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Overgrazing decreases soil organic carbon stocks the most under dry climates and low soil pH: A meta-analysis shows

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ABSTRACT

Grasslands occupy about 40% of the world's land surface and store approximately 10% of the global soil organic carbon (SOC) stock. This SOC pool, in which a larger proportion is held in the topsoil (0–0.3 m), is strongly influenced by grassland management. Despite this, it is not yet fully understood how grassland SOC stocks respond to degradation, particularly for the different environmental conditions found globally. The objective of this review was to elucidate the impact of grassland degradation on changes in SOC stocks and the main environmental controls, worldwide, as a prerequisite for rehabilitation. A comprehensive meta-analysis was conducted using 55 studies with 628 soil profiles under temperate, humid, sub-humid, tropical and semi-arid conditions, to compare SOC stocks in the topsoil of non-degraded and degraded grassland soils. Grassland degradation significantly reduced SOC stocks by 16% in dry climates (<600 mm) compared to 8% in wet climates (>1000 mm) and Asia was the most affected continent (−23.7%). Moreover, the depletion of SOC stock induced by degradation was more pronounced in sandy (<20% clay) soils with a high SOC depletion of 10% compared to 1% in clayey (≥32% clay) soils. Furthermore, grassland degradation significantly reduced SOC by 14% in acidic soils (pH ≤ 5), while SOC changes were negligible for higher pH. Assuming that 30% of grasslands worldwide are degraded, the amount of SOC likely to be lost would be 4.05 Gt C, with a 95% confidence between 1.8 and 6.3 Gt C (*i.e.* from 1.2 to 4.2% of the whole grassland soil stock). These results by pointing to greater SOC losses from grasslands under dry climates and sandy acidic soils allow identification of grassland soils for which SOC stocks are the most vulnerable, while also informing on rehabilitation measures.

1. Introduction

Soil is the third largest reservoir of carbon (C) next to the lithosphere and the oceans. Globally, soil contains about twice the amount of C in the atmosphere and more than three times in above-ground biomass (Batjes, 1996; Batjes and Sombroek, 1997; Jobbágy and Jackson, 2000). Historically, terrestrial C pools, have been largely depleted by anthropogenic activities such as deforestation, tillage and overgrazing (Lal, 2004). It has been widely argued that a shift in land use or land management in agroecosystems could potentially sequester as much as 30–40% organic C back into the soil (Lal, 2004). A meta-analysis of 74 studies by Guo and Gifford (2002) reported that conversion of croplands to grasslands could result to soil organic C (SOC) gains of 19%, while a global analysis of 115 studies by Conant et al. (2001) estimated much lower SOC gains varying from 3 to 5%. Under degraded croplands in the Highveld region of South Africa characterized by a temperate climate, with 6–8 months dry spells Preger et al. (2010) indicated that consideration of the initial level of degradation was important. In that study, they observed 30% SOC stock gains (*i.e.* 300 kg C ha^{-1} yr^{-1}) when less degraded croplands were converted to grasslands to as much as 70% (*i.e.* 500 kg C ha^{-1} yr^{-1}) for heavily degraded croplands. The variable response of SOC stocks to shifts in land use may be related to environmental factors including precipitation as shown by Guo and Gifford (2002), who reported greater SOC gains in areas with low mean annual precipitation (<500 mm) than in areas with greater mean annual precipitation (>500 mm).

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Indeed, is has been argued that because of such discrepancies in the results, the actual SOC sequestration potential of soil remains largely uncertain (Powlson et al., 2011).

Grasslands cover about 40% of the world's land surface (Suttie et al., 2005) and store approximately 10% of the global soil organic carbon (SOC) stock of 1500 Gt (West and Post, 2002). Grasslands are an essential component of the biogeochemical carbon cycle and provide key ecosystem goods and services (Suttie et al., 2005; FAO, 2010). Grasslands including both pastures and rangelands support biodiversity and are used extensively for the production of forage to sustain the world's livestock (Asner et al., 2004; Bradford and Thurow, 2006). Not only is the SOC pool in grassland soil critical for climate change, but it yields important feedbacks to soil fertility, plant productivity, soil aggregate stability, water holding capacity and overland flow regulation (Sombroek et al., 1993; Lal, 2004).

Bai et al. (2008) estimated that up to 25% of grasslands worldwide have been affected by grassland degradation. So far, the relative effect of degradation on SOC stocks has been difficult to predict because of the paucity of data (FAO, 2010), particularly in grassland soils. Because a greater proportion (ca 39–70%) of the SOC stock to 1 m depth is held in the top 0.3 m of the soil (Batjes, 1996), it has been postulated that grassland soils could be highly sensitive to, and strongly vulnerable to grassland degradation than previously thought.

