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Review

SOC changes were more sensitive in alpine grasslands than in temperate grasslands during grassland transformation in China: A meta-analysis

Wen-Shan Yang [a,b], Yu Liu [a,b], Jingxue Zhao [a,c], Xiaofeng Chang [a], Martin Wiesmeier [d], Jian Sun [b,e], Manuel López-Vicente [f], Roberto García-Ruiz [g], José Alfonso Gómez [h], Huakun Zhou [b], Jianjun Shi [i], Gao-Lin Wu [a,b,i,j,*]

[a] *State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A & F University, Yangling, Shaanxi 712100, China*
[b] *Qinghai Provincial Key Laboratory of Restoration Ecology of Cold Area, Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining, 810008 China*
[c] *State Key Laboratory of Grassland Agro-ecosystem, Institute of Innovation Ecology & College of Life Sciences, Lanzhou University, Lanzhou, 730000, China*
[d] *TUM School of Life Sciences Weihenstephan, Technical University of Munich, Freising 85354, Germany*
[e] *Key Laboratory of Alpine Ecology and Biodiversity, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China*
[f] *Group Aquaterra, Advanced Scientific Research Center, University of A Coruña. As Carballeiras, S/n, Campus de Elviña, 15071 La Coruña, Spain*
[g] *Department of Animal and Plant Biology and Ecology, University of Jaén, 23071 Jaén, Spain*
[h] *Institute for Sustainable Agriculture, Spanish National Research Council (CSIC), Cordoba, Spain*
[i] *Qinghai Provincial Key Laboratory of Adaptive Management on Alpine Grassland, Qinghai Academy of Animal and Veterinary Science, Qinghai University, Xining 810016, China*
[j] *CAS Center for Excellence in Quaternary Science and Global Change, Xi'an, 710061, China*

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ABSTRACT

The effect of grassland utilization and management changes (grassland transformations) may change soil carbon storage even to carbon emission. Grassland types may present a greater contribution to changes in soil carbon storage during grassland utilization and management changes, however, few studies focused on effects of grassland types on changes in soil organic carbon (SOC) stocks during grassland transformations. Here, a comprehensive meta-analysis was conducted to explore the effects of grassland transformation on SOC stocks among grassland types based on 325 peer-reviewed studies over China. The results showed that SOC changes were more sensitive in alpine grasslands than in temperate grasslands during grassland transformation. Especially in the C loss process, the SOC loss rates (Rs) of alpine grasslands were 3.3 and 7.3 times that of temperate grasslands on 1–5 and 6–10 years, respectively. Additionally, the higher SOC stock was the major factor of the SOC loss of alpine grasslands, and the initial SOC stock of alpine grasslands was about 3 times that of temperate grasslands. The low-temperature environmental conditions may limit the carbon decomposition and emission in alpine grasslands, but excessive disturbance will destroy the protective effect of low temperature. Therefore, the results proposed that soils of alpine grasslands in high-altitude areas have a large carbon sink potential but are also vulnerable and more attention should be paid to alpine grasslands relative to temperate grasslands. The future plan should be focused on maintaining of the low-temperature habitat and protecting of the existing soil carbon storage in alpine grasslands, and improving soil carbon sink capacity in temperate grasslands, because improving soil carbon sink capacity during sustainable utilization of grassland ecosystem is of great significance for coping with future reducing carbon emission.

1. Introduction

Globally, grasslands are one of the most extensive vegetation types, accounting for nearly 20% of the land surface area and containing 12% of the earth's soil organic matter (SOM) (Scurlock and Hall, 1998; Schlesinger and Bernhardt, 2013). Given their area extension and

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* Corresponding author. State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China.
E-mail addresses: wugaolin@nwsuaf.edu.cn, gaolinwu@gmail.com (G.-L. Wu).

