47[b]	3.21[a]	3.34[a]	1.44[b]	1.81[a]	1.87[a]
SD	0.81	1.37	1.06	0.48	0.78	0.59
Min	0.88	0.84	1.54	0.52	0.46	0.89
Median	2.51	3.23	3.33	1.45	1.85	1.89
Max	4.15	5.27	5.22	2.40	3.04	2.73
SE	0.13	0.21	0.17	0.07	0.12	0.09
CV	0.33	0.43	0.32	0.33	0.43	0.32
Winter						
Mean	0.87[a]	1.12[a]	1.12[a]	0.51[a]	0.63[a]	0.63[a]
SD	3.16	3.16	3.16	3.16	3.16	3.16
Min	0.25	0.08	0.09	0.15	0.05	0.05
Median	0.62	0.65	0.64	0.36	0.37	0.37
Max	2.19	2.76	3.06	1.27	1.61	1.60
SE	0.59	0.59	0.59	0.59	0.59	0.59
CV	3.62	2.83	2.82	6.18	5.02	5.03

Means followed by different superscript letters ([a–b]) in the same row are significantly different (P < 0.05).

seasons. The lowest mean CO_2 emission from soil was 0.87 g CO_2-C m^{-2} d^{-1} in NB during winter and the maximum was 3.34 g CO_2-C m^{-2} d^{-1} in AM during summer. The average daily CO_2-C emissions per m^2 for the study period were significantly lower in NB than AB and AM, by 30% and 34%, respectively. When expressed as mg CO_2-C g C^{-1} d^{-1}, the average CO_2-C from soil was 26% and 29% lower in NB than AB and AM, respectively. In both cases there was no significant difference between AB and AM. The greatest differences in CO_2-C from soil (per m^2 and per gram of C in the soil) occurred during summer period, while there were no significant differences among the treatments in winter.

The results of CO_2-C fluxes from soil expressed either per area basis or per gram of C in the soils are shown in Fig. 2C and D, respectively. The patterns of CO_2-C fluxes from soil were similar in all treatments (NB, AB and AM) during the study period with greatest fluxes observed in summer from October to April, and lowest in winter from May to September. Regardless of treatment, on average, 65% of CO_2-C emissions from soil occurred during summer, which coincided with greater precipitation (90% of total annual rainfall) and highest air temperature (average 19 °C; Fig. 2). During summer periods, CO_2-C fluxes from soil were generally lower under NB than AB and AM, with greater differences at 12 out of 14 sampling events. However, there were no significant differences between AB and AM during this period. During the winter periods, CO_2-C emissions from soil in all treatments were statistically similar. In addition, annual burning did not show significant effect on CO_2-C emissions from soil during the winter period (Fig. 3).

3.4. Controls of SOCs and CO_2 emissions from soil

For all data sets, CO_2 emissions from soil per unit of surface area increased significantly with the increase in SWC, SOCs, SOCc, ρb, ST and C:N ratio, but decreased with the increasing of SONs (Table 3). CO_2-C expressed per gram of C in the soil shown the same trend, increasing with SWC followed by SOCc and SOCs, C:N, ρb and MWD but decreased with increasing SONs (Table 3).

Table 3

Coefficients of determination (r) between CO_2 emissions from soil per m^2 and per gram of carbon in the soil and multiple soil factors: top-soil organic carbon and nitrogen (SOCc; SONc), SOC stocks (SOCs), SON stocks (SONs), carbon to nitrogen ratio (C:N), soil bulk density (ρb); Mean weight diameter (MWD); soil temperature (ST); and soil water content (SWC).

	SOCc	SONc	SOCs	SONs	C:N	ρb	MWD	ST	SWC
g CO_2-C m^{-2}	0.50[*]	0.16	0.59[*]	−0.15	0.46[*]	0.49[*]	0.38[*]	0.47[*]	0.67[*]
g CO_2-C gC^{-1}	0.55[*]	0.15	0.55[*]	−0.23	0.54[*]	0.50[*]	0.47[*]	0.34[*]	0.72[*]

[*] Statistically significant determinants at P < 0.05 level.

