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Abstract

Livestock grazing intensity (GI) is thought to have a major impact on soil organic carbon (SOC) storage and soil quality indicators in grassland agroecosystems. To critically investigate this, we conducted a global review and meta-analysis of 83 studies of extensive grazing, covering 164 sites across different countries and climate zones. Unlike previous published reviews we have normalized the SOC and total nitrogen (TN) data to a 30 cm depth to be compatible with IPCC guidelines. We also calculated a normalized GI and divided the data into four main groups depending on the regional climate (dry warm, DW; dry cool, DC; moist warm, MW; moist cool, MC). Our results show that taken across all climatic zones and GIs, grazing results in a decrease in SOC storage, although its impact on SOC is climate-dependent. All GI levels increased SOC stocks under the MW climate (+7.6%) whilst there were reductions under the MC climate (-19%). Nevertheless, under the DW and DC climates, only the low (+5.8%) and low to medium (+16.1%) grazing intensities, respectively, were associated with increased SOC stocks. High GI significantly increased SOC for C4-dominated grassland compared to C3-dominated grassland and C3-C4 mixed grasslands. It was also associated with significant increases in rate of TN change and bulk density but has no effect on soil pH. To protect grassland soils from degradation, recommended GI and management practices will differ according to climate region and grass's type (C3 or C4 or C3-C4 mixed).

1. Introduction

Grasslands cover approximately 40% of the earth’s land surface (Wang and Fang, 2009) and represent about 70% of the agricultural area (Conant, 2012). They store about 10% of terrestrial biomass and make a contribution of about 20-30% to the global pool of soil organic carbon (SOC) (Scurlock and Hall, 1998; Conant et al., 2012). Grasslands have some potential to sequester atmospheric CO_2 as stable carbon (C) in the soil (Reid et al., 2004) and hence could contribute to mitigation of climate change (Allard et al., 2007). However, the accumulation and storage of C in grasslands is influenced by many factors especially biotic factors e.g. grazing intensity (GI), animal type and grass species (Conant et al., 2001; Olff et al., 2002; Jones and Donnelly, 2004; McSherry and Ritchie, 2013). Nevertheless, although grasslands have high SOC contents, recent studies have suggested that intensive livestock management has led to C losses from many grasslands around the world and thereby, grassland soils could become a source rather than a sink for greenhouse gas (GHG) emissions (Janzen, 2006; Ciais et al., 2010; Powlson et al., 2011). Grazing intensity has the potential to modify soil structure, function and capacity to store organic carbon (OC) (Cui et al., 2005) and could significantly change grassland’s C stocks (Cui et al., 2005). As SOC has a major influence on soil physical structure and a range of ecosystem services (e.g. nutrient retention, water storage, pollutant attenuation), its reduction could lead to reduced soil fertility and consequently, land degradation (Rounsevell et al., 1999) and a high risk under climate change (Lal, 2009). However, investigating the effects of GI on SOC is hampered by the heterogeneity in grassland types and variations in environment. This is exacerbated by the fact that all previous published meta-analyses studies on this topic (e.g. McSherry and Ritchie, 2013; Lu et al., 2017; Zhou et al., 2017) pooled the data of different studies together without considering the differences in soil depth at which the SOC, and TN were measured thus producing highly uncertain/contradictory results.

High GI and moisture gradients (Cingolani et al., 2005) could indirectly alter grass species composition by decreasing water availability (Pineiro et al., 2010). This decreases plant community composition, aboveground biomass, leaf area and light interception and thereby, net primary production (NPP) (Manley et al., 1997; Hart, 2001; Pineiro et al., 2010). However, according to Derner and Schuman (2007), Pineiro et al. (2010) and McSherry and Ritchie (2013), high GI can increase soil C sequestration but only when mean annual precipitation is 600 mm or less with different responses received from different soil types. It has also been shown to increase root C contents (a primary control of SOC formation) at the driest and wettest sites, but decrease root C contents at intermediate precipitation levels (400 mm to 850 mm) (Pineiro et al., 2010). Wang et al. (2017) reported that the composition of plant species and soil condition in the Tibetan pastures were not only affected by GI but also by the local environmental factors. Moreover, Russell et al. (2013) found that a short period of mob grazing (grazing at high intensity for a short period of time) was effective at increasing soil organic matter and diversity in forage species composition. Though, overgrazing to the point of stripping surface vegetation can result in soil-degradation and loss of the fertile topsoil, especially where precipitation is low and evaporation is high (Xie and Wittig, 2004).

