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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:

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

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:

$$\nu = \frac{S_{grassland}^2}{n_{grassland}X_{grassland}^2} + \frac{S_{cropland}^2}{n_{cropland}X_{cropland}^2} \tag{2}$$

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:

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

The weighted standard error (SE) was calculated by:

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

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

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

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).

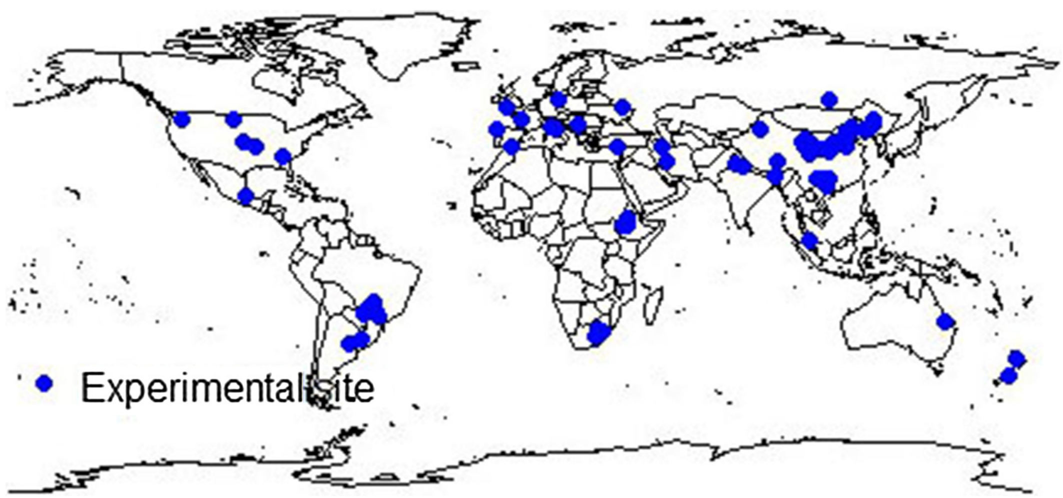

Fig. 1. Global distribution of experiments related to the conversion of grassland to agricultural land used in this meta-analysis.

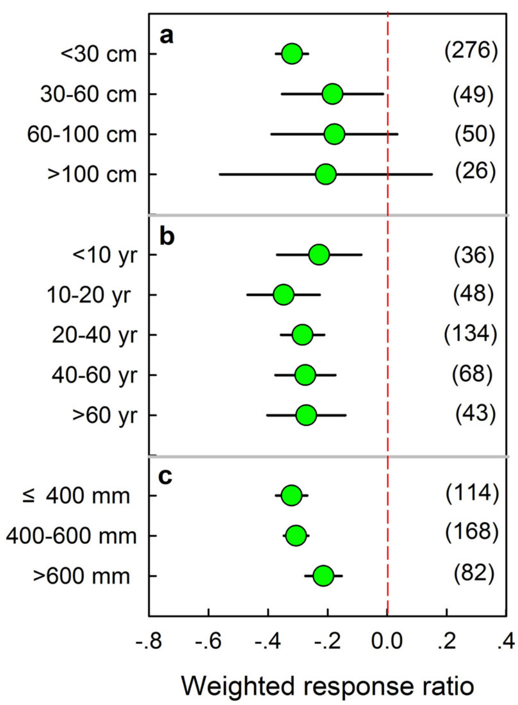

Fig. 2. Effects of conversion of grassland to agricultural land on soil organic carbon (SOC). The data are expressed as the weighted response ratio with 95% confident intervals. The numbers of studies included are indicated in parentheses.