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carbon stocks, grassland ecosystems play key roles in carbon cycling and carbon balancing (Scurlock et al., 2002; Piao et al., 2009; Abdalla et al., 2018; Jiang et al., 2020). And grassland ecosystems can be a source of feedback for global climate through their strong but susceptible disturbed potential for carbon sequestration (Anderson, 1991; Wang and Fang, 2009; Derner et al., 2006). China's grassland area and carbon stocks account for approximately 6–8% and 9–16% of the world's grassland area and carbon stocks, respectively (Ni, 2002; Fan et al., 2008; Deng et al., 2017). Therefore, minor changes in the largest organic carbon pool (soil organic carbon pool) in the terrestrial ecosystems may lead to a lot of CO_2 emissions (Callesen et al., 2003; Wang et al., 2011). And SOC stock changes in China's grasslands may have a significant impact on global climate change and the carbon cycle (Wang et al., 2011). Historically, unreasonable land use such as extensive cultivation and overgrazing have caused a series of serious ecological problems such as grassland degradation and desertification, which have greatly affected China's sustainable social and economic development (Zhao et al., 2005; Wu et al., 2003; Zhou et al., 2005; Ren et al., 2007). To prevent land degradation and mitigate climate change, measures such as returning farmland to grasslands (naturally or artificial restored), grazing exclusion and establishing artificial grassland on degraded grasslands were implemented (Zhou et al., 2005; Huang et al., 2013; Álvarez-Martínez et al., 2016; Tarhouni et al., 2017; Wang et al., 2018). These changes in grassland utilization and management (grassland transformations) result in changes in grassland ecosystem carbon stocks, especially in the top 30 cm of grassland soils which contain 80–90% of grass roots (Jackson et al., 1996; Xie et al., 2007; Wang et al., 2011). Therefore, understanding the impact of grassland transformation on the SOC in the top 30 cm is very important for reacting to future climate change.

Considerable effort has been invested to explore the sequestration and loss of SOC caused by grassland transformation (Laganiere et al., 2010; Li et al., 2012, 2020; Shi et al., 2013; Wei et al., 2014; Wang et al., 2011; Deng et al., 2016; Zhou et al., 2019; Koga et al., 2020; Luo et al., 2020). It is well known that unreasonable grazing and reclamation on grassland can easily lead to SOC loss, while grazing exclusion and artificial grassland establishment can promote SOC accumulation (Conant et al., 2001; Wang et al., 2011; Deng et al., 2014a, 2014b, 2016, 2017, 2014b). Through analysis of data from 113 papers, Wang et al. (2011) have found that overgrazing and conversion of freely grazed grassland to cropland led to a decline in SOC and caused 30%–35% of grassland SOC loss in China. Deng et al. (2016, 2017) showed that the establishment of artificial grassland and grazing exclusion significantly increased soil C stocks and belowground biomass C stocks at a rate of 0.30 Mg ha^{-1} yr^{-1} and 0.32 Mg ha $^{-1}$ yr^{-1}. However, the effects of grassland transformation on SOC may be variable across different grassland types, especially between temperate grasslands and alpine grasslands where there are significant differences in hydrothermal conditions and vegetation types. China's grasslands are mainly distributed in the semi-arid and arid temperate regions (north China) and in the high and cold alpine regions (west China), including temperate grasslands (desert steppe, temperate steppe, meadow steppe, and mountain meadow) and alpine grasslands (alpine steppe and alpine meadow) (Ni, 2002; Chinese Academy of Sciences, 2001). Moreover, the carbon of alpine and temperate grasslands account for more than 85% of the total grassland, and the carbon (in both vegetation and soils) of alpine grasslands is about 1.7 times that of temperate grasslands (Ni, 2002). Due to the specific regions and grassland types, understanding the soil organic carbon changes of two grassland types during grassland transformation plays an important role in achieving scientific grassland management and sustainable development.

Although a large number of studies have reported changes in China's grassland SOC due to grassland transformations (Wang et al., 2011, 2016; Deng et al., 2014a, 2014b, 2017, 2014b; Tang et al., 2019), most of these studies have only focused on changes in SOC stocks for single grassland types (e.g., temperate or alpine grasslands) or grassland transformation types (Zhou et al., 2005; Hu et al., 2016; Xiong et al., 2016; Deng et al., 2017). Additionally, small-scale field studies are difficult to obtain a broad conclusion about temperate and alpine grasslands due to their large area. Therefore, it is necessary to summarize and analyze systematically the published reports to explore a relatively universal conclusion, which benefit to gain a better understanding of soil carbon sequestration and emission of grassland ecosystem during transformation. Here, the 325 reported studies were selected to conduct a synthesis on grassland transformations in China. Specifically, our objectives were to: (1) examine the effects of grassland transformation on SOC changes in two grassland types (temperate and alpine grasslands); and (2) explore the major driving factors of SOC changes between temperate and alpine grasslands. This study analyzed the difference response of SOC to grassland transformation for temperate and alpine grasslands at a large-scale, which will better for optimizing management of grassland ecosystem, coping with future reducing carbon emission and achieving sustainable development.