Furthermore, high GI can alter SOC by changing the competitive abilities of different microbial phyla because of the link between GI, carbon availability and ecosystem functions (Eldridge et al., 2017a). However, the relationship between GI and SOC is non-linear (Eldridge et al., 2017b). Previous studies have found mixed results (Derner et al., 2006; McSherry and Ritchie, 2013; Zhou et al., 2017), with studies showing increases (Reeder and Schuman, 2002; Li et al., 2011; Silveira et al., 2014), no affect (Frank et al., 2002; Shrestha and Stahl, 2008; Cao et al., 2013) or decreases (Zuo et al., 2008; Golluscio et al., 2009; Reszkowska et al., 2011; Qiu et al., 2013) in SOC stocks. The review by McSherry and Ritchie (2013) showed that GI effects on SOC are highly context-specific, where higher GI increased SOC on C4-dominated and C4-C3 mixed grasslands, but decreased SOC in C3-dominated grasslands. Other recent reviews by Lu et al. (2017) and Zhou et al. (2017) found that high GI significantly decreased belowground C and N pools. They found GI interacts with elevation and mean annual temperature (Lu et al., 2017), or with soil depth, livestock type and climatic conditions (Zhou et al., 2017).

Understanding the impacts of GI on SOC accumulation and storage in grasslands is crucial to provide the most effective soil C management options. However, although all those previous reviews are valuable, scientific understanding would be improved by normalizing the sampling depth and GI. In this study, to be compatible with the IPCC guidelines, reduce these errors and make a comprehensive evaluation for GI we have normalized the soil depth for all studies to 30 cm using a quadratic density function based on Smith et al. (2000) and calculated a normalized GI. The major objective of this meta-analysis was to investigate the impacts of GI on SOC in extensively grazed grassland soils at a global scale. Additionally, and because of its importance for C biogeochemistry, we discuss the impacts of GI on total nitrogen (TN) and other soil properties (mainly pH and bulk density) in grasslands. We also investigated whether climatic variations can control the ecological effects of GI practices on SOC in grasslands. The specific hypotheses we critically evaluated are as follows: 1) higher GI decreases SOC and TN in soils 2) the impacts of GI on SOC are modified by environmental and biotic factors, and 3) the effects of GI on SOC stocks depends on climatic zone and soil texture.

2. Materials and Methods

2.1. Data collection

To collect published studies that have investigated the impacts of GI on SOC and other selected soil properties (TN, pH and BD) under grassland, we performed a comprehensive search on the Web of Science database (accessed between January 2015 and February 2017) using the keywords: grazing; soil organic carbon; grassland; GI; total nitrogen and carbon sequestration. In an attempt to have the best possible coverage, we also checked all references in the papers found in the Web of Science search. Only studies which were longer than one year and measured SOC or TN were selected. This study accounted for the differences in grass growing seasons at each experimental site. Our searches resulted in 83 studies that investigated the impacts of grazing on SOC and other selected soil properties, carried out at 164 sites covering different countries, climatic zones and management systems (Fig. 1). The studies were segregated into four groups depending on the regional climate zones (dry cool (DC); dry warm (DW); moist cool (MC) and moist warm (MW)).

We defined the climatic zones based on thermal and moisture regimes: cool, warm, dry, and moist zone according to Smith et al. (2008). The cool zone covers the temperate (oceanic, sub-continental, and continental) and boreal (oceanic, sub-continental and continental) areas, whilst the warm zone covers the tropics (lowland and highland) and subtropics (summer rainfall, winter rainfall, and low rainfall) areas. The dry zone includes the areas where the annual precipitation is equal or below 500 mm, whilst the moist zone includes areas where the annual precipitation is above 500 mm. Coordinates, grass type (i.e. shrubby, woody, steppe, and prairie), annual mean climatic conditions as well as grazing details, soil texture, original depth (OD), initial and final BD and pH, changes in SOC and

TN (kg m^{-2}); values were added where available or we put plus (+) for increased and minus (-) for decreased, as shown in Tables 1-4.

