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Impact of land use conversion on soil organic carbon stocks in an agro-pastoral ecotone of Inner Mongolia

ZHAO Wei[1,2], HU Zhongmin[1], *LI Shenggong[1], GUO Qun[1], YANG Hao[1], ZHANG Tonghui[3]

1. Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China;
2. University of Chinese Academy of Sciences, Beijing 100049, China;
3. Naiman Desertification Research Station, Northwest Institute of Eco-Environment and Resources, CAS, Lanzhou 730000, China

Abstract: Soil organic carbon (SOC) stocks in terrestrial ecosystems vary considerably with land use types. Grassland, forest, and cropland coexist in the agro-pastoral ecotone of Inner Mongolia, China. Using SOC data compiled from literature and field investigations, this study compared SOC stocks and their vertical distributions among three types of ecosystems. The results indicate that grassland had the largest SOC stock, which was 1.5- and 1.8-folds more than stocks in forest and cropland, respectively. Relative to the stock in 0–100 cm depth, grassland held more than 40% of its SOC stock in the upper 20 cm soil layer; forest and cropland both held over 30% of their respective SOC stocks in the upper 20 cm soil layer. SOC stocks in grazed grasslands were remarkably promoted after ≥20 years of grazing exclusion. Conservational cultivation substantially increased the SOC stocks in cropland, especially in the 0–40 cm depth. Stand ages, tree species, and forest types did not have obvious impacts on forest SOC stocks in the study area likely due to the younger stand ages. Our study implies that soil carbon loss should be taken into account during the implementation of ecological projects, such as reclamation and afforestation, in the arid and semi-arid regions of China.

Keywords: soil organic carbon; soil carbon profile; land use change; grazing; tillage; forest age

1 Introduction

Soil is the largest carbon sink of global terrestrial biosphere with around 1500 Pg of organic carbon stored in its upper 1 m depth (Jobbágy and Jackson, 2000), which is 2–3 times the

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Author: Zhao Wei (1982–), PhD Candidate, specialized in global carbon cycle and climate change.
E-mail: zhaow.12b@igsnrr.ac.cn
***Corresponding author:** Li Shenggong, Professor, specialized in global carbon and water cycle. E-mail: lisg@igsnrr.ac.cn

carbon pool of vegetation or atmosphere (IPCC, 2007). Soil organic carbon (SOC) is very sensitive to natural and/or human disturbances, leading to negative or positive feedbacks on terrestrial carbon cycle and climate change. As the core of coupled human-environment systems and a potential field in the study of global environmental change (Liu *et al*., 2010), land use and cover change (LUCC) is the key driver of SOC dynamics (Houghton and Hackler, 2003). LUCC is the second largest source of greenhouse gas emissions, and is responsible for 12.5% of the human-induced carbon emissions from 1990 to 2010 (Houghton *et al*., 2012). The gross emission due to tropical land use change reached 1.3±0.7 Pg C yr^{-1} during 1990–2007 (Pan *et al*., 2011). Ciais *et al*. (2011) reported that 4 t C ha^{-1} was sequestrated on average in soils due to the conversion of farmland into forest and grassland during 1901–2000 in Europe. Therefore, LUCC-induced soil C dynamics play a major role in terrestrial ecosystem carbon budget in the global climate change context and have been put into the center of scientific research and policy actions as a strategy of the 2015 International Year of Soils (Smith *et al*., 2015).

The agro-pastoral ecotone located in Inner Mongolia, with an area of 6.5×10^5 km^2 and an arid and semi-arid climate (Zhao *et al*., 2002), is strongly influenced by various environmental drivers (Ahlstrom *et al*., 2015) such as water shortage and wind erosion. Its structure, function, and carbon sink-source shift are vulnerable to environmental changes (Midgley *et al*., 2004). Land degradation and desertification have occurred in the past several decades due to harsh natural conditions, overgrazing, and improper cultivation. In order to cope with environmental degradation and hazardous sand storms, the Chinese government has initiated several ecological restoration projects such as the "Three North Shelter Forest System Project" (1979–2050) and the "Beijing-Tianjin Sandstorm Source Controlling Program" (2000–2010), which have influenced the patterns of land use and land cover in the agro-pastoral ecotone (Wu *et al*., 2013; He *et al*., 2015). Grassland, forest and cropland ecosystems coexist and are thus ideal locations to study how land use conversion alters soil C stocks.