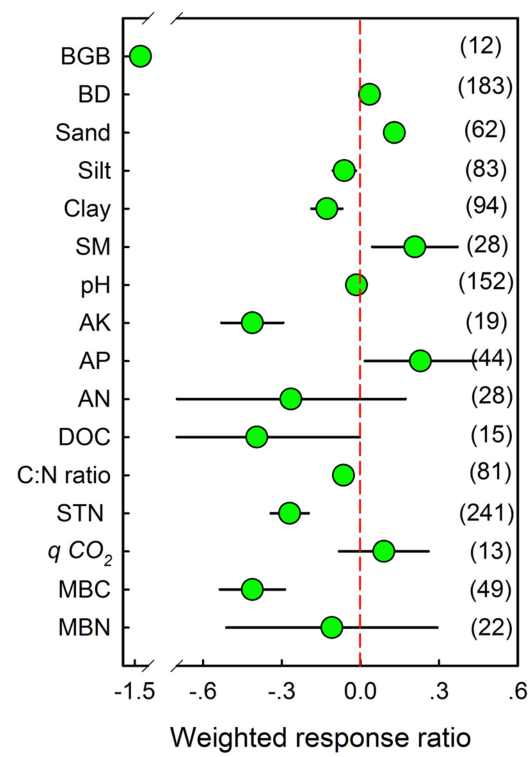

Fig. 3. Effects of conversion of grassland to agricultural land on soil properties. The data are expressed as the weighted response ratio with 95% confident intervals. The numbers of studies included are indicated in parentheses. Bulk density (BD), soil moisture (SM), microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), available potassium (AK), available phosphorus (AP), available nitrogen (AN), dissolved organic carbon (DOC), and soil total nitrogen (STN).

3.2. Other variables

Responses to grassland conversion differed for some soil variables (Fig. 3). Relative to controls, we observed significant decreases in plant belowground biomass, soil silt, clay, pH, MBC, AK, DOC, C:N ratio and STN by 130.53%, 6.18%, 12.81%, 1.49%, 41.20%, 41.21%, 39.53%, 6.49% and 26.98%, respectively (Fig. 3). However, relative to controls, reclaimed grassland experienced increased soil BD, sand content, SM and AP by 3.46%, 12.9%, 20.76% and 22.90%, respectively (Fig. 3). In addition, there was no significant effect of grassland conversion to agricultural land on soil AN, MBN or $q\ CO_2$.

3.3. Correlations between SOC losses and environmental factors

The SOC showed a significant negative correlation with the BD and sand content but a significant positive correlation with silt and clay content (Fig. 4). Moreover, we also found significant negative correlations between the RR of SOC and soil pH and SM (Fig. 5a) but positive correlations were found between the RR of SOC and the RRs of STN, MBC and MBN after grassland conversion to agricultural land (Fig. 5b, c; Fig. 6). However, we did not detect significant relationships between SOC and available soil N (Fig. 5d). Furthermore, MAP showed a significant positive relationship with changes in SOC, whereas MAT was not correlated with SOC responses (Fig. 7).

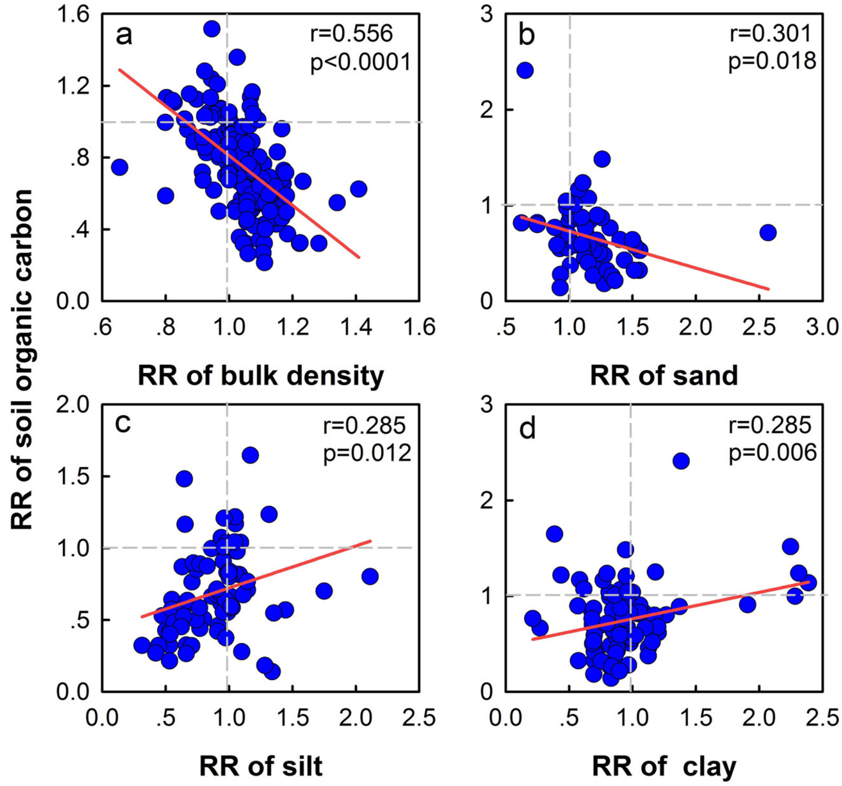

Fig. 4. Relationships between response ratio (RR) of soil organic carbon (SOC) and RR of soil bulk density (a), sand content (b), silt content (c) and clay content (d) after grasslands were converted to agricultural lands.