2. Materials and methods

2.1. Data preparation

The studies included in this database were collected from peer-reviewed journal articles before September 2019 by using the Web of Science (http://apps.webofknowledge.com/) and China National Knowledge Resource Integrated (CNKI) (www.cnki.net/) online scientific reference services. The keywords and phrases used for literature research were as follows: (i) "grassland use", "land use", "grassland cultivation", "grassland restoration", "artificial grassland", "Grain for Green", or "grassland conversion"; (ii) "grassland management", "grazing", "grazing exclusion", "enclosure", "fencing", "fence", "grazing removal", "exclosure", or "no grazing"; (iii) "soil carbon", or "SOC". The final database papers are selected by the following criteria: (*i*) data on SOC stocks or data that enabled a calculation of SOC stocks (SOC or SOM concentration, bulk density and sampling depth); (*ii*) data on both initial SOC stocks and SOC stocks after transformation of grassland; (*iii*) climate data (mean annual temperature (MAT), mean annual precipitation (MAP)) and details on the transformation age (the years since grassland transformed); (*iv*) experiments used paired sites, chronosequence or retrospective designs (which had similar soil conditions before and after transformation of grassland); and (*v*) each observation value in the selected paper should have adequate replications (≥ 3). In total, 325 studies were collected in the databset (Appendix Dataset S1), which were located in northern and western China (Fig. 1). For each study, we collected the related data: site location (longitude and latitude), climatic information (MAP and MAT), altitude, SOC stock or SOC/SOM concentration, bulk density, soil depth and grassland type (alpine grasslands or temperate grasslands). The related data was directly obtained from texts and tables or extracted by using the GetData Graph Digitizer (version 2.24, http://www.getdata-graph-digitizer.com/) from figures. For those studies done on the same site, we considered different transformation years as independent observations.

Finally, we obtained 1410 observations (Appendix Table S1) from 338 sites (Fig. 1), which the transformation age covers from 1 to 75 years. This database included five types of grassland transformation: grazing to no grazing (grazing exclusion), no grazing to grazing (grassland grazing), grassland to farmland (grassland reclamation), farmland to grassland (returning farmland to grassland), and degraded grassland to artificial grassland (reestablishing artificial grassland or reseeding on degraded grassland). Given the climatic differences, we divided the grasslands into temperate grasslands (1009 observations) and alpine grasslands (401 observations). And the age of transformation was divided into four groups: 0–5, 6–10, 11–20, and >20 years.

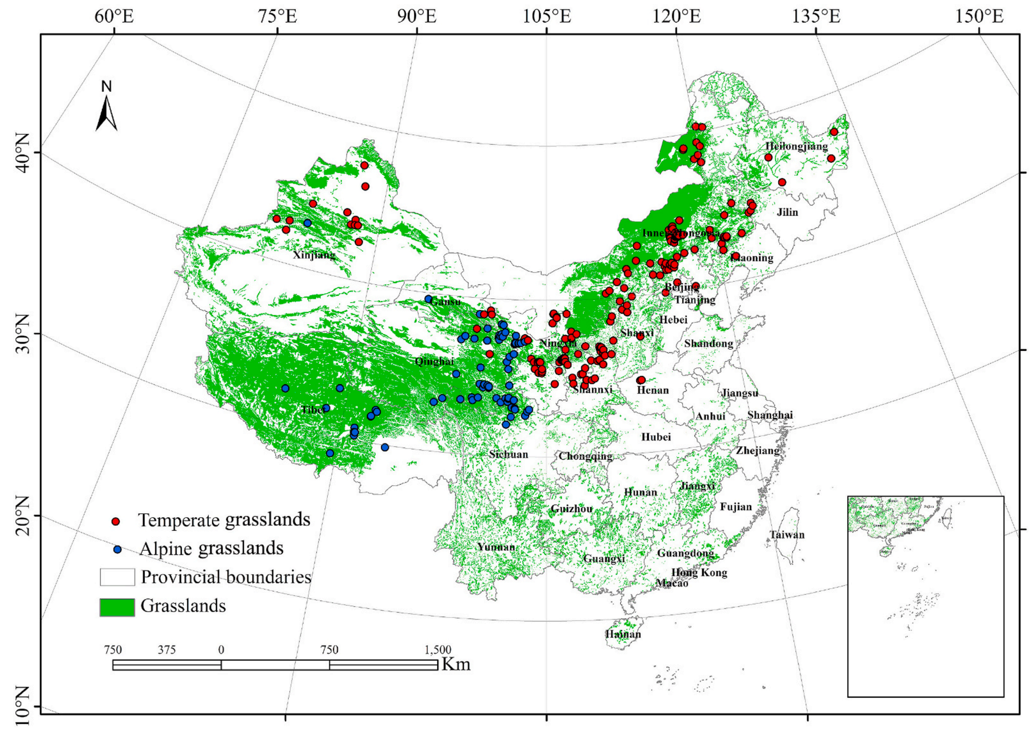

Fig. 1. Distribution of individual study sites. There are 338 research sites, including 242 temperate grassland sites and 96 alpine grassland sites. The temperate grassland sites mainly distribute in the semi-arid and arid temperate regions (north China), and the alpine grassland sites mainly distribute in the high and cold alpine regions (west China).

