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Synthesis of soil carbon losses in response to conversion of grassland to agriculture land

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ABSTRACT

The conversion of grassland to cropland is one of the major changes in land use, and it accelerates both soil erosion and the loss of soil organic carbon (SOC). However, the general patterns of SOC loss after grassland cultivation are rarely assessed, and the potential mechanisms remain unclear. Here, a meta-analysis of 81 case studies was performed to show that SOC decreased with soil depths of 0–60 cm after grassland conversion, but no significant differences were found at depths > 60 cm. SOC also declined significantly with the duration of grassland conversion. The response ratio of SOC changes tended to reach equilibrium after 20 years of grassland cropping. Our results indicate that reduction in SOC mainly depended on changes in precipitation, soil physical-chemical properties and soil microbes. These conclusions highlight the importance of improving the accuracy of predictions on SOC losses and on the global carbon cycle in the face of land-use changes worldwide.

1. Introduction

Grasslands, which cover nearly 40% of the terrestrial land surface and store more than one-third of the total terrestrial carbon, have experienced accelerated changes in ecosystem structure and functioning driven by land-use change (White et al., 2000; Claassen, 2011). Clearing grassland to implement subsistence agriculture results in rapid and extensive soil erosion and a loss of soil organic carbon (SOC) in many ways (Claassen, 2011; White et al., 2000; Ding et al., 2013). It can increase CO_2 emissions from soil (Wang et al., 2009; Solomon et al., 2007; Oberholzer et al., 2014), which may have an effect on global climate and continental carbon cycles (Guo and Gifford, 2002; Solomon et al., 2007; Celik, 2005). Nonetheless, it remains unclear for general response patterns of SOC losses and the general driving factors after grassland converted to agricultural land at a global scale.

Many factors regulate the effect of grassland cultivation on SOC, such as soil depth, cultivation duration and climate. Previous studies investigating how grassland cultivation affects SOC change mostly focused on the top 30 cm soil layer (Shang et al., 2012; Poeplau et al., 2011; Wang et al., 2009), which is the depth recommended by the IPCC (2003). This results in a lack of knowledge about the stabilization of SOC in subsoil (Wiesmeier et al., 2012; Don et al., 2011; van Straaten et al., 2015), which is a problem because the subsoil SOC accounts for up to 30–75% of the total soil carbon pool (Batjes, 2014; Rumpel et al., 2002) and is influenced by land-use change (Poeplau et al., 2011; Ding et al., 2013; Guo and Gifford, 2002; Shi et al., 2013). Similarly, little information is available regarding the changes in SOC over a chronosequence of cultivated lands that were converted from grasslands (Solomon et al., 2007). Knowing how SOC changes under long-term cultivation conditions is important to identify strategies for the sustainable management of cropped soils on former grasslands. Additionally, climate could also explain a large proportion of SOC variation (Mahecha et al., 2011; Shi et al., 2013), and high temperatures and precipitation coupled with high plant productivity could lead to positive effects on carbon inputs into the soil (Luo et al., 2017). Higher precipitation might alleviate the negative effect of reclaiming on SOC loss due to more inputs from vegetation biomass. This information is required to provide an accurate assessment of SOC losses after native grassland conversion to cropland (Wiesmeier et al., 2012).

The conversion of grassland to cropland has the effect of releasing

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extra soil carbon into the atmosphere which contributes to the atmospheric CO_2 accumulation (White et al., 2000). A lot of experimental studies have revealed the fact of SOC loss after grassland cultivation, but the magnitudes of the SOC dynamics varied greatly depending on the climatic and soil conditions etc. The actual degree of change depends on several factors, including the removal of plant biomass (Zucca et al., 2010), altered soil physical and chemical properties (Post and Kwon, 2000) and biochemical properties of organic substrates (Lange et al., 2015; Jangid et al., 2011). Plant harvest results in lower inputs of above- and belowground biomass and plant cover (Poeplau and Don, 2013; Wang et al., 2011), which reduces carbon accumulate in soil (Poeplau et al., 2011) and increases wind and water erosion (Six et al., 2000). Moreover, variation in soil physical (e.g., bulk density, soil texture) and chemical properties (e.g., pH, soil nitrogen content) may also have other effects on SOC changes (Guo and Gifford, 2002; Doetterl et al., 2015), which could affect the supply of carbon available for microbial processes related to SOC decomposition in the substrate. Further, soil microbial communities are changed after grassland cultivation due to altered substrate quality (Prescott, 2005; Belay-Tedla et al., 2009), and altered microbial activities affect SOC losses. However, it remains elusive for SOC loss in response to changes in soil physical-chemical properties and microbial changes that occur after the conversion of grassland to agricultural land.

To reveal the global patterns and underlying mechanisms of SOC losses caused by grassland conversion to agricultural land, we performed a meta-analysis by creating a dataset from 81 studies. We addressed the following questions: 1) How do grassland soil sampling depth, conversion duration and precipitation influence the degree of SOC losses? 2) What is the relationship between SOC change and soil environment? 3) What are the mechanisms driving SOC loss in grasslands converted to agricultural lands?