Previous studies have investigated SOC stock dynamics in different land use types. Li *et al*. (2014) found that forests have higher SOC contents than grassland and cropland ecosystems at the 100 cm depth; however, in the upper 40 cm depth, grassland ecosystems have higher SOC content than other two systems. Fang *et al*. (2013) indicated that SOC content in 0–30 cm layer was similar between grazing-excluded grassland and cropland, and both are more than that of free grazing grassland. Xu *et al*. (2011) showed that SOC stock in 0–50 cm soil layers of grasslands were higher than those in cultivated cropland. However, inconsistent results were drawn on SOC stock change as a result of the sampling soil depth, and management practices (Don *et al*., 2011; Laganiere *et al*., 2010; Sun *et al*., 2016). Therefore, synthetic analyses of SOC stock differences among land use types are imperative to assess soil carbon dynamics and carbon sequestration potential due to LUCC.

In this paper, we compile SOC stock data for 150 sites in the agro-pastoral ecotone in Inner Mongolia of China. These data were obtained from both field investigations and literature surveys. Our main objectives were to (1) compare SOC stocks and their vertical distributions in grassland, forest, and cropland and (2) explore the effects of management measures on the SOC stocks in grassland and cropland, and the effects of stand age, forest type and tree species on the SOC stocks in forest.

2 Materials and methods

2.1 Study area

The study area is located in the eastern part of the agro-pastoral ecotone in North China (41.70°N to 44.54°N, 115.13°E to 122.37°E). Administratively, it includes Chifeng City, Tongliao City and a part of Xilin Gol League in Inner Mongolia, China (Figure 1). The area has a semi-arid temperate continental monsoon climate. The mean annual temperature ranges between 2.0°C and 6.7°C and the mean annual precipitation ranges between 320 mm and 470 mm, over two thirds of which falls in the growing season from May to September. The soils are Kastanozem. The original vegetation is sparse forest grassland, and stems from the Eurasian steppe (Zhao *et al.*, 2002). The major grass species include *Leymus chinensis* and *Stipa baicalensis*. The main tree species are *Ulmus pumila*, *Populus simonii*, *Pinus sylvestris* var. *mongolica,* and *Pinus tabulaeformis*. The most common crop is *Zea mays*, accompanied by other crops such as *Triticum aestivum* and *Avena nuda*. Grassland, forest and cropland coexist due to frequent human activities such as cultivation, grazing, and the implementation of ecological projects in recent decades. In the agro-pastoral ecotone of Inner Mongolia, vegetation coverage is 29% for grassland, 9% for forest, and 8% for cropland (Zhao *et al.*, 2002).

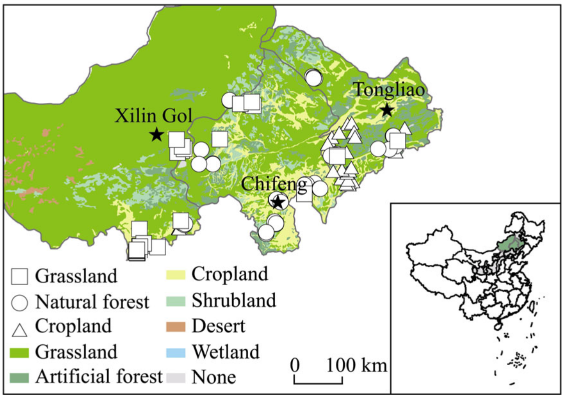

Figure 1 Geographical position of the study area and distribution of sampling sites. This figure was produced using ArcGIS 10.2 (Environmental Systems Research Institute). The background is the vegetation map according to the Editorial Committee of Vegetation Map of China (ECVMC, 2007).

2.2 Data compilation

2.2.1 Literature survey

We collected SOC stock data of grasslands, forests and croplands in the study area from literature published between 2000 and 2014 in the Web of Science and China National Knowledge Infrastructure. The soil samples were collected from not less than three depths. When only soil organic matter was available, a factor of 0.58 was used to convert it to SOC (Poeplau *et al.*, 2011). When soil bulk density was not available, the soil bulk density of the closest site was used. The raw data were obtained from tables or extracted from graphs in the papers using the Get Data Graph Digitizer (Version 2.20, Russian Federation). In total, there were 71 grassland sites and 13 cropland sites.