2.2. Data calculation and analysis

2.2.1. SOC stocks

When SOC stocks had been reported in the article, the units were turned to “Mg ha^{-1}”. Casein case that no SOC stocks were reported, the SOC stocks were calculated by the following equations:

$$C_S = \frac{SOC \times BD \times D}{10} \tag{1}$$

where $\boldsymbol{C_s}$ is the SOC stock (Mg ha^{-1}); ***SOC*** is the SOC concentration (g kg^{-1}); ***BD*** is the soil bulk density (g cm^{-3}); and ***D*** is soil thickness (cm). When only soil organic matter (SOM) contents instead of SOC contents were provided, the SOC content was calculated by the following formula assuming that SOM contains 58% C (Mann, 1986):

$$SOC = 0.58 \times SOM \tag{2}$$

Similarly, if the soil bulk density was not provided in the observations, the relationship established based on measurements of 784 samples obtained from the National Soil Survey Office between ***BD*** and ***SOC*** content (Wu et al., 2003) was used to calculate the ***BD***:

$$BD = -0.1229\ln(SOC) + 1.2901 \quad (for \ \ SOC < 6\%) \tag{3}$$

$$BD = 1.3774e^{-0.0413SOC} (for \ \ SOC > 6\%) \tag{4}$$

In order to compare SOC data from observations with different soil depths, the methodology adopted by Yang et al. (2011) and Deng et al. (2014a) was used. The original SOC data was converted to 0–30 cm soil depth using the depth functions developed by Jobbagy and Jackson (2000):

$$\gamma = 1 - \beta^{d} \tag{5}$$

$$X_{30} = \frac{1 - \beta^{30}}{1 - \beta^{d0}} \times X_{d0} \tag{6}$$

where γ is the cumulative proportion of the SOC stock from the soil surface to the depth **d** (cm); $\boldsymbol{\beta}$ (0.9786) is the relative rate of decrease in the SOC stock with soil depth; $\boldsymbol{X_{30}}$ denotes the SOC stock in the upper 30 cm; $\mathbf{d_0}$ is the original soil depth available in the individual studies (cm); and $\boldsymbol{X_{d0}}$ is the original SOC stock.

2.2.2. SOC changes

The SOC stock changes ($\boldsymbol{\Delta C}$, Mg ha^{-1}) and the percentage of $\Delta \boldsymbol{C}$ to initial SOC stock ($\boldsymbol{\Delta C\%}$, %) due to grassland transformation were calculated for each observation using the following equations:

$$\Delta C = C_{Sa} - C_{Sb} \tag{7}$$

$$\Delta C\% = \frac{\Delta C}{I} * 100 \tag{8}$$

where $\boldsymbol{C_{Sb}}$ and $\boldsymbol{C_{Sa}}$ are the SOC stocks before and after grassland transformation (Mg ha^{-1}), respectively, and ***I*** is the initial SOC stock ($\boldsymbol{C_{Sb}}$).

To reflect the variation of the different grassland transformations, the mean values of $\boldsymbol{\Delta C}$ and $\boldsymbol{\Delta C\%}$ were calculated for each transformation type, and 95% confidence interval (CI) of $\boldsymbol{\Delta C}$ and $\boldsymbol{\Delta C\%}$ were calculated by using the following equations (Luo et al., 2006; Deng et al., 2017):

$$95\%\mathrm{CI} = 1.96 \times SE_{\mathrm{total}} \tag{9}$$

$$SE_{\mathrm{total}} = \sqrt{\frac{Vs}{n}} \tag{10}$$

where $\boldsymbol{SE_{total}}$ is the standard error of the relative $\boldsymbol{\Delta C}$, and $\boldsymbol{V_S}$ and ***n*** is the variance of the relative $\boldsymbol{\Delta C}$ and the number of observations, respectively. In this study, the 95% CI was calculated for each transformation type. The observed effect sizes were considered statistically different from zero if the 95% CI did not include zero.