2.2. Estimation methods applied

In some studies SOC and TN values are given as concentrations. To convert these values to stocks (kg m^{-2}), the following equations were applied (IGBP-DIS, 1998):

$$\text{SOC (kg m}^{-2}\text{)} = [\text{depth (cm)} * \text{BD (g cm}^{-3}\text{)} * \text{SOC (\%C in g per100g soil)}]/1000 \qquad (1)$$

$$\text{TN (kg m}^{-2}\text{)} = [\text{depth (cm)} * \text{BD (g cm}^{-3}\text{)} * \text{TN (\%TN in g per100g soil)}]/1000 \qquad (2)$$

In cases where there were more than one year of values reported in the original paper we used the mean value in this meta-analysis. However, because studies reported the SOC and TN content from different soil depths, we used a quadratic density function based on Smith et al. (2000) to derive a scaling cumulative distribution function (c.d.f.) for soil density as a function of soil depth up to 1m. This allows SOC and TN at a given depth d (m) to be scaled to the equivalent values at 0.30 m as follows:

$$\mathrm{cdf(d)} = \left(22.1 - \frac{33.3\mathrm{d}^2}{2} + \frac{14.9\mathrm{d}^3}{3}\right)/10.41667 \qquad (3)$$

$$\mathrm{SOC(0.3m)} = \mathrm{SOC(d)} \times (\mathrm{cdf(0.3)})/(\mathrm{cdf(d)}) \qquad (4)$$

Different methods were used to measure soil pH in different studies, e.g. using pH probe/meter in deionized water or 0.01 M $CaCl_2$ in 1:1 and 1:2 or 1:5 (v:v) soils: solution ratios. We did not adjust pH results recorded by different methods, but where a range of values were reported, we took the mean value. Also, where a range of air temperatures was reported, we used mean annual value in degree Celsius (°C) as reported for the years of the study in the meta-analysis. The mean annual precipitation (mm) value for each study period was taken from the original papers. However, where the mean annual precipitation or mean annual temperature were not reported, those values were taken from the CRU 3.24 climate data set (Harris et al., 2013).

The GI reported in each of the studies was estimated in different ways, and was usually subjective considering local practices, usually described as high, medium (or moderate) and low. To undertake this analysis we required a continuous variable for grazing intensity and so the method described below was developed for this study and used to classify the GI used for each of the experiments in a comparable way. As available fodder was not described in all studies it was necessary to estimate the amount of plant dry material available (DM) on each site annually and to calculate the fodder requirements for the animals grazed at each experimental plot in a consistent manner. To achieve this, the annual NPP, expressed as dry vegetable matter (DM) (Mg DM ha^{-1} y^{-1}) in terms of C was predicted for each location using the Miami model (Lieth, 1972; Grieser et al., 2006), and calculated using mean annual precipitation (P, in mm), and mean annual temperature (T, in ^{o}C) reported in each study or determined from the CRU TS 3.4 dataset. (The possible effect of N fertilizer was not considered because of data scarcity).

$$NPP = \text{minimum} (NPP_T; NPP_P) \tag{5}$$

$$NPP_T = 30 (1 + \exp (1.315 - 0.119\ T) \tag{6}$$

$$NPP_p = 30 (1 - \exp (-0.000664\ P)) \tag{7}$$

where NPP_T is the net primary production calculated based upon temperature and NPP_p is the net primary production calculated based upon precipitation (Lieth, 1972; Grieser et al., 2006).

The available surface vegetable dry matter (SVDM) available for animal grazing for each location was calculated using the following relationship, assuming an allocation of NPP to above ground biomass of 50% (Li et al., 1994):

$$SVDM = NPP \times 0.5\ (\text{Mg DM ha}^{-1}\ y^{-1}) \tag{8}$$

An animal unit month (AUM) is considered as a bovine weighing of 500 kg requiring 350 kg of DM a month of feed based on the animal equivalent chart (USDA-Animal equivalent chart). The carrying capacity (CC) of grassland is the number of animal unit months that the land will support, based upon the available forage dry matter and the fodder requirement, and this we calculated as:

$$CC = SVDM / 0.350\ AUM\ ha^{-1}\ y^{-1} \tag{9}$$

The GI was calculated from the ratio of the number of animal unit months actually grazed up to carrying capacity. The actual number of animal unit months (AAUM) depended on the type of animal: i) cows =1; ii) steers = 0.7; iii) sheep = 0.2; iv) goats = 0.2, v) domesticated yaks as 0.7 (USDA-Animal equivalent chart). The AAUM was calculated as the product of stocking density per ha multiplied by the number of months grazed per year in ha^{-1} y^{-1}.