2.2.2 Field investigation

Soil samples were collected in 2011 from 0–10, 10–20, 20–30, 30–50 and 50–100 cm depths by digging a hole with a shovel from three quadrats (1 m × 1 m) in a plot of at least 40 m × 40 m at each cropland site, and from three quadrats (20 m × 50 m) at each forest site (>200 m distance between adjacent sites). Soil bulk density was determined with the core method (using a cylindrical metal 100 cm^3 corer) with three replicas at each depth and the soil samples were dried at 65°C for more than 24 h until the weight remained unchanged. SOC content was measured using the modified Mebius method (Nelson and Sommers, 1982). Briefly, a 0.5 g soil sample was digested with 5 ml of 1 N $K_2Cr_2O_7$ and 10 ml of concentrated H_2SO_4 at 180°C for 5 min, followed by titration of the digests with standardized $FeSO_4$. We investigated 23 cropland sites and 43 forest sites.

2.2.3 Data calculation and analysis

The SOC stock at each depth (layer) was calculated using Eq. (1):

$$D_{SOCi} = BD_i \times h_i \times C_i \times 10^{-2}, \quad (1)$$

where D_{SOCi}, BD_i, and h_i represent SOC stock (kg m^{-2}), soil bulk density (g cm^{-3}), and thickness (Eclesia *et al.*, 2012) of the *i* layer (cm), respectively; C_i is the SOC content (g kg^{-1}).

Sampling depths for SOC varied in different studies. To compare SOC data collected from different studies and field investigations, the original SOC data were converted to SOC stock in the top 100 cm depth at each 20-cm interval using the SOC depth distribution functions developed by Yang *et al.* (2007). SOC data in the upper three depths from literature survey and in the five depths (0–100 cm) from field investigation were used to fit Eq. (2). At each 20-cm interval depth, we obtained the SOC content in volume at *h* using Eq. (2) and then calculated the SOC stock using Eq. (3) (Yang *et al*., 2007):

$$C_{soch} = a \times \exp^{b \times h}, \quad (2)$$

$$D_{soch} = \int_{h_1}^{h_2} C_{soch} d(h) \times 10, \quad (3)$$

where *a* and *b* are the coefficients, *h*, h_1, and h_2 are soil depths, and C_{soch} and D_{soch} are SOC content in volume (g cm^{-3}) and SOC stock (kg cm^{-2}) at each depth. The SOC stock dataset was compiled with five fixed depths: 0–20, 20–40, 40–60, 60–80, and 80–100 cm. The coefficient of determination of fit for most SOC sites was above 70% (all sites for grassland, 36 of 43 sites for forest, and 26 of 36 sites for cropland).

In this study, grasslands were split into grazed (29 sites) and grazing-excluded (GE) (42 sites) sites. The latter was further divided into two groups (25 sites for GE<20a and 17 sites for GE⩾20a) according to the duration for grassland restoration of He *et al.* (2008). Forests were classified either as natural forest (16 sites) and plantation (27 sites) or as coniferous forest (14 sites) and broad-leaf forest (29 sites). Stand ages of the forests, determined by drilling three tree-ring cores, were grouped into three classes: 0–15a (9 sites), 16–30a (17 sites), and >30a (17 sites). Croplands were either under conventional cultivation (tillage) (21 sites) or under conservation cultivation (no-tillage) (15 sites). All statistical analyses were conducted using one-way analysis of variance (ANOVA) with a significance level of 0.05. ANOVA and correlation analyses were performed using SPSS 16.0 (Chicago, IL, USA).

3 Results

3.1 SOC stocks in different ecosystem types

On average, SOC stocks in the top 1 m differed significantly among the three land use types (p<0.05), of which grassland (10.8±0.87 kg m^{-2}) had significantly higher SOC stocks than forest (7.9±0.89 kg m^{-2}, p<0.05) and cropland (6.4±0.66 kg m^{-2}, p<0.01), but forest SOC stocks did not differ significantly from those of cropland (p=0.296) (Figure 2a). In addition, spatial variation in SOC stocks (SD=5.78, CV=73%) was higher in forest than in grassland

(SD=7.26, *CV*=67%) and cropland (SD=3.88, *CV*=60%).