In order to gain the SOC stock change ($\boldsymbol{\Delta C}$) dynamic of each grassland transformation, we linearly regressed the $\boldsymbol{\Delta C}$ and the transformation age. The slope of the linear regression (**ΔC** change rate (**R_k**), Mg ha^{-1} yr^{-1}) indicated the dynamics of SOC stock changes. We identified the effect of grassland transformations on SOC sequestration by the direction of the SOC stock changes (**ΔC**) and the **ΔC** change rate (**R_k**), so that each grassland transformation type corresponded to a C source (**ΔC** and $R_k < 0$) or C sink (ΔC and $R_k > 0$) transformation.

2.2.3. SOC change (sequestration/loss) rate (Rs)

To explore the dynamics of SOC stock changes (**ΔC**) in more detail and to estimate the carbon sequestration potential of each grassland restoration measure, the SOC change (sequestration/loss) rate (**Rs**, Mg ha^{-1} yr^{-1}) was calculated using the following equation:

$$R_s = \frac{\Delta C}{Y} \tag{11}$$

where **ΔC** is the SOC stock change; **Y** is the grassland transformation age. A 95% CI of **Rs** was calculated using equations (9) and (10).

2.2.4. Driving factors of SOC stock changes

Two-way ANOVE to detect the effects of transformation type, grassland type and their interaction on SOC change after grassland transformation. To gain insights into the driving factors of SOC changes responses to grassland transformation, we performed a stepwise regression analysis between the initial SOC stock (**I**), mean annual temperature (**MAT**), mean annual precipitation (**MAP**), altitude (**AL**) and SOC changes (ΔC).

3. Results

3.1. Grassland transformation effect on the SOC changes of temperate and alpine grasslands

Grassland transformation type (**ΔC**: $F = 204.116$, $P < 0.001$; **C**%: $F = 87.285$, $P < 0.001$; **Rs**: $F = 134.703$, $P < 0.001$) has a significant effect on SOC changes (Table 1). Through the directions (">0" or "<0") of SOC changes (**ΔC)** and **ΔC** change rate (**R_k**), we have reclassified the grassland transformation to three types (Table 2). They were: (1) C sink transformation included grazing to no grazing (grazing exclusion) and farmland to grassland (returning farmland to grassland); (2) C source transformation included grassland to farmland (grassland reclamation) and no grazing to grazing (grassland grazing); and (3) C sink-source transformation included degraded grassland to artificial grassland (reestablishing artificial grassland or reseeding).

Table 1

Types of SOC stock changes of grassland transformations. "+" and "-" respectively represent values of ΔC and **R_k** "> 0" and "< 0". "> 0", the grassland transformation was considered as C sink transformation; "< 0", the grassland transformation was considered as C source transformation. The five grassland transformations are: grazing to no grazing (grazing exclusion), no grazing to grazing (grassland grazing), grassland to farmland (grassland reclamation), farmland to grassland (returning farmland to grassland), and degraded grassland to artificial grassland (reestablishing artificial grassland or reseeding on degraded grassland).

Transformation	Total		Temperate		Alpine		Transformation type
	ΔC	R_k	ΔC	R_k	ΔC	R_k	
Grazing to no grazing	+*	+*	+*	+*	+*	+*	C sink
Farmland to grassland	+*	+*	+*	+*	+*	+*	
Grassland to farmland	-*	-*	-*	-*	-*	-*	C source
No grazing to grazing	-*	-*	-*	-*	-*	-*	
Degraded grassland to artificial grassland	+*	–	+*	-*	+*	-*	C sink - source

Note: ΔC and R_k indicate SOC stock changes and the slope of **ΔC** and **Y**, respectively. * indicates a significant difference from 0.

Grassland type (**ΔC**: $F = 32.476$, $P < 0.001$; **C**%: $F = 32.898$, $P < 0.001$; **Rs**: $F = 26.574$, $P < 0.001$) also has a significant effect on SOC changes (Table 1). On the one hand, the SOC stock changes of grassland reclamation and grazing, returning farmland to grassland were higher in alpine grassland than in temperate grasslands, but the SOC stock changes of grazing exclusion, reestablishing artificial grassland and reseeding on degraded grassland were higher in temperate grasslands than in alpine grasslands (Fig. 2A and B). Due to grassland transformation, the alpine grasslands SOC lost 6.05 Mg ha^{-1} (-0.06 ± 0.58%), but temperate grasslands SOC accumulated 5.9 Mg ha^{-1} ($+28.64 \pm 0.47$%) (Fig. 2C and D). On the other hand, the magnitude of SOC change rate (**Rs**) was higher in alpine grasslands than in temperate grasslands (Fig. 2E and F). Especially in C source transformations, the SOC loss rates (**Rs**) of alpine grasslands were 3.3 and 7.3 times that of temperate grasslands on 1–5 and 6–10 years, respectively (Fig. 2, F).