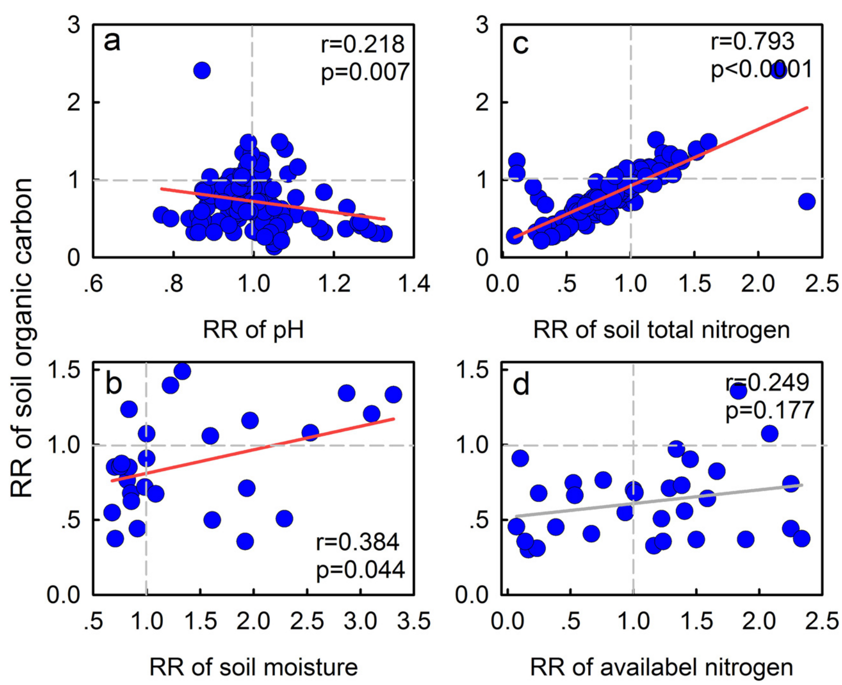

Fig. 5. Relationships between response ratio (RR) of soil organic carbon (SOC) and RR of soil pH (a), soil moisture (b), soil total nitrogen (c) and available nitrogen (d) after grasslands were converted to agricultural lands.

4. Discussion

4.1. SOC losses after grassland conversion

Our results demonstrated that grassland conversion generally results in SOC losses across grassland ecosystems worldwide, which agrees with most previous studies (Wang et al., 2009; Ding et al., 2013; Solomon et al., 2007). We found that SOC decreased in the 0–30-cm and 30–60-cm soil layers after grassland conversion but did not change in the > 60-cm soil layers, indicating that soil sampling depth should occur at least down to 60 cm in future studies working on this topic. Subsoil SOC losses may be partly attributed to plant root litter and root

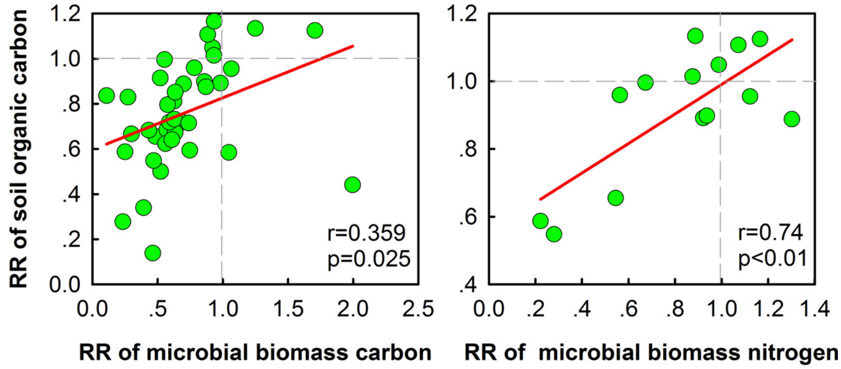

Fig. 6. Relationships between response ratio (RR) of soil organic carbon (SOC) and RR of soil microbial biomass carbon (a) and nitrogen (b) after grasslands were converted to agricultural lands.

