Journal of Environmental Management 223 (2018) 74–84

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Review

Soil organic carbon stock in grasslands: Effects of inorganic fertilizers, liming and grazing in different climate settings

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A R T I C L E I N F O

Keywords:
Grassland soils
Soil improvement
Land management
Climate change
Carbon sequestration
Nitrogen amendment

A B S T R A C T

Grasslands store about 34% of the global terrestrial carbon (C) and are vital for the provision of various ecosystem services such as forage and climate regulation. About 89% of this grassland C is stored in the soil and is affected by management activities but the effects of these management activities on C storage under different climate settings are not known. In this study, we synthesized the effects of fertilizer (nitrogen and phosphorus) application, liming and grazing regime on the stock of SOC in global grasslands, under different site specific climatic settings using a meta-analysis of 341 datasets. We found an overall significant reduction (−8.5%) in the stock of SOC in global managed grasslands, mainly attributable to grazing (−15.0%), and only partially attenuated by fertilizer addition (+6.7%) and liming (+5.8%), indicating that management to improve biomass production does not contribute sufficient organic matter to replace that lost by direct removal by animals. Management activities had the greatest effect in the tropics (−22.4%) due primarily to heavy grazing, and the least effect in the temperate zone (−4.5%). The negative management effect reduced significantly with increasing mean annual temperature and mean annual precipitation in the temperate zone, suggesting that temperate grassland soils are potential C sinks in the face of climate change. For a sustainable management of grasslands that will provide adequate forage for livestock and mitigate climate change through C sequestration, we recommend that future tropical grassland management policies should focus on reducing the intensity of grazing. Also, to verify our findings for temperate grasslands and to better inform land management policy, future research should focus on the impacts of the projected climate change on net greenhouse gas exchange and potential climate feedbacks.

1. Introduction

Grasslands cover approximately 40% of the earth's surface (excluding Antarctica and Greenland), are distributed across all continents and over a wide range of geological and climatic conditions (Suttie et al., 2005; White et al., 2000). About 34% of the global terrestrial carbon (C) is stored in grasslands and a significant (89%) amount of the C sequestered by the grassland vegetation is stored in the soil (Ajtay et al., 1979; White et al., 2000), which is vital for the provision of ecosystem services and particularly for climate regulation (Buckingham et al., 2013).

The distribution and productivity of grasslands is mainly limited by climate and inherent soil properties. Globally, 28% of grasslands are distributed in semi-arid areas, 19% in arid areas, 23% in humid areas and 20% in cold areas (White et al., 2000). Climate exerts an overriding influence on the size of the grassland soil C store through its control on plant growth, and therefore rates of litter and plant exudate inputs to soil and the rates of C loss through decomposition, leaching and erosion, and these processes are particularly sensitive to precipitation and temperature patterns (Albaladejo et al., 2013; Bellamy et al., 2005; Rees et al., 2005). Currently, climate is changing, with nearly 0.8 °C rise in global average temperature since the 19th Century and a greater warming as well as altered precipitation patterns expected throughout the 21st Century (IPCC, 2013; Jenkins et al., 2008). Thus grasslands that naturally exist at the margins of their climatic and edaphic envelope, or whose continued existence depends on management activities may be particularly sensitive to climate change, with poorly understood consequences for soil C stocks and feedback to climate change.

Globally, grasslands are managed to increase biomass productivity in order to support livestock production, and are either being directly grazed, or cut for fodder, typically as hay or silage, or a combination of all three. Management activities are primarily used to change the status of soil properties thereby creating optimum conditions for plant growth. Soil characteristics that have been associated with rapid grassland establishment and increased productivity include relatively high sand and silt and low clay contents, and therefore moderate

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https://doi.org/10.1016/j.jenvman.2018.06.013
Received 8 October 2017; Received in revised form 4 June 2018; Accepted 6 June 2018
0301-4797/

drainage, friable consistency, small aggregates, slightly acidic condition, and high nutrient levels (Epstein, 2012; Fay et al., 2012; Gibbs, 1980). Nutrient levels and acid status can be improved by fertilization and liming to raise the soil pH, and these are typically the most common management activities for improving or maintaining grassland productivity. As well as the intended increase in aboveground biomass, fertilization and liming potentially lead to greater production of root exudates and litter, and often have unintended effects on soil properties such as microbial populations and their activities that influence decomposition processes (Alonso et al., 2012; Hoffmann et al., 2014; Soussana et al., 2007). These management activities therefore have implications for soil C storage and sequestration.

Grazing regime itself may also influence net soil C storage. For example, soil C gain may result from over-compensatory plant growth (Tanentzap and Coomes, 2012) and increased inputs from enhanced root production (Frank et al., 2002). Conversely, overgrazing could lead to soil C loss through reduced plant productivity and litter inputs (Conant and Paustian, 2002; Mestdagh et al., 2006), or to exposure of bare soil and C loss via erosion (Evans, 1997). Thus a complex array of direct grazing effects and indirect grazing-related management effects on soil C storage may occur simultaneously. It is perhaps not surprising, therefore, that observed effects of liming, fertilizer application and grazing regime on soil C stock have been contradictory, and that increases, decreases and no change in soil C stock have been reported in different grassland ecosystems (Table S1) with specific climatic and soil conditions.