$$GI = AAUM /CC \tag{10}$$

As changes in SOC stocks are related to the initial SOC and the annual carbon input to the soil. We calculated the annual carbon input (CIN) to be the quantity of annual NPP carbon not grazed by the animals, and calculated as:

$$CIN = NPP\ (1-GI). \tag{11}$$

2.3. Data analyses

We used Minitab 17 (Minitab, Inc., State College, PA) to conduct the data exploration, conditioning and analyses. The complete data set was analysed to estimate the overall impact of grazing on grassland SOC and selected soil properties, and then to analyse the impact of climatic zone and GI. We have sufficient data to estimate the change in SOC stock (n=83) related to grazing for the top 30 cm or the profile over the period of the experiment that could be normalized to an annual rate per year. For a subset of the data (n=64) it was possible to estimate the change in total nitrogen per year during the experiment, bulk density change (n=43) and pH (n=30).

The data collected were segregated into four climatic zones for the meta-analysis: DC (n=26), DW (n=33), MC (n=9) and MW (n=15). The data were also grouped by the calculated GI: low (LG; GI = 0 to 0.33), medium (MG; GI = 0.33 to 0.66), high (HG; GI = 0.66 to 1.0) and overgrazed (OG; GH ≤1.0). The tests were also grouped by animal type bovine (B), which included yaks, steers, cows and heifers; caprine (C), including sheep and goats; and a mixture of both bovine and caprine (M). The tests were also grouped by soil type and texture: clay, clay-loam, loam, sandy-loam and sandy; and grassland type: grassland, shrubby grassland, woody grassland, steppe, and prairie. We also tested grass by photosynthesis type: C3, C4 and mixed.

We used different analytical procedures for each group and parameter that related to the available published data. An analysis of the effects of grazing on on SOC, TN, pH and BD was made by the methods of Hedges et al. (1999) and Luo et al. (2006) using the response ratio (RR) defined as the natural logarithm of the ratio of the value or the parameter measured on the grazing treatment to that without grazing (control).

$$\text{Ln (RR)} = \ln \text{(grazed treatment parameter value/un-grazed (control) parameter value)} \qquad (12)$$

The rate of change (R) was calculated in the form ln (RR) by dividing by the length of the experiment in years (y).

$$R = \ln (RR)/y \qquad (13)$$

The descriptive statistics of the annual change in SOC, TN, BD and pH due to grazing including mean, median, standard deviation, and 95% confidence intervals for each were calculated. One way ANOVAs were performed to investigate the impact of factors: climate, GI, grass and animal types on SOC, TN and other selected soil properties, and the rates of change. Principle component analysis was used to determine significant explanatory variables and response variables and determine the differences between climate zones. In addition, regressions or mixed models such as GLM’s, were used to determine significant explanatory variables.

3. Results

3.1. Estimation of NPP and grazing intensities

Mean NPP for the period 1960-2000 covered a wide range of values reflecting the global diversity of NPP under different climate zones (Fig. 1). No statistically significant differences in NPP between the DC, DM and MC climate zones was found; however, the NPP values at the MW climate were significantly different from those under the other climate zones (Fig. 2 and Table 5). The calculated and reported estimates of GI show considerable overlap, and only three experiments represented ‘overgrazing’ i.e. beyond the carrying capacity (Fig. 3).

They also illustrated the different definitions of the levels of grazing used in the literature for each domain.

A linear regression of annual NPP remaining available as a possible OC input to the soil, with the calculated GI and climate zones ($p<0.001$, $R^2= 67\%$), demonstrated that the SOC stock under the MC climate zone is much higher than under the other climate zones (Fig. 4). An ANOVA showed that un-grazed SOC is different between the different climate zones as shown in Table 6 and explains 21% of the variation. A GLM showed that adding NPP and pH explained 41% of the un-grazed SOC value.

3.2. Impacts of grazing intensity on SOC and other selected soil properties using the response ratio ln (RR)

An analysis of all studies together and using the response ratio ln (RR) of grazed compared to un-grazed grassland, showed that GI was associated with a decrease of overall SOC stocks by a response ratio of -0.0774 (-8%; StDev=0.358). It was also associated with a slight increase in pH of 0.029 (+3%; StDev=0.044), an increase in TN of 0.06 (+6%; StDev=0.772) and BD of 0.070 (+7%; StDev=0.083). However, an ANOVA of the SOC, TN, BD and pH showed that whilst climate zone significantly affects SOC change (p=0.011) and pH (p=0.014), it did not significantly impact BD (p=0.144) or TN (p=0.118) (Table 7). At all GI levels, grazing increased SOC stocks under the MW climate (+7.6%), but decreased them under the MC climate (+19.5%). However, for the DW and DC climates, only the low (+5.8%) and low to medium (+16.1%) grazing intensities, respectively, led to increases in SOC (Fig. 5).