exudates and topsoil SOC translocation (e.g., tillage disturbance, DOC leaching, or bioturbation) (Rumpel and Kögel-Knabner, 2011). This result was mainly consistent with a previous meta-analysis by Guo and Gifford (2002), who reported a 59% loss of SOC below soil depths of 60 cm. Several studies have reported that SOC decreased below depths of 30 cm after the conversion of grassland to cropland (Ding et al., 2013; Don et al., 2011; Guo and Gifford, 2002), indicating that monitoring only the top 30 cm of soil does not provide an accurate prediction for the degree of SOC change, and further efforts are required to better understand the effect of grassland cultivation on SOC changes in deeper soil layers.

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 (Fig. 2b), indicating that cultivation age plays an important role in shaping the trajectory of SOC dynamics. This is the first study, to our knowledge, that quantifies the dynamics and the duration involved in SOC reaching a steady state after the conversion of grassland to agricultural land; specifically, our results indicate that disturbance does not affect long-term carbon dynamics but does cause changes in carbon within a 20-year period (Luo and Weng, 2011). These findings provide valuable implications for the carbon sequestration potential in ecosystems after grassland conversion; carbon sequestration potential can be estimated using the information on the dynamics and duration of SOC losses before SOC reaches a steady state.

In this study, the SOC was significantly reduced at different precipitation levels, though any negative impacts of grassland conversion on SOC can be alleviated with increased precipitation levels; this finding might indicate that arid/semi-arid regions may experience larger and faster carbon losses compared to the response of humid regions to grassland conversion. Generally, arid/semi-arid regions are more fragile because of lower plant carbon input and lower microbial activity (Zhou et al., 2009). Nevertheless, the SOC losses caused by grassland cultivation are still severe in regions with high precipitation, indicating that land-use change has a stronger impact on SOC than precipitation. Therefore, grassland conversion should be cautiously considered in grassland regions, especially in regions with lower precipitation.

4.2. Main mechanisms of SOC losses with grassland cultivation

Our results demonstrated that rates of changes in SOC content reduce markedly with the grassland conversion, and we revealed the following possible mechanisms. First, our results showed that grassland converted to cropland deceased belowground biomass by 130.53%. The reduction in belowground biomass generally decreases litter input into soil, which likely reduces organic matter accumulate in soil. Moreover, the persistent removal of net primary productivity from agricultural land will increase the carbon output of the ecosystem (Abegaz et al., 2016; Lorenz and Lal, 2005). Further, vegetation removal causes an increase in carbon loss through wind and water erosion because of the lower plant canopy and mulch cover (Wang et al., 2009; Chen et al., 2010; Li et al., 2014). These results have been demonstrated by many previous studies, including both individual experiments and meta-analyses (Nautiyal et al., 2010; Solomon et al., 2007; Guo and Gifford, 2002).

Second, our results indicated that grassland conversion also impacted the basic soil physical-chemical characteristics, which are closely coupled with SOC dynamics. Specifically, we found that decreased SOC was negatively linearly correlated with RR of BD and sand content but positively correlated with that in silt and clay content (Fig. 5), suggesting that soil texture was an important factor affecting the SOC loss after grassland conversion. The breakdown by tillage leads to large aggregates transforming into fine aggregates, which makes them more susceptible to erosion by wind and water under soil cropping conditions

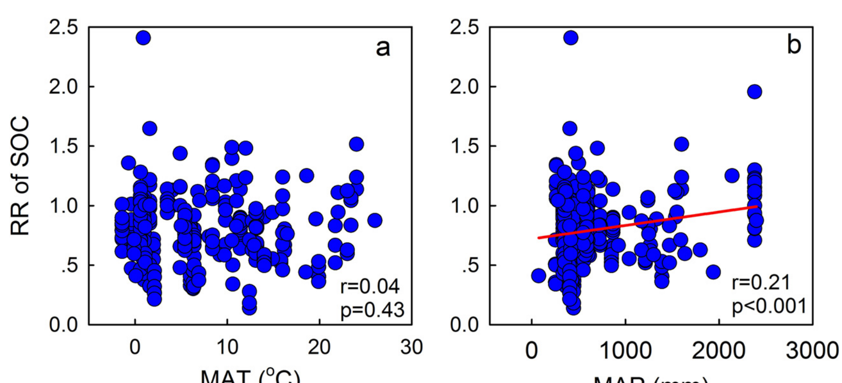

Fig. 7. Relationships between response ratios (RR) of SOC and mean annual temperature (MAT) (a) and mean annual precipitation (MAP) (b).