However, grazing effects on SOC stocks have been found to be highly variable with some studies showing a decrease in SOC with grazing, for example, Martinsen et al. (2011) found that SOC stocks declined by 14% after 7 years of grazing in Norway, with 0.76 kg C m^{-2} in ungrazed compared to 0.64 kg C m^{-2} in heavily grazed grasslands. Steffens et al. (2008) found that 30 years of grazing in semi-arid Mongolian grasslands resulted in 45% decrease in SOC stocks, with 0.64 kg C m^{-2} in grazed compared to 1.17 kg C m^{-2} in ungrazed grasslands. Franzluebbers and Stuedmann (2009) observed that 56% of SOC stocks were lost after 12 years of grazing, with 0.051 kg C m^{-2} in heavily grazed compared with 0.117 kg C m^{-2} under ungrazed grasslands. In contrast, some studies have shown that grazing results in an increase in SOC stocks (Smoliak et al., 1972; Bauer et al., 1987; Frank et al., 1995; Derner et al., 1997), while others have reported no difference in SOC stocks after grazing (*e.g.* Johnston et al., 1971; Domaar et al., 1977). These contradictory findings demonstrate that the underlying processes affecting the response of SOC stocks to grassland degradation are not well understood. Thus, there is a need to study grassland degradation over a wide range of environmental and management conditions.

SOC losses due to degradation are dependent on soil texture. A number of studies have shown that fine-textured soils relatively have greater SOC stocks than coarse textured soils (Hassink, 1992, 1997; Bird et al., 2000; Brye and Kucharik, 2003). However, the effect of grassland degradation in soils differing in texture is largely unknown. In a previous study, Parton et al. (1987) using 560 soil profiles showed that SOC stocks and soil texture were correlated, with SOC stocks greater in fine textured soils than sandy textured soils. Across two degraded grassland soils with contrasting texture in the USA, Potter et al. (2001) found that grassland degradation reduced SOC stocks by 41% in coarse-textured than fine-textured soils. Clayey soils have a greater stabilizing influence on SOC than sandy soils, probably due to a large surface area, which form stable organo-mineral complexes that protect C from microbial decomposition (Feller and Beare, 1997; Six et al., 2000). Soil texture may interact and be confounded with other environmental factors such as climate, which may profoundly affect SOC depletion in grassland soils (Feller and Beare, 1997). Climate can impose constraints on the processes that control SOC stabilization, which may result in different changes of SOC under different environmental conditions (Virto et al., 2012). In a review of 12 studies totalling 22 data points, Conant and Paustian (2002) identified mean annual precipitation (MAP) as the main factor controlling C sequestration in degraded grasslands. Since the publication of that review, studies covering a wider range of environmental conditions have become available, thus allowing a robust evaluation of the impact of not only climate, but also, altitude, soil properties, time and grass type (C_3 *vs* C_4) and their likely interactions on SOC dynamics.

Because the response of soils to grassland degradation is expected to vary from site to site, the main objective of this review was to assess the level of SOC stock depletion in grassland soils worldwide and to identify the main environmental factors of

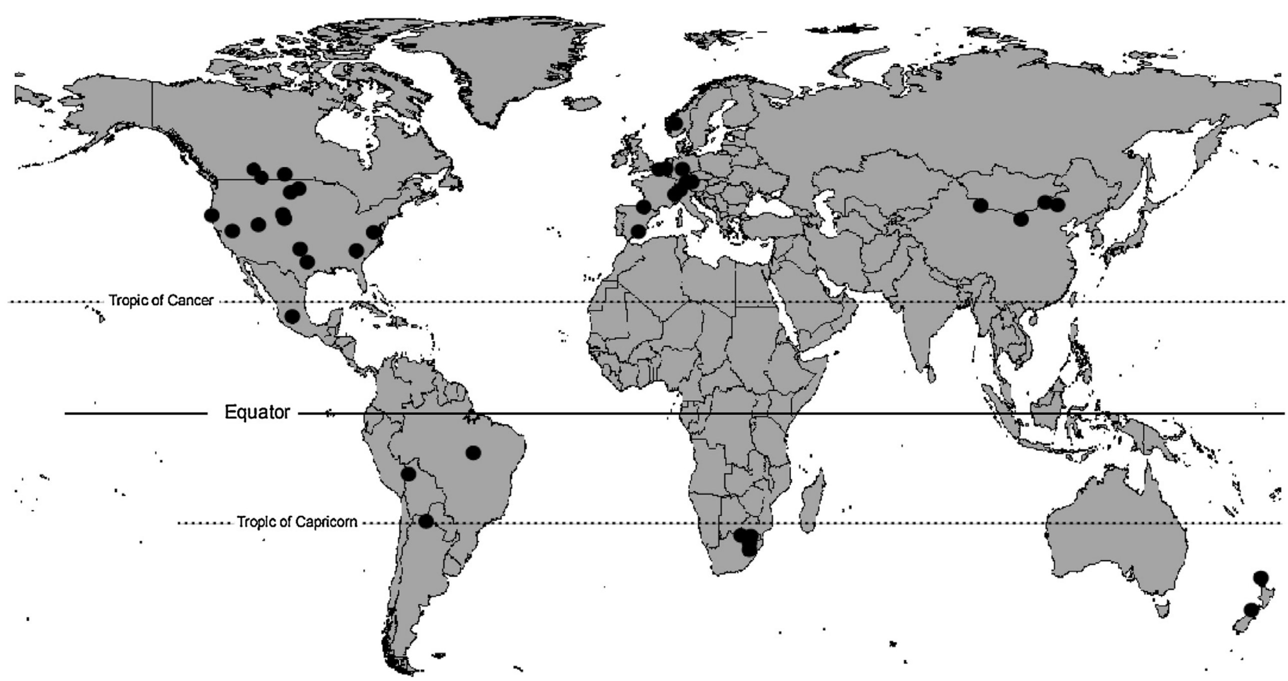

Fig. 1. Location of the study sites included in the literature review.