Analysis of the impact of animal type (bovine, caprine and mixed) on ln (RR) of SOC across all climate types showed no significant difference (p=0.89). Neither soil texture (clay, clay-loam, loam, sandy-loam and sandy) (p=0.75), nor grassland characteristics (grassland, shrubby grassland, woody grassland, steppe, and prairie) (p=0.079) significantly affected SOC. However, an ANOVA for grass photosynthesis type (C3, C4 and mixed) showed that there was a significant difference (p=0.003) with C4 grasslands increasing SOC by 0.056 (StDev=0.341), and C3 grasses and mixed grass decreasing SOC by -0.155 (StDev=0.233) and -0.25 (StDev=0.435), respectively (Table 8).

3.3. Impacts of grazing intensity on SOC with annual rate of response ratio ln (RR)

The annual rate of change, R, of the response ratio ln (RR), show that GI overall decreased SOC, with an annual rate of -0.009 (StDev=0.037), but increased pH at a rate of 0.003 (StDev=0.006), TN at a rate of 0.0005 (StDev= 0.0047) and BD at a rate of 0.009 (StDev=0.021). However an ANOVA of the SOC, TN, BD and pH showed that, whilst climate zone significantly impacts the rate of SOC change ($p<0.001$), rate of TN ($p=0.047$) and rate of BD change ($p=0.009$), it did not significantly impact the rate of pH change ($p=0.201$; Table 9). It also showed that GI was associated with more rapid decreases in SOC in DW and MC climates, than in DC and MW climates (Table 9).

3.4. Interactions between climate zone, grazing intensity and soils

The effect of soil texture was tested by ANOVA both for the entire data set (n=67) and for each climatic region (DC, n=22; DW, n=21; MC, n=6 & MW, n=14), but no statistical differences were found between texture classes (data not shown).

3.5. Interactions of significant explanatory variable on response ratio ln (RR).

Principle component analysis (PCA) showed that the main explanatory variables for response ratio ln (RR) were climate zone, initial SOC, grazing intensity and NPP. PCA component 1-4 derived from this parameter subset showed a different pattern for each climate zone with DW and DC being similar and MW and MC exhibiting different patterns (Figure 6). When the contribution of each variable to the four components is examined in radar plots (Figure 7), it is observed that the pattern of interaction or each variable is different for each climate zone indicating that SOC change is governed by different factors.

4. Discussion

4.1. Comparison of methods used here with previous analyses

In this systematic global review and meta-analysis we collected 83 published studies, on the impacts of GI of grasslands on SOC and other selected soil properties (TN, pH and BD), covering 164 sites and representing different countries and climatic zones. However, unlike the previous published reviews (e.g. McSherry and Ritchie, 2013; Lu et al., 2017; Zhou et al., 2017), we depth-normalized the SOC and TN data in line with IPCC guidelines. We also calculated a normalized GI. The purpose was to attempt to harmonise very heterogeneous data. Additionally, the calculation of the normalized GI allowed us to compare across experiments, since reported grazing intensities were subjective, considering the normal local management practices. We found the calculated GI overlapped with the GI from the collected literature, which suggests that our normalization method is unlikely to have introduced additional errors. The extracted mean annual temperatures and annual rainfall at each site from the CRU 3.4 dataset all agreed well with the values reported in publications, where given, providing confidence to the calculation of NPP using the Miami model at each experimental site. Our value of excess NPP for a given GI are similar for all climate zones except for MW, where the value is almost double that in the other climate zones. Here, climate, especially temperature and rainfall, influences grass productivity and thereby NPP (Chu et al., 2016). Climate zones also play a major role in the initial SOC contents, and values for the different zones were significantly different ($p<0.05$) from each other (i.e. SOC was highest for MC, and lowest for the DW climate zone). Estimation of uncertainty is of crucial importance since it has a large impact on the management decisions. In this study, some approximations and assumptions incorporated in the methods we used may have created uncertainty in the final results. To consider this, we have conservatively estimated it by calculating the standard deviation for all values as shown in the Tables 5-9.