(Six et al., 2000). A decrease in DOC in cropland may indicate an increase in water erosion. Moreover, previous studies reported that SOC was lost through mineralization due to enhanced soil aeration by tillage (Ding et al., 2013; Chen et al., 2010). In this meta-analysis, grassland conversion increased SM. This may be caused by cropland generally receive more irrigation than grassland (Ding et al., 2013; Guo and Gifford, 2002). Increase in SM may trigger a positive feedback, accelerating soil organic matter decomposition through amelioration of soil texture and improving the capacity of soil water conservation (Savadogo et al., 2007). We also found a strongly coupled relationship between SOC and STN that was consistent with previous studies (Chen et al., 2010; Wang et al., 2009). Furthermore, soil C:N ratios significantly reduced with grassland conversion, which indicates that the supply of N fertilizer could not compensate for SOC and STN losses in agricultural land. Nonetheless, available soil N content was not significantly different after grassland conversion. This may be because the addition of nitrogen fertilizer in most of the croplands affected the amount of mineral N available. In summary, these changes in soil physical-chemical properties will affect the degree of change in SOC after grassland cultivation.

Third, changes in soil microbes could affect SOC losses after grassland conversion. This may be due to soil aggregate fragmentation by tillage, which causes microorganisms to use more available carbon energy in disturbed ecosystems (Chen et al., 2010). Soil microbes have been reported to change after grassland conversion or when SOC changes (Lauber et al., 2008). Our results also showed that the grassland conversion-induced decreases in MBC was positively linearly correlated with that in SOC. Moreover, we did not detect a significant difference in soil $q\ CO_2$ (ratio of respired C to biomass C) (Fig. 3), indicating soil microbial respiration may decrease after grassland conversion. Nevertheless, we are aware that, although the MBC and MBN can provide comprehensive information about soil microbial potentials in degrading SOC, they cannot inform us of the contribution of specific soil microbes to SOC losses. More studies are needed to link information on soil microbes with the processes involved in SOC losses; this information would enable the quantification of their relationship.

Finally, our results further demonstrated that MAP was more important than MAT to the degree of SOC change after grassland conversion. This result is consistent with previous research that assessed drivers of SOC change across grassland regions in China (Hu et al., 2016). This result illustrates that grasslands are mainly water limited, indicating that SOC is more sensitive to precipitation than to temperature. Precipitation could affect SOC change by its direct impact on SOC formation and decomposition processes and its indirect effect on soil carbon input (via plant productivity) and soil properties (Luo et al., 2017). However, many recent studies do not evaluate the responses of belowground carbon processes caused by grassland conversion, especially their interactions with environmental factors. Thus, future research may need to learn about environmental factors (climate, edaphic, biotic factors) using both modeling and experiments to more accurately predict the responses of ecosystem C cycles to land-use change (Luo et al., 2017).

5. Conclusions

This synthesis revealed that grassland conversion to agricultural land resulted in soil carbon losses worldwide. The amount of SOC loss depends on precipitation, duration of the subsequent agricultural land, soil depth, and soil physicochemical and biochemical properties. Our results indicated that, worldwide, grasslands with wetter climates presented higher resistance to losses in SOC, but the losses were still significant. The decrease in SOC mainly occurred at soil depths < 60 cm, and SOC loss reached an equilibrium state within 20 years of grassland conversion. Furthermore, our results showed that soil nitrogen losses could not keep up with the pace of SOC losses, as indicated by reduced soil C:N ratios. These conclusions could have important implications on improving the accuracy of predictions on SOC losses and on the global carbon cycle in the face of land-use changes occurring worldwide.

Acknowledgments

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2018.08.011.

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