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

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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.

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

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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):

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

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