SOC stocks decreased with depth for each land use type. The difference in SOC stocks between different land use types narrowed with soil depth (Figure 2b). At the 0–40 cm depth, grassland SOC stock was significantly higher by 52% than that of forest (p<0.05); at the 40–100 cm depth, grassland SOC stock was more than that of forest by 13.5% but was not significantly higher. Compared to cropland, grassland SOC stocks were higher by 79% (p<0.05) at the 0–60 cm depth and by 30% (p>0.05) at the 60–100 cm depth. Vertical distribution was described by the proportion of SOC content in the 0–20 cm depth relative to that in 0–100 cm depth (Jobbágy and Jackson, 2000). The vertical distribution patterns of SOC stocks indicate that less SOC is stored in the upper layer of soil (0–20 cm) in forest (34%) and cropland (34%) than in grassland (41%) in the study area.

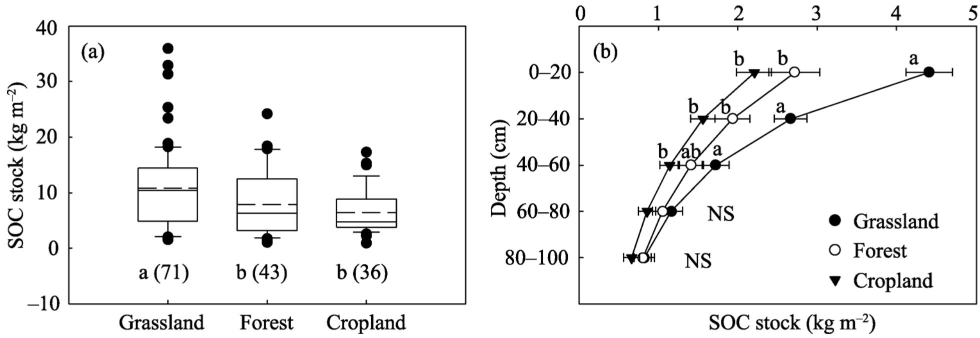

Figure 2 Box plot of soil carbon stocks (a) and their vertical distributions (b) for grassland, forest and cropland. Different letters indicate a significant difference in the total soil carbon stocks and soil carbon stocks of different depths between different land use types at the 0.05 level. NS signifies no significant difference. Bars denote standard error. Values in parentheses indicate the number of samples. Box plots display the median (solid line), mean (dotted line), interquartile range (upper and lower edge of box), 10–90 percentile (whiskers) and outliers (circles).

3.2 Effects of grazing exclusion on SOC stocks in grassland

SOC stock was on average 12.2 kg m^{-2} for grazing-excluded (GE) grassland, which is marginally significantly higher than the 8.7 kg m^{-2} for grazed grassland (p=0.051). SOC stocks increased significantly with the duration of GE (R^2=0.19, p<0.01). When the duration of GE was less than 20 years, the SOC stock of GE grassland was 10.5 kg m^{-2}, being higher than that of grazing grassland, but not significantly. However, carbon stock (14.7 kg m^{-2}) was significantly increased when the duration of GE exceeded 20 years (p<0.01) (Figure 3a). Such an increase was still observed even when the duration of GE was 30 years, which is the longest GE duration in this dataset.

SOC stock declined with depth for grazed and GE grassland (Figure 3b). At the 0–40 cm depth, the SOC stock in ≥20a GE grasslands was significantly higher than that in grazed grassland (p<0.05). Throughout the soil profile up to 1 m, no significant difference in SOC stocks was found between the <20 year GE grassland and grazed grassland (p=0.061), although slightly higher SOC stocks were observed at each layer in the GE grassland (<20a) than in grazed grassland (Figure 3b). Larger differences in SOC stocks were detected in the upper layers than in deeper layers among the studied grasslands: e.g., SOC stocks at the 0–20 cm depth in the ≥20 year GE grassland were 71% and 64% higher, respectively, than in the <20 year GE grassland and grazed grassland, and these percentages declined to 41%

and 40%, respectively, at the 20–40 cm depth (Figure 3b).