3.2. Driving factors of SOC changes of temperate and alpine grasslands

The initial SOC stock (**I**) was the strongest factor affecting SOC stock changes (**ΔC**) during the total and temperate grassland transformation (stepwise regression) (Table 3). And the relationship between initial SOC stock and SOC stock changes was positive in C sink transformation, but negative in C source transformation (Table 3, Fig. 3). It is worth noting that the effect of initial SOC stock on SOC changes was stronger in C source transformation than in C sink transformation (Table 3, Fig. 3). More importantly, the SOC changes of total grasslands was only affected by initial SOC stock in C source transformation, while affected by initial SOC stock and environmental factors (**AL**, **MAP** and **MAT**) in C sink transformation (Table 3).

Additionally, the initial SOC stock was significantly higher in alpine grasslands than in temperate grasslands for the same transformation age group, and the average initial SOC stock of alpine grasslands was about 3 times that of temperate grasslands (Fig. 4A and B). The magnitude of SOC change rate (**Rs**) increased with the initial SOC stock increasing, and the slope of **Rs** change was higher in alpine grasslands than in temperate grasslands (Fig. 4C and D).

4. Discussion

4.1. Grassland transformation on SOC stock changes

Grassland utilization and management changes have significant effects on SOC changes. Consistent with most previous studies (Wang et al., 2011; Deng et al., 2014a, 2014b, 2016, 2017, 2014b), our results showed that SOC stocks increased in C sink (sink-source) transformations (grazing exclusion, returning farmland to grassland and establishing artificial grassland on degraded grassland), but decreased in C source transformations (grassland reclamation and grazing). And vegetation changes and soil disturbance caused by grassland transformations are supposed to be the main reasons leading to changes in SOC storage (Ding et al., 2013; Zhou et al., 2017; Song et al., 2018). Compared with the study of Wang et al. (2011), we further analyzed the effect of grassland type on the SOC stock changes during grassland transformation. The SOC changes significantly varied between temperate and alpine grasslands, and the changes more sensitive in alpine grasslands (Fig. 2).

The alpine grasslands lost SOC and presented as a C source during grassland transformation, which is probably caused by two reasons. Firstly, the SOC change rates (**Rs**) of alpine grasslands were significantly higher than that of temperate grasslands in C source transformations, which lead to alpine grasslands losing too much SOC during unreasonable grassland utilization. Secondly, the SOC accumulation rate of alpine grasslands was higher than that of temperate grasslands but weak, and the restored age of alpine grasslands was shorter (almost no more than 20 years). This resulted in less SOC accumulated during the restoration

Table 2
Two-way ANOVA results of the effects of transformation type (C sink, C source and C sink-source transformations), grassland type (temperate and alpine grasslands) and their interaction on SOC change parameters after grassland transformation.

Source	*df*	ΔC		$\Delta C\%$		R_S	
		F	P	F	P	F	P
Transformation type	2	204.116	0.000***	87.285	0.000***	134.703	0.000***
Grassland type	1	32.476	0.000***	32.898	0.000***	26.574	0.000***
Transformation type * Grassland type	2	20.325	0.000***	3.555	0.029*	25.140	0.000***

Note: * correlation is significant at the 0.05 level ($P < 0.05$); *** correlation is significant at the 0.001 level ($P < 0.001$).