A number of global-scale reviews and meta-analyses have also reported inconsistent effects of grazing (Dlamini et al., 2016; Mcsherry and Ritchie, 2013; Pineiro et al., 2010; Zhou et al., 2016), fertilizer application (Geisseler et al., 2016; Liu and Greaver, 2010; Lu et al., 2011; Yue et al., 2016), liming (Paradelo et al., 2015) and grassland improvement (Conant et al., 2001, 2017) on grassland soil C stock. For example, Zhou et al. (2016) reported a 10.28% grazing-induced reduction in soil C stock, whereas Pineiro et al. (2010) and Mcsherry and Ritchie, 2013 showed that grazing caused an increase, a decrease and no change in soil C stock with grazing effect size ranging from −0.33 to +0.38, depending on soil characteristics, climate and grazing intensity. Also, in separate analyses, N addition has been reported to cause a decrease (effect size = −0.0026; Lu et al., 2011), no change (Liu and Greaver, 2010) and an increase (+19.75%; Yue et al., 2016) in the C stock of grassland mineral soil layers. The differences in outcome could be attributed to a failure to account for context-specific differences in management, such as rates of fertilizer and lime application in different climatic zones (Dessureault-Rompré et al., 2010; Iturri and Buschiazzo, 2016), or grazing regimes that vary depending on climatic influences on productivity (Oba et al., 2000), or failure to consider the influence of soil type and characteristics (Mills et al., 2005; Srinivasarao et al., 2009).

The interactive effects of non-management factors (e.g. climate and soil) and fertilizer or lime application rates have not been synthesized for global grasslands. The few global studies (Dlamini et al., 2016; Mcsherry and Ritchie, 2013; Zhou et al., 2016) that considered interactive effects of grazing regime and non-management factors reported conflicting results. For example, Mcsherry and Ritchie, 2013 reported that grazing-induced changes in soil C stock were insensitive to either climate or soil texture, Dlamini et al. (2016) reported that significant soil C reduction due to over-grazing occurred only in cold (mean annual temperature, MAT < 0 °C) and dry (mean annual precipitation, MAP < 600 mm) climates, and in acidic (pH < 5.0) and coarse-textured (< 32% clay) soils, whereas Zhou et al. (2016) found a significant reduction in soil C only in semi-humid and humid regions (MAP ≥ 400 mm). In order to inform appropriate management decisions in global grasslands and models that integrate climate and land management, there is need to resolve the conflicting results of previous studies. This may be better achieved if the effects of site-specific characteristics and grazing-related management activities within different climatic zones are considered.

Our aim in this study is to investigate how grassland SOC stock responds to management activities in different climatic zones, and the influence of soil properties, in a single meta-analysis. Specifically, we determine the effect size (relative size of change in SOC stock) attributable to grazing-related management (liming and fertilizer addition) and grazing regime in different climatic settings, using a global meta-analysis approach. We focus on soil C stock rather than greenhouse gas inventory because understanding the fate of C stock is important not just for climate change mitigation but the provision of other ecosystem services such as maintaining soil quality, which is of immediate concern to farmers that manage the grasslands for livestock production. The result of this study will not only help to detect the overall pattern of response of SOC stock to major grassland management activities but also identify grasslands that are most likely to serve as either a C sink or a C source in the face of climate change. This will better inform policy decisions on future grassland management for sustainable provision of ecosystem services. We hypothesize that 1) the response of SOC stock to management activities will be significantly influenced by site-specific climatic setting and soil characteristics, and 2) fertilizer application, liming and grazing will result in an overall reduction in SOC stock.

2. Methodology

2.1. Data selection and extraction

All the data used for this study were extracted from peer-reviewed journal articles published before January 2017. A search for the articles was conducted in Web of Science between June and December 2016, using all combinations of the following groups of search terms: 1) management, liming, lime addition, fertilizer, nitrogen addition, nitrogen fertilizer application or grazing, 2) soil carbon, soil carbon stock, soil carbon storage or carbon sequestration, 3) grassland, pasture or meadow.

Our searches produced 2881 journal articles which we screened following a number of criteria: 1) they were grassland field studies in which SOC data (concentration in % or g/kg, stock in g/m^2 or Mg/ha, or both) were recorded in response to either liming, fertilizer application or grazing regime, 2) SOC data were recorded for both the managed field and a well-defined control field, and measurements were made at the same temporal and spatial scales, 3) only one of the target management practices such as grazing regime or nitrogen fertilizer varied while other management activities were absent or remained constant, 4) the depth of soil samples used for SOC determination were clearly specified, 5) the mean, sample sizes, measures of variability such as standard deviation, standard error or coefficient of variation can be extracted from the study, 6) experimental and control plots were established within the same ecosystem and had similar environmental characteristics at the beginning of the study, 7) management activities such as grazing intensity were clearly described quantitatively and/or qualitatively, and 8) experimental duration was clearly specified and was at least one entire growing season in order to avoid the effect of short term noise. In cases where two or more studies reported the same data from the same experiment, we chose one of the studies and excluded others, except if they provided supporting environmental information about the site. In order not to violate the key assumption of meta-analysis that studies must be independent, we chose data for the last year of sampling in studies where sampling was conducted annually from the same site. We excluded studies where either multiple nutrient fertilizers (e.g. NPK fertilizers) or organic manure (e.g. livestock slurry or industrial effluent) were applied. This was done to enable us to detect the exact effects of single nutrient fertilizers and prevent the confounding effects of high C and multiple nutrient contents of organic manures. We considered different management levels (e.g. different N levels or forms, or livestock stocking densities) sharing the same control plot as independent observations.