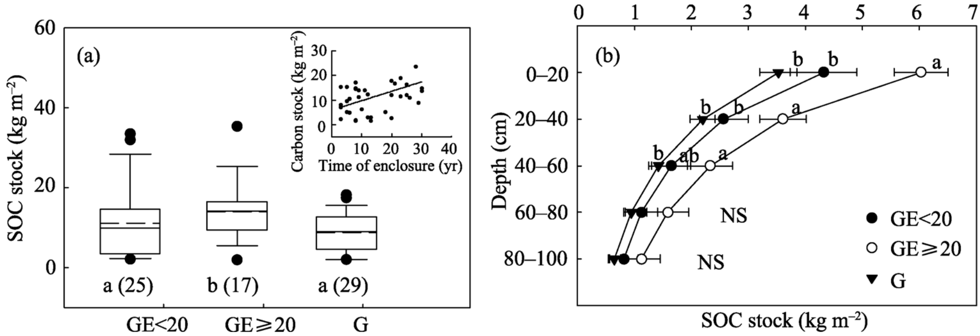

Figure 3 Comparison of SOC stocks (a) and their vertical distributions (b) between grazing-excluded (GE) (GE<20a, GE⩾20a) and grazed (G) grasslands. The inset panel shows the relationship between SOC stock and the duration of GE. G, GE<20, and GE⩾20 represent grazed grasslands, <20 years GE, and⩾20 years GE grasslands, respectively. Different letters indicate a significant difference (p<0.05) in the total SOC stocks and SOC stocks at different depths among grassland types. Bars denote standard error. NS signifies no significant difference. Values in parentheses indicate the number of samples.

3.3 Effects of stand age, species identity, and forest type on SOC stocks in forest

SOC stocks increased evidently but not significantly with forest stand age (p>0.05). The average SOC stocks were 5.2, 8.0, and 9.3 kg m^{-2} in the 0–15, 16–30 and >30 year age classes, respectively (Figure 4a). Irrespective of tree species, significant linear positive correlations were found between SOC stocks and stand ages for plantations (R^2=0.21, p<0.05), but not for natural forests (p=0.27). Similar to the grasslands, SOC stocks declined with depth, and increased with forest age for each depth (Figure 4b).

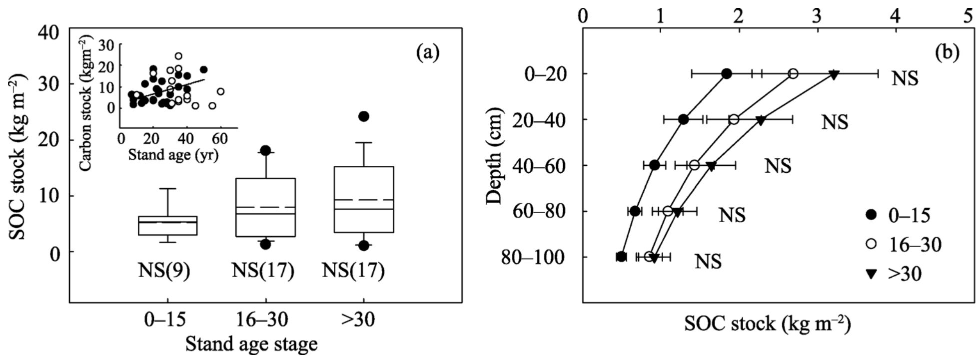

Figure 4 Effects of forest stand age on SOC stocks (a) and their vertical distribution (b). The inset panel in (a) shows the relationship between SOC stocks and forest stand age. Bars denote standard error. NS signifies no significant difference. Values in parentheses indicate the number of samples.

No significant differences in SOC stocks were found between coniferous (8.1 kg m^{-2}) and broadleaf forests (7.8 kg m^{-2}) (p=0.90) (Figure 5a) and between natural forests (8.7 kg m^{-2}) and plantations (7.4 kg m^{-2}) (p=0.50) (Figure 5c). Vertical distribution of SOC stocks was similar among the forest types (Figures 5b and 5d), but the SOC stock at each depth was slightly higher for natural forests than for plantations (Figure 5d).