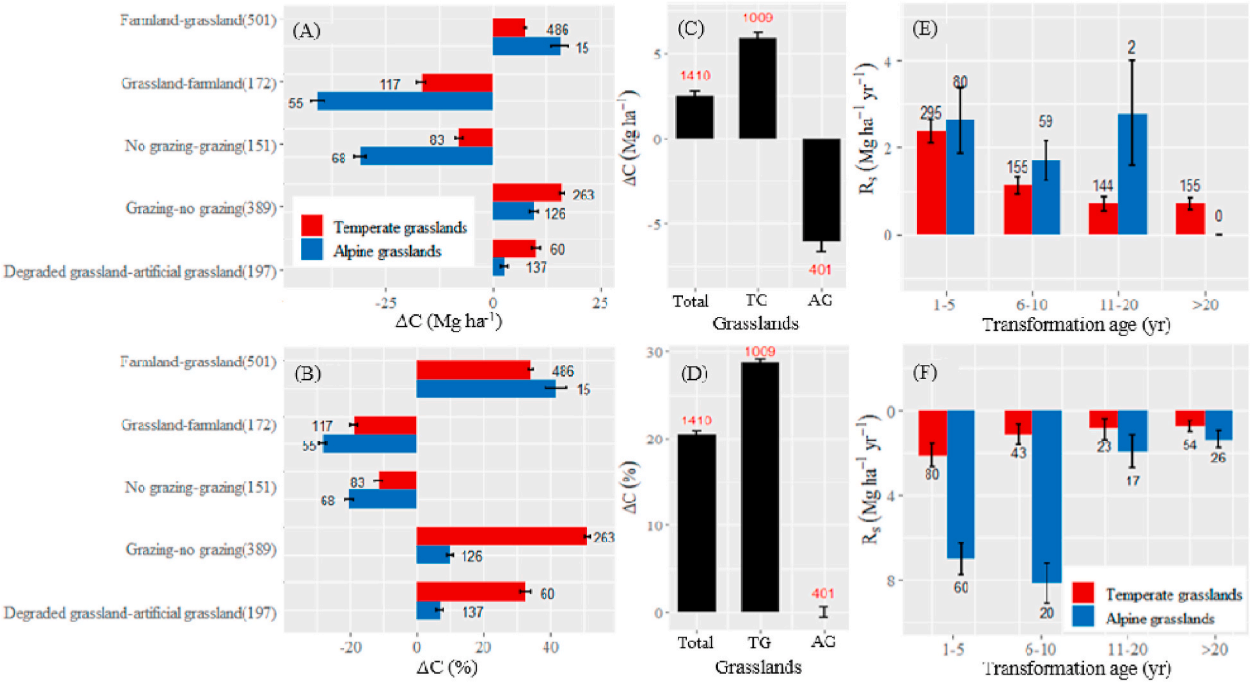

Fig. 2. (A and C), SOC stock changes (ΔC) due to grassland transformation (Mg ha^{-1}); (B and D), percentage of ΔC to initial SOC stocks (%); E, SOC change rates (Rs, Mg ha^{-1} yr^{-1}) in different transformation age groups of C sink transformations; F, SOC change rates (Rs, Mg ha^{-1} yr^{-1}) in different transformation age groups of C source transformations. Bars with error bars indicate mean and 95% confidence intervals. Total, total grasslands; TG, temperate grasslands; AG, alpine grasslands. The values in parentheses and next to the error bars are the corresponding numbers of observations. The five grassland transformations are: grazing to no grazing (grazing exclusion), no grazing to grazing (grassland grazing), grassland to farmland (grassland reclamation), farmland to grassland (returning farmland to grassland), and degraded grassland to artificial grassland (reestablishing artificial grassland or reseeding on degraded grassland).

Table 3
Stepwise regression to detect the driving factors (mean annual temperature (***MAT***), mean annual precipitation (***MAP***), altitude (***AL***), initial SOC stocks (***I***)) determining SOC changes (ΔC) following different grassland transformations. The C sink transformations include grazing to no grazing (grazing exclusion) and farmland to grassland (returning farmland to grassland); and the C source transformations include no grazing to grazing (grassland grazing) and grassland to farmland (grassland reclamation).

Grassland	Transformation type	Equations	R^2	*P*	n
Total	C sink	ΔC = **0.148I**-0.109AL+0.108MAP-0.078MAT+0.343	0.045	0.000***	890
	C source	ΔC = **-0.423I**-0.573	0.241	0.000***	323
Temperate grasslands	C sink	ΔC = **0.236I**-0.099AL+0.461	0.032	0.000***	749
	C source	ΔC = **-0.628I**-0.311AL-0.749	0.379	0.000***	200
Alpine grasslands	C sink	ΔC = 0.413MAP-0.350AL+0.706	0.243	0.000***	141
	C source	ΔC = 0.696AL-0.262I-1.708	0.090	0.004**	123

Note: n indicates the number of observations. ** correlation is significant at the 0.01 level (2-tailed) ($P < 0.01$); *** correlation is significant at the 0.001 level (2-tailed) ($P < 0.001$).