4.2. Impacts of grazing intensity on soil organic carbon (SOC)

By pooling all the data and ignoring the regional climatic zones we found that higher GI, was generally associated with a decrease in SOC stocks. Similar results were found by Lu et al. (2017) and Zhou et al. (2017) amongst others. However, analysing the data according to climate zone revealed that the impact of GI on SOC is clearly climate dependent, so that the same GI level under specific climate zones could have different impacts on SOC compared to others. This can be explained by the interactions between GI and the environmental parameters (e.g. temperature and precipitation) at each climate zone. The different GI levels have significantly different effects on individual plant species occurrences and covers and thereby, SOC. Generally, grazing simulates pasture growth, so although the animals under high GI consume more C from the system and respire it, grazing returns (urine and faeces) recycle the C, so the input to the soil remains similar. In addition, the amount and quality of animal urine and dung, and typical manure management practices in each climate zone, may also stimulate grass regrowth differently. Below we discuss our results for each climate zone in more detail.

4.2.1. Impacts of grazing intensity on soil organic carbon (SOC) under dry/warm climates

Under the DW climate, where soil is dry and temperature and evapotranspiration are high, GI has detrimental effects on SOC at all levels apart from low GI, under which SOC increases by 5.8%. In this climate zone, Angassa (2014) reported a decline in species richness under high GI and suggested low to medium grazing intensities for promoting and conserving key forage species. Low GI could stimulate grass regrowth and mobilise nutrients within the soil and therefore, is recommended for steppe-type ecosystems such as those found in Inner Mongolia (Steffens et al., 2008). Fernandez et al. (2008) reported that high GI affects soil fertility and has long-term potential implications for the sustainability of grazing in semi-arid environments. It can also increase CO_2 fluxes from soil and reduce the potential of grasslands to capture CO_2 by reducing aboveground biomass (Frank et al., 2002), thereby reducing the source of SOC from above- and below-ground inputs. Similarly, in a mixed prairie, high GI has been shown to change grass composition (reduced tallgrasses) resulting in reduced litter accumulation and ground cover (Fuhlendorf et al., 2002). It is also likely to increase nutrient losses (particularly N) (Craine et al., 2009), affect bacterial and fungal community structures (Huhe et al., 2017), and hence threaten longer term sustainability . However, according to Talore et al. (2016), although high GI reduces the total C and total N soil content and its C/N ratio, a resting period of 1-2 years followed by three consecutive grazing years at low GI would be ideal for a sustainable livestock production in South Africa. Although Walters et al. (2017) reported that management of GI, by rotational grazing (which incorporated long periods of rest) control through fencing increased SOC on red Lixisol soils.

4.2.2. Impacts of grazing intensity on soil organic carbon (SOC) under moist/cool climates

In the MC climate zone, where soil is moist for longer periods and the temperature is low, all type of GIs led to a decrease in SOC. The activity of soil microorganisms is supressed due to low temperature and high water saturation of the soil (i.e. reducing oxygen availability). High rainfall decreases microbial biomass, likely due to high demand of nutrients from the soil for the peak growth of vegetation during that time (Devi et al., 2014) and decreases soil pH. Many other studies have found that frequent disturbances of grassland by grazing practices at different intensities decrease C sequestration in soils (e.g. Klumpp et al., 2007; 2009; Wu et al., 2009, 2010). Sun et al. (2011) reported that higher GI under alpine meadows, reduced plant biomass productivity and changed the species composition and thereby, decreased SOC. Moreover, Wu et al. (2009) and Dong et al. (2012) found that high GI decreased, not only SOC, but also soil N in the Qinghai-Tibetan Plateau. Further, trampling by cattle decreases soil carbon storage by stimulating organic matter decomposition, due to the destruction of soil aggregates by mechanical stress, alters soil microbial community structure, leads to lower fungal to bacterial ratios (Hiltbrunner et al., 2012), and increases denitrification rates and N losses (Su et al., 2005; Jones et al., 2017). Pappas & Koukoura (2011) found that medium GI could enhance soil carbon accumulation at higher altitudes. The trade-off between above- and below-ground C storage is positively associated with net ecosystem productivity. However, increasing grass productivity by adding more N fertilizer then intensifying the GI accordingly can increase SOC (Klumpp et al., 2007). Although the use of added N to enhance productivity in temperate grasslands is widespread, it can lead to an enhancement of N losses particularly as GI increases. This can lead to a situation where despite increases in C sequestration the losses of non-CO_2 GHGs increase and the net GHG balance remains close to zero (or becomes positive), offsetting the benefits of C sequestration (Jones et al., 2017; Soussana et al., 2007). In circumstances where soils have a high nutrient capital (e.g. upland sheep grazing), it can be more appropriate to recommend no or low-intensity grazing as a management practices for enhancing plant and soil C sequestration (Smith et al., 2014). In contrast, Gao et al. (2007; 2009) and Li et al (2011) reported that higher GI increased soil C and N storage in alpine meadows through changes in the species composition and biomass allocation pattern. Although grazing in the warm-season is good for plant diversity conservation and nutrient storage in the topsoil, whilst grazing in the cold season is suitable for nutrient storage in deep soil layers (Gao-Lin et al., 2017). Pavlů et al. (2007) demonstrated that high GI creates canopy gaps, relaxes intra- and inter-specific competition for light, and ultimately favours the establishment of short-stature, less-palatable forb species.