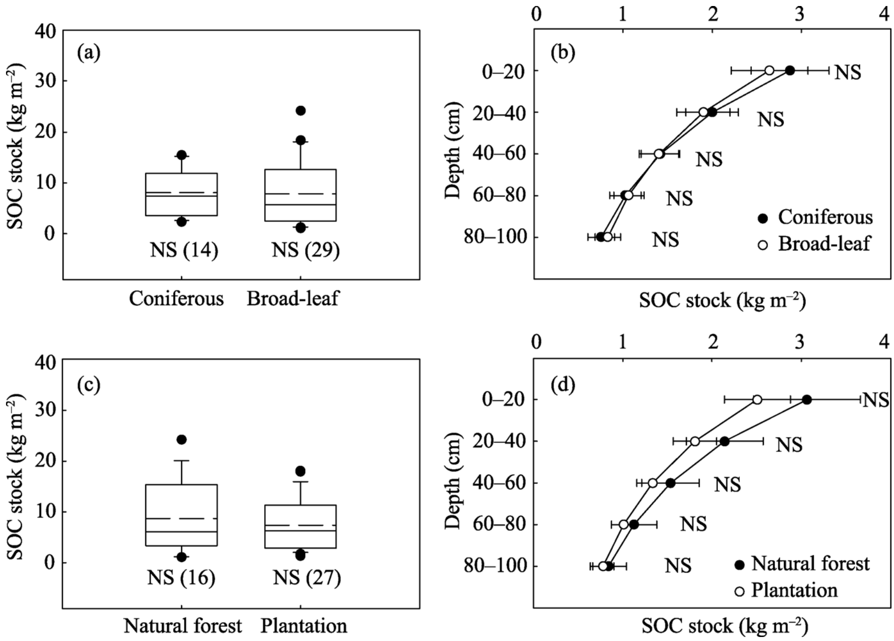

Figure 5 Comparisons of SOC stocks (a, c) and their vertical distribution (b, d) between coniferous and broad-leaf forests (a, b) and between natural forests and plantation (c, d). Bars denote standard error. NS signifies no significant difference. Values in parentheses indicate the number of samples.

3.4 Effects of tillage on SOC stocks in cropland

In cropland, the SOC stock of conservation cultivated land (no-tillage, 8.4 kg m^{-2}) was significantly higher than that of conventionally cultivated land (tillage, 5.1 kg m^{-2}) (p<0.05) (Figure 6a). On average, no-tillage significantly increased cropland SOC stock by 65% (3.3 kg m^{-2}, p<0.05) compared to tillage (Figure 6a). In terms of vertical distribution, the effect of no-tillage on SOC content largely occurred in the 0–40 cm depth (p<0.05) (Figure 6b). Compared to tilled croplands, the SOC stocks of no-tillage croplands were greater on average by 1.5, 0.9, 0.5, 0.3, and 0.2 kg m^{-2} at the 0–20, 20–40, 40–60, 60–80, and 80–100 cm depths, respectively. Specifically, the average SOC stocks at the 0–20 cm and 20–40 cm