4. Discussion

4.1. Long-term burning and mowing impacts on CO_2 emissions from soil

The overall 30% greater CO_2 emissions from soil in AB than NB (Table 2) implies significant stimulation of CO_2 emissions when grassland management changes from no burn to annual burn systems. This finding is consistent with several studies worldwide which reported greater CO_2-C emissions from soil per m^2 in "burn" compared to "no burn" treatment (e.g. Knapp et al., 1998; Rutigliano et al., 2007; Ward et al., 2007; Jia et al., 2012). The greater CO_2 efflux from soil has been attributed to an increase in nitrogen availability from burning which enhance microbial respiration. Another explanation could be a change in organic matter quality consecutive to burning. Assuming that there is a greater proportion of charcoal with low aggregation potential, the charcoal lowers the soil aggregate stability and consequently the protection of C from the decomposers. There was, therefore, likely lower C protection under long-term annual burning at the study site which resulted in NB having 26% lower CO_2-C emissions per gram of C from soil than in AB (Table 2). In support of this, some literature showed that the SOC stability is strongly related to the stabilization of soil aggregates (e.g. Singh et al., 2009; Carrizo et al., 2015). However, there are studies who observed reductions (e.g. Ma et al., 2004) or no changes of CO_2-C emissions from soil in response to fire (Castaldi et al., 2012), for example, laboratory experiments by Guerrero et al. (2001) reported an increase in aggregate stability after fire despite a decrease in soil organic matter.

Consistent with AB, AM stimulated greater CO_2 emissions from soil than NB during the study period, which agreed with the results by Antonsen and Olsson (2005) and Li and Sun (2011). Mowing increases ST due to the removal of vegetation and exposure of the top-soil to direct sunlight, which enhances microbial activity and plant-roots growth. Another explanation for stimulation of CO_2 emissions from soil by mowing was given by Antonsen and Olsson (2005) who indicated the stimulation of arbuscular mycorrhizal fungi growth after mowing. However, contrary to our results, some studies (e.g. Bremer et al., 1998; Han et al., 2012; Jia et al., 2012), found mowing to decrease CO_2 emissions from soil in comparison to NB and they attributed it to the reduction in canopy photosynthesis.

In the present study, lower CO_2 emissions from the soil under NB with tree encroachment than AB and AM were explained by difference of microclimatic conditions due to difference of soil cover. Tree coverage can significantly influence CO_2 emissions from soils due do its effect on soil microclimate (Smith and Johnson, 2004; McCulley et al., 2007). For example, Smith and Johnson (2004) reported that soil respiration rate in woodlands was 38% less compared to grasslands, which they explained by the change in the soil microclimate (moisture and temperature). Carbone et al. (2008) also reported 86% lower CO_2 emissions from NB encroached by shrubs than pure grass over five months (910 vs. 126 g C m^{-2}), which was attributed to differences in soil water availability and below ground C allocation and plant productivity. However, Smith and Johnson (2004) found no difference in fine root biomass between grasslands and woodlands.
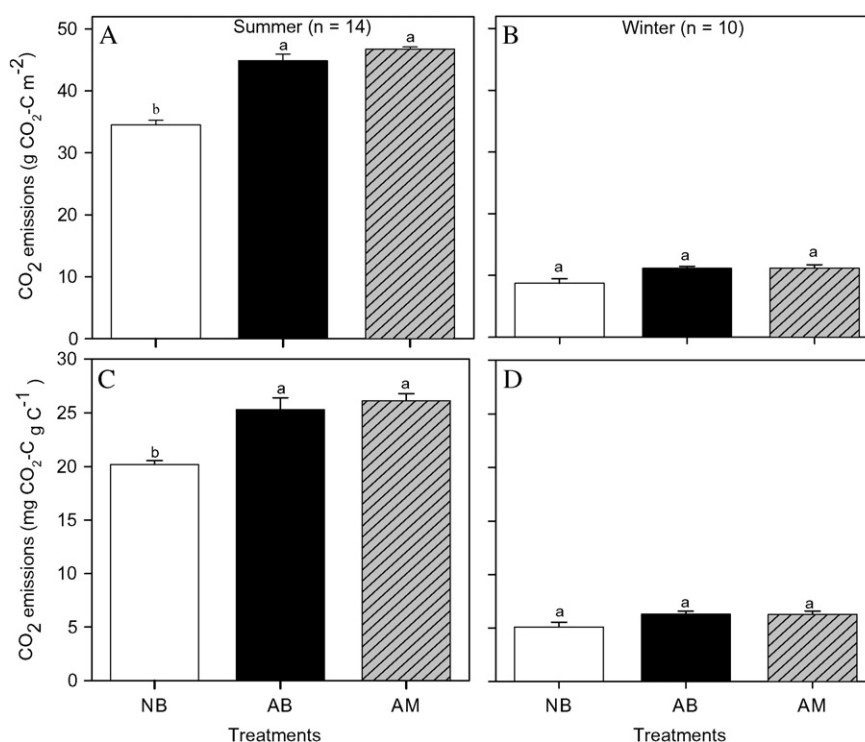
Fig. 3. Cumulative means $\pm$ SE of daily CO_2 fluxes (g C-CO_2 m^{-2}) from soil for no burn (NB), annual burn (AB) and annual mow (AM) treatments for (A) summer and (B) winter and daily CO_2 emissions (mg C-CO_2 g C^{-1}) for (C) summer and (D) winter. Within the same season and CO_2 emissions unit, different lower case letter indicates significant differences between the treatments.