4.2.3. Impacts of grazing intensity on soil organic carbon (SOC) under moist/warm climates

In the MW climate zone, where both moisture and temperature are high, all GIs have a beneficial impact on SOC. Temperature increases soil microbial C due to faster decomposition of plant residues and immobilization of products in the microbial biomass. However, Devi et al. (2014) found that only medium GI may benefit sub-tropical grasslands, by influencing nutrient dynamics and could be prescribed for the management of these grasslands. Da Silva et al. (2014) reported that light GI was a useful management for enhancing C sequestration whilst high GI led to a reduced number of plants, plant basal area, and amount of deposited dead plant material. Nevertheless, Wright et al. (2004) reported that a long-term grazing at low GI of Bermuda-grass pastures can increase SOC and SON concentrations and could have strong potential for C and N sequestration. This is mainly due to enhanced turnover of plant material and excreta under low GI. Franzluebbers et al. (2000)

found that a long-grazed pastures in the Southern Piedmont USA have great potential to restore natural soil fertility, sequester soil organic C and N and increase soil biological activity compared to other land use management. The processing of forage through cattle and deposition of faeces onto the pasture can increase the long-term storage of SOC (Franzluebbers et al., 2000). Other studies (e.g. Kieft, 1994; Shrestha and Stahl, 2008) found no consistent impacts of GI on soil C and N, C/N ratios and microbial biomass and respiration rate.

4.2.4. Impacts of grazing intensity on soil organic carbon (SOC) under dry/cool climates

In the DC climate zone, where both moisture and temperature are low, low to medium GIs are beneficial for SOC, while high GI impact is unknown as this study found no relevant published data. According to Ganjegunte et al. (2005) and Han et al. (2008) low to medium GI is the most sustainable grazing management system to increase SOC. Han et al. (2008) reported that high GI diminished grass regrowth, decreased litter deposition and decreased SOC. Steffens et al. (2008) reported that sheep grazing at high GI deteriorated physical and chemical parameters of steppe top-soils and depleted SOC and could be improved by reducing GI or excluding from grazing. Further, long-term grazing at different intensity levels significantly reduced SOC and TN in an Inner Mongolian grassland (Li et al., 2008; Ma et al., 2016). Also, soil compaction induced by sheep trampling changes selected soil properties and possibly enhances soil vulnerability to water and nutrient loss, and thereby reduces plant available water, and thus grassland productivity (Zhao et al., 2007). In contrast, Reeder and Schuman (2002) found that grazing at high and low intensities increased SOC, partly due to rapid annual shoot turnover and redistribution of C within the plant-soil system as a result of changes in plant species composition.

4.3. Impacts of grazing intensity on C3/C4 dominated grass or C3-C4 mixed grasslands

Our results show that on average GI was associated with significantly increased SOC for C4 dominated grasslands, whilst it significantly decreased SOC for C3 dominated grasslands and C3-C4 mixed grasslands. Similar findings were reported by McSherry and Ritchie (2013). The reason for increased SOC levels under grazed C4-dominated grass, especially in tropical grasslands, is the ability of the grass to adapt and compensate for grazing practices (Ritchie et al., 2014). C4 grasses adapt to high GI by having many rhizomes and other storage organs that enable them to respond quickly to grass defoliation by animals (McNaughton, 1985; Dubeux et al., 2007). In addition to the warm temperature that encourages macrodecomposers to incorporate plant and animal materials in the soil (Risch et al., 2012), C4-grasses can compensate the loss by sacrificing stems for leaves (Ziter and MacDougall, 2013), and by containing higher levels of lignin and cellulose (Barton et al., 1976). As C4 dominated grasslands would be generally in the moist warm climate zone these results are self-consistent.