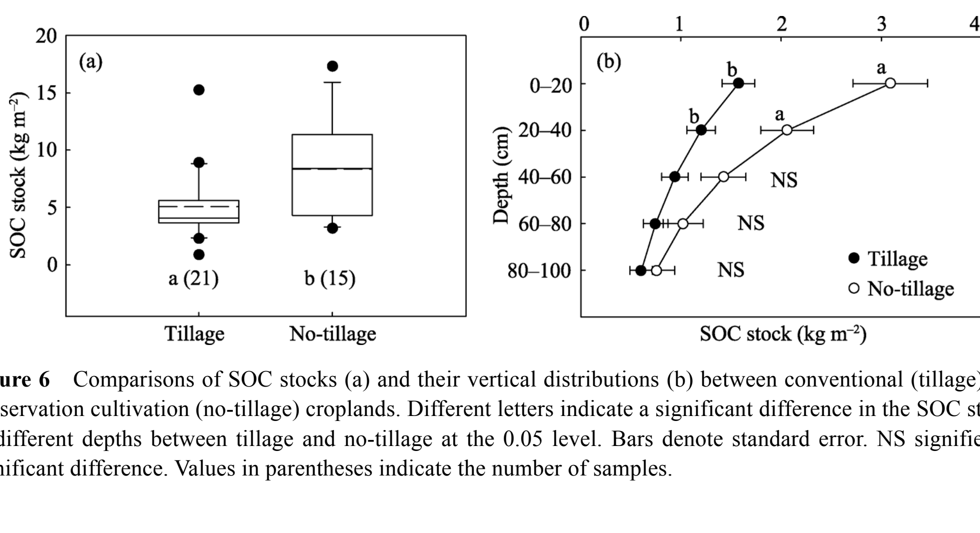

Figure 6 Comparisons of SOC stocks (a) and their vertical distributions (b) between conventional (tillage) and conservation cultivation (no-tillage) croplands. Different letters indicate a significant difference in the SOC stocks of different depths between tillage and no-tillage at the 0.05 level. Bars denote standard error. NS signifies no significant difference. Values in parentheses indicate the number of samples.

depths were 96% and 71% significantly greater, respectively, in the no-tillage croplands than in the tilled croplands ($p<0.05$).

4 Discussion

4.1 Comparison of SOC stocks among land use types

Among the three land use types in the agro-pastoral ecotone in Inner Mongolia, grassland exhibited the highest SOC stock, followed by forest and cropland. Grassland that stored more SOC than forest is consistent with the findings of Wei *et al*. (2012). They reported that grassland ecosystems would have more SOC than planted forests on the Loess Plateau, which is located in a similar climate zone relative to our study area. The higher SOC stock in the grassland compared to the forest is likely ascribed to: (1) low forest stand density leading to less carbon input into the soil from litter; (2) plantations being mainly established on abandoned farmland, which had low SOC stock due to frequent tillage – restoring SOC takes several years to decades. A meta-analysis also shows that, in temperate zones, grassland ecosystems have more SOC than planted forests converted from croplands (Poeplau *et al*., 2011). Two reasons likely explain the higher SOC stocks in grassland versus cropland systems. Firstly, grassland is not subjected to regular crop harvest (Solomon *et al*., 2000) and is no-tillage, which increases the biomass inputs and enhances the physical protection of SOC stocks (Post and Kwon, 2000). Secondly, cropland upper soil carbon is easily taken away by the wind, especially during spring, due to surface bareness. Our result is in good agreement with a previous study conducted in the Xilin River Basin of Inner Mongolia that reported the stored total organic carbon in the uppermost 30 cm soil layer was greater in the grassland than in the cropland (Qi *et al*., 2012).

Afforestation is supposed to be the plausible pathway to promote terrestrial ecosystem carbon stocks (Lal, 2004; Li *et al*., 2012); however, in arid and semi-arid regions, the carbon sequestration potential via afforestation is disputable due to water shortage and drought, which have been shown to be unfavorable for forest sustainability and SOC accumulation (Cao, 2008; Cao *et al*., 2010; Wu *et al*., 2014). A synthetic analysis shows that the establishment of grassland in temperate zones renders a long lasting carbon sink whereas afforestation of grasslands leads to mostly SOC losses or lack of an SOC sink even after 100 years (Poeplau *et al*., 2011). This suggests that afforestation or cultivation on original grassland would likely decrease the SOC stock and that grassland restoration would be helpful for increasing SOC stock in semi-arid regions.

In this study, over one third of the SOC was stored in the top 20 cm depth relative to the total depth studied (0–100 cm), being higher on average in grasslands (41%) than in forests (34%) and croplands (34%). This SOC vertical distribution pattern in grassland is similar to that across the world (39%) (Jobbágy and Jackson, 2000), but is slightly higher than that averaged over China (34%) (Yang *et al*., 2007). Although they are located in the same climate zone, the grassland in our study area had a much higher percentage of SOC (41%) in its 0–20 cm layer than the Loess Plateau (26.8%) (Wei *et al*., 2012). This implies that conversion from grassland to other land use types would influence SOC content more remarkably in the upper soil layers than in the deeper soil layers. Deng *et al*. (2014) also found that land use conversion in China's 'Grain-for-Green' project led to greater SOC changes in upper soil (0–20 cm) than in deeper soil. Grassland stored more SOC in the 0–20 cm depth than forest and cropland, and thus would give rise to more SOC loss than the deeper depth when disturbed. Thus, protecting the surface SOC of grassland from destruction plays a major role in ensuring SOC stability in terrestrial ecosystems. This implies that grassland restoration or conversion from croplands and forests to grassland systems may increase SOC sequestration in the agro-pastoral ecotone in Inner Mongolia.