2. Materials and methods

2.1. Data preparation

We searched the peer-reviewed literature using Web of Science and the China Knowledge Resource Integrated Database (CNKI). From these publications, we compiled data on the following relevant factors: SOC concentration or stock; soil sampling depth; conversion duration; climate data, including mean annual temperature (MAT) and mean annual precipitation (MAP). We also included data from these studies on plant belowground biomass (BGB), soil bulk density (BD), soil texture (sand, silt and clay content), soil moisture (SM), pH, soil total nitrogen (STN), C:N ratio, dissolved organic carbon (DOC), available potassium (AK), available phosphorus (AP), available nitrogen (AN), metabolic quotient ($q\ CO_2$), soil microbial carbon (MBC) and soil microbial nitrogen (MBN) in the cases that they were individually or simultaneously available. In the current study, the definition of grassland is native grassland or land used for grazing purposes that includes natural grassland.

To meet the statistical requirement of independent observations from different studies, we collected the data from the last observation of each experiment. We directly obtained the data from tables, while data from figures were extracted using the Engauge software (Free Software Foundation, Inc., Boston, MA, USA). Finally, we established a global dataset from 81 published studies (Appendix A), compiling a total of 398 observations (Table S1). The global distribution of study sites included in this meta-analysis is shown in Fig. 1. In order to examine the effects of soil sampling depths, we grouped soil depth by < 30 cm, 30–60 cm, 60–100 cm, and > 100 cm, respectively. To test the differences in responses of SOC from short-term to long-term conversion, grassland cultivation duration was grouped into one of five lengths: < 10 years, 10–20 years, 20–40 years, 40–60 years and > 60 years, respectively. The study sites were considered as arid/semiarid, semi-humid and humid climate when MAP was ≤400 mm, 400–600 mm and > 600 mm, respectively.

2.2. Meta-analysis

Data were analyzed using the traditional meta-analysis method described by Hedges et al., (1999). The meta-analysis was conducted using MetaWin 2.1 software package (Sinauer Associates, Inc., Sunderland, MA, USA). We used the response ratio (RR) to evaluate the effects of grassland conversion, and the following equation was applied to calculate the RR:

$$\mathrm{RR} = \ln\left(\frac{X_{cropland}}{X_{grassland}}\right) = \ln(X_{cropland}) - ln(X_{grassland}) \quad (1)$$

where $X_{grassland}$ and $X_{cropland}$ are the mean of the soil variables in grassland and agricultural land, respectively. The statistical distribution of the RRs calculated using this method was assumed to be normally distributed (Hedges et al., 1999). The variance (ν) of RR was calculated by:

$$\nu = \frac{S^2_{grassland}}{n_{grassland}x^2_{grassland}} + \frac{S^2_{cropland}}{n_{cropland}x^2_{cropland}} \quad (2)$$

where $n_{grassland}$ and $n_{cropland}$ are the sample sizes of grassland and agricultural land, respectively, and $S_{grazing}$ and $S_{cropland}$ are the SDs of the concerned variable for the groups of grassland and agricultural land, respectively. The reciprocal of ν was used as the weighting factor w for each RR.

We calculated the mean weighted response ratio (RR_{++}) from the individual RRs for the grassland and agricultural land. Here, m is the numbers of groups (e.g., precipitation, conversion duration or soil depth), and k is the number of comparisons. The mean weighted response ratios were calculated using the following equation:

$$RR_{++} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}RR_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}} \quad (3)$$

The weighted standard error (SE) was calculated by:

$$\mathrm{S}(RR_{++}) = \sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}}} \quad (4)$$

The 95% confidence interval (95% CI) was calculated by:

$$95\%\ \mathrm{CI} = RR_{++} \pm 1.96S(RR_{++}) \quad (5)$$

Crop cultivation was considered to have no significant impact on a variable when the 95% confidence interval overlapped with zero (Gurevitch and Hedges, 2001). Statistical confidence levels were considered significant when $P < 0.05$. Regression analyses were performed to evaluate the relationships between the RRs for (i) the SOC and BD, sand, silt and clay contents; (ii) SOC and pH, SM, STN, and AN; and (iii) SOC and MBC and MBN.

3. Results

3.1. SOC losses after conversion of grassland to agricultural land

Considering the entire dataset of SOC, grassland conversion significantly decreased SOC in all groups (Fig. 2). Grassland conversion significantly decreased SOC by 31.96% (95% CI: 37.33% to -26.59%) and 18.36% (95% CI: 35.33% to 1.39%) at the < 30-cm and 30–60-cm soil layers, respectively, but SOC did not significantly change at depths > 60 cm (Fig. 2a). The SOC significantly decreased by 22.84%–34.79% from < 10 years to ≥60 years. There is also a strong trend indicating that SOC response became constant after 20 years (Fig. 2b). The SOC mean weighted response ratios (RR_{++}) to grassland conversion were significantly different from zero, and the RR_{++} of SOC gradually increased with increasing precipitation levels (Fig. 2c).