4.2. Seasonal change effects on CO_2 emissions from soil

In the present study, significant differences in CO_2-C per m^2 and per g of C in the soil between treatments were only observed in summer (rainy) seasons (Table 2 and Fig. 2) coinciding with high precipitation, air and ST, which was consistent with what Chen et al. (2002) found in relatively similar conditions in the tropical savannah of northern Australia. They found that 70% of CO_2-C emissions from soil were emitted during rainy seasons, where 95% of the precipitation occurred during this period. The greater CO_2-C emissions from soil during the summer seasons were attributed to higher temperature and precipitation. In this study, CO_2-C emissions from soil were positively correlated to ST ($r = 0.47$ and 0.34 for CO_2-C per m^2 and per g of C in the soil, respectively) and SWC ($r = 0.67$ and 0.72 for CO_2-C per m^{-2} and per g of C in the soil, respectively). It is well known that soil temperature and water content are the most essential microclimatic factors controlling CO_2-C emissions from soils. Thus, the absence of significant differences in CO_2 emissions from soil among the treatments over the dry period can be explained by lower soil moisture in the root zone, which reduces fine root growth and soil microbial activity (Chen et al., 2002).

4.3. Relevance of grassland burning for C emissions in Africa: end note

Since burning will also produce CO_2 and other greenhouse gases such as CO, NO$_x$ and non-methane hydrocarbons (Jain et al., 2006) and the fact that burned area represents up to 80% of the total grassland area in some region (Csiszar et al., 2005), the implications on GHG to the atmosphere through AB at global scale are huge. Annual burning and respiration have already been reported to induce significant C losses into the atmosphere (van der Werf et al., 2006), it suggests >95% of the 58 Pg C year^{-1} fixed by plant through net primary production would eventually be emitted into the atmosphere. Van der werf et al. (2006) estimated the greatest emissions as a result of biomass burning

to come from Africa (49%), South America (13%), equatorial Asia (11%), boreal regions (9%), and Australia (6%).

5. Conclusions

In this study performed on long-term (62-years) grassland management trial in South Africa, CO_2-C emissions from soil under no burned grasslands were compared to annual burning and mowing treatments. Annual burning and mowing resulted in 30% and 34%, respectively, greater CO_2-C emissions per m^2 than no-burning. These differences could be explained by lower stability of SOC in annual burning treatment. Since in this study the higher the aggregation (mean weight dimeter), the lower the CO_2 fluxes from soil which propose a decrease in soil organic matter physical protection occurs upon annual burning and mowing and that is likely to be one of the causes of the increased CO_2 efflux from soil compared to no-burned grasslands.

They are several implications of these results. The first one is that burning, which is a common practice in grasslands of the developing world, should be avoided because of a significant increase in CO_2 emissions from soil. Greenhouse gases other than CO_2 are also emitted during burning and these need to be further investigated. This result directly implies that alternative grassland management practices have to be found. While burning abandonment appeared to lessen CO_2 emissions, it poses a major threat to forage production as grass species get replaced by woody ones. The third implication is that grass mowing is beneficial for avoiding the release of fire-derived GHGs emissions and maintaining the grass sward in good conditions. Mowing, however, slightly decrease grass palatability (Fynn et al., 2004) and this might constitute a major limitation for its broad adoption.

There is a need to find grassland management emitting low amount of CO_2 while sustaining high grass diversity. Following our results, a combination of mowing and burning and/or controlled grazing (such as the high density short duration one: Chaplot et al., 2016) should be tested. Further research needs also to be performed on the underlying

reasons of the variation in CO_2 emissions from soil between different treatments.

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