4.2 Impacts of management on soil organic carbon

The SOC stock of GE grassland increased by 40% on average relative to the grazed grassland in this study. Grazing can lower vegetation coverage and reduce carbon input (Dai *et al.*, 2014). GE is considered to be an effective way to improve carbon sequestration (Hu *et al.*, 2015; Pei *et al.*, 2008; Steffens *et al.*, 2008; Su *et al.*, 2005). GE can promote grass growth and biomass accumulation and thereby increase litter-derived carbon input to the soil (Hu *et al.*, 2015). Mostly, when vegetation is restored, the avoidance or decrease of wind or water erosion can effectively reduce direct carbon loss from the soil (Hu *et al.*, 2005; Wiesmeier *et al.*, 2015; Zhou *et al.*, 2011). Our study demonstrated that compared to grazed grassland, SOC stocks showed a significant increasing trend for more than 20 years after GE. An obvious increase in SOC stocks was found even after 30 years of GE, the longest GE time in our dataset. However, our result disagrees with the finding of Hu *et al.* (2015), who reported that, in North China, the achievement of an SOC stable state takes about 15 years on average after the grassland is fenced against grazing. A major reason for this discrepancy is likely that SOC accumulates slowly in arid and semi-arid regions (Werth *et al.*, 2005) due to droughts. Therefore, more time is required for SOC equilibrium in our study area than in North China. Additionally, in our study, GE grassland is mainly distributed in the agro-pastoral regions, and although fenced, is influenced occasionally by humans or livestock. Further, in a study performed in a region adjacent to our study area, Zhang *et al.* (2014) suggested that it takes at least 50 years to attain the equilibrium of SOC stock for grasslands recovered from degradation. Lastly, different research scales and grassland types are probable reasons for this discrepancy.

In forests, SOC stocks either in the entire profile up to 100 cm or in each depth (20 cm intervals) was observed to increase with stand age. Globally, there is an overall increasing trend in SOC stocks through time across all biomes (Pregitzer and Euskirchen, 2004). Tree species and forest types did not present obvious impacts on forest SOC stocks probably because most of the forests studied were relatively young. The average stand age was 26 and 31 years for coniferous and broad-leaf forests, and 23 and 39 years for plantation and natural forest.

In cropland, compared with conventional cultivation (tillage), conservational cultivation (no-tillage) increased SOC stock by 65% and 48% at 0–100 cm and 0–20 cm depths, respectively. Many studies have reported that no-tillage can largely increase SOC stock; tillage disturbs the soil physical aggregate structure, which can increase microbial activity and improve organic matter decomposition (Ogle *et al.*, 2012; Post and Kwon, 2000). However, this increase is primarily limited to the top soil layer (e.g., 0–30 cm) (Ogle *et al.*, 2005; Powlson *et al.*, 2014). The mechanisms of SOC stock increase are not yet fully understood (Ogle *et al.*, 2012). Other than the direct increase in carbon input to the soil through litter and/or stubble mulching, the reduction of erosion and runoff and amelioration of water holding capacity might be also important contributors (Palm *et al*., 2014). Apart from tillage, factors such as crop type, crop rotation, fertilization, and irrigation have direct or indirect effects on SOC dynamics.

5 Conclusions

Our results reveal that SOC stocks in grasslands were significantly higher than those of forests and croplands in the agro-pastoral ecotone in Inner Mongolia of China. Compared to forests and croplands, grasslands stored much more SOC in the surface layer, especially in the 0–40 cm depth. For grasslands and croplands, management practices (e.g., grazing exclusion and tillage) significantly impacted SOC dynamics. The SOC stock of GE grassland was significantly increased after more than 20 years of GE relative to grazing grassland. Conservational cultivation (no-tillage) could improve SOC stocks in croplands, especially in the 0–40 cm soil layer, compared to conventional cultivation (tillage). Our study highlights that in terms of carbon sequestration, reclamation and afforestation should be implemented with caution in arid and semi-arid regions of China.

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