4.4. Impacts of grazing intensity on other selected soil properties (TN, BD and pH)

There were too few data points in each climate zone to assess the impact of grazing intensity on pH, BD and TN separately for each climate zone. However, pooling data across all climate zones suggests that on average GI could significantly increase the rate of change of TN and BD but the effect on soil pH was small. Many studies have found higher BD (e.g. Dong et al., 2012; Luan et al., 2014; Abril and Bucher, 1999; He et al., 2011) and high pH (e.g. Yong-Zhong et al., 2005; Pei et al., 2008; Enriquez et al., 2015) in response to high GI in different climate zones. Grazing intensity increases soil BD and lowers soil moisture content, mainly due to high animal trampling (He et al., 2011; Zhang et al., 2017), leading to higher denitrification losses (Oenema et al., 1997) and may increase the risk of soil erosion by wind (Kolbl et al., 2011). However, some studies have found lower BD due to GI, e.g. Li et al. (2008) and Schuman et al (1999). High GI was reported to decreases soil pH (Hiernaux et al.1999; Cui et al. 2005; Zhang et al., 2017). Also, many studies (e.g. Wright et al., 2004; Ganjegunte et al., 2005; Han et al., 2008; Li et al., 2011) have found that GI increases TN, while others suggest it decreases TN (e.g. Li et al., 2008; Ma et al., 2016; Zhou et al., 2017) or had no change (Schuman et al., 1999).

5. Concluding remarks

The impact of GI on SOC stocks differs between the different climate zones, but that lower GIs increase SOC stocks in three of the four climate zones (list the three here), whereas higher GIs result in increased SOC in only one climate zone (include the 4th here). Although our model for predicting biomass production does not take into account extra gains in productivity that can be achieved (promoting increased C sequestration), the benefits (in terms of net GHG emissions) of N use will often be offset by increased losses of non-CO_2 GHG emissions (particularly at higher GIs). There are also differences between C3, C4 and mixed grasslands in their response to GI, and rate of TN change and BD tend to increase under high GI. The effects of GI management on SOC are mediated by ground cover and high organic matter supply and/or less soil erosion (Waters et al., 2017). High GI can decrease net primary productivity (Wardle, 2002) and result in the loss of palatable, larger-leafed species causing domination of unpalatable small-leafed species which produce litter of low quality for soil microbes and fauna (Cornelissen et al., 1999; Shengjie et al. (2017). This reduction of some plant-species could also result in decreasing chemical quality of the organic C stock in soil (Larreguy et al., 2017). Moreover, high GI can shift the fungal:bacterial ratio towards dominance by fungi, which are more tolerant of periodic drought and seasonal fluctuations in soil moisture than bacteria (Bagchi and Ritchie, 2010; Bagchi et al., 2017). Best management practices for GI, therefore, need to be tailored to local bioclimatic conditions to avoid loss of soil carbon. Policy makers in each climatic zone should decide on the level of GI depending on the local climate and grass types they have. Such climate impacts should be considered in future grassland management and conservation plans. The optimal use of GI and grass species has the potential to significantly increase SOC and SON sequestration, and alters C and N cycling in soil. In addition, the breeding of plants with deeper or bushy root ecosystems e.g. *Festulolium* (ryegrass x fescue hybrid), which have greater efficiency in resource use, could improve carbon storage, water and nutrient retention, as well as biomass yields (Kell, 2011; Humphreys et al., 2003). In a world of a changing climate, livestock production will be negatively affected, especially in arid and semiarid regions, due to e.g. diseases and water availability. Our results have important implications for setting future grassland management policies that account for climate change. High GI under increased frequency of drought and heatwave events may increase GHG emissions and turn grasslands into C sources (Ciais et al., 2005; McSherry and Ritchie, 2013). Additionally, long-term drought in combination with high atmospheric CO_2 concentration can? decrease soil microbial biomass and promote a shifts in functional microbial types, and thereby modify biogeochemical cycles and SOC storage (Barnard et al., 2006; Pinay et al., 2007). Further, high GI on dry areas or C3 grassland reduces C storage and makes it vulnerable to climate change, whilst increases C sequestration under C4 grasslands. Thus considering climate will allow us to properly address sustainability of SOC, conservation of biodiversity, reduction of greenhouse gas emissions and mitigation of climate change as the geographical location of the bio-climatic envelope of the flora and fauna of current climatic zones moves with the evolving climatic disruption.

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