process of alpine grasslands. In fact, the soil carbon of alpine grasslands was difficult to decompose and mostly remains in soils for a long time due to the harsh alpine environment (low temperatures, limited precipitation and low oxygen concentrations at high altitudes) (Hobbie et al., 2000; Ni, 2002; Crowther et al., 2016). In other words, alpine grasslands may accumulate soil C more easily than temperate grasslands when undisturbed. However, once the alpine grassland was disturbed (reclamation and grazing), the SOC loss rate was approximately 3.7–4.8 times the SOC accumulation rate of alpine grassland restoration (grazing exclusion and returning farmland to grassland) within 10 years (Fig. 2E and F). Therefore, we suggest that grassland management decision-makers should pay more attention to the restoration, protection

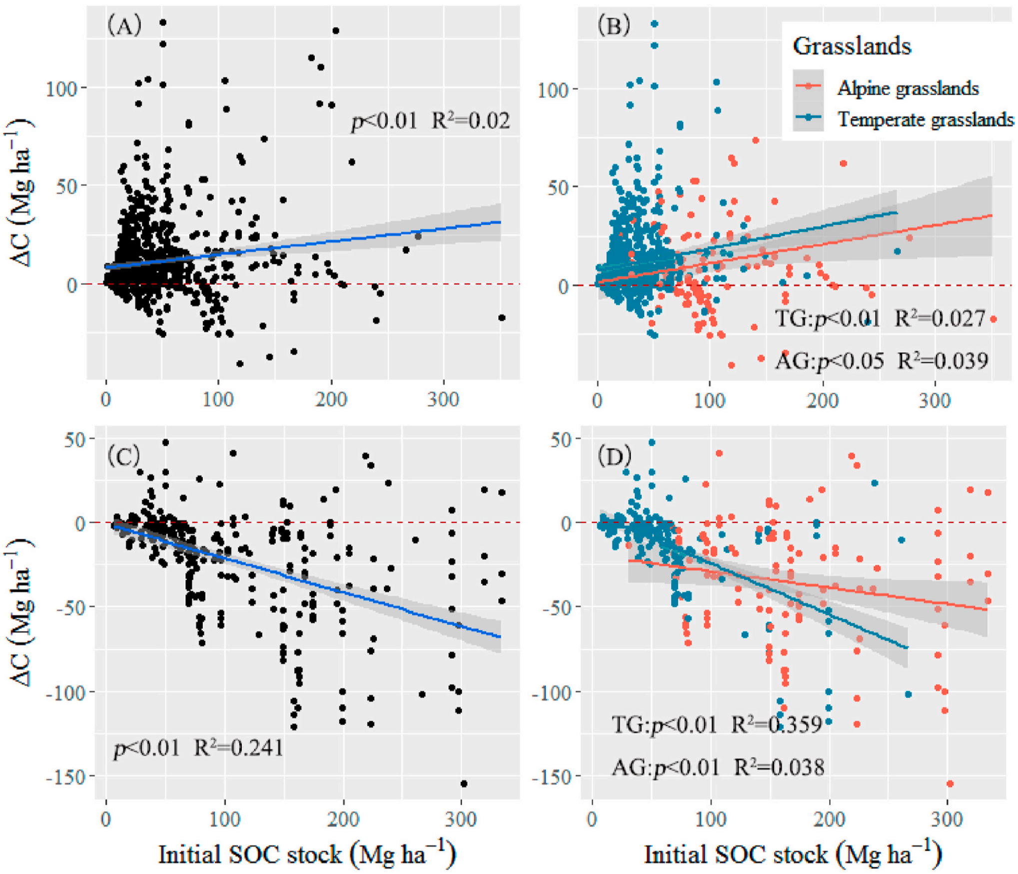

Figure 3. The relationship between ΔC and initial SOC stock (I) in C sink (A and B) and C source (C and D) transformation (A and C: total grassland, B and D: temperate grassland and alpine grassland). TG is temperate grassland and AG is alpine grassland.

and sustainable utilization of alpine grasslands.

It is reported that 30% of the alpine grassland has been degraded and still continuing, which has led to a large loss of soil organic carbon (Liu et al., 2018; Peng et al., 2020). And grazing pressure is one of the main disturbances and threats to grasslands owing to increasing animal feed demand (Niu et al., 2016; Zhou et al., 2017). Numerous studies have shown that grazing intensity significantly affects the response of grassland ecosystem processes to grazing (Stahlheber and D'Antonio, 2013; Zhou et al., 2017). For example, moderate grazing would increase plant species diversity and aboveground biomass, which is conducive to maintaining ecosystem stability (Connell, 1978; Yan et al., 2013; Gong et al., 2014). However, soil carbon and nitrogen were increased by light grazing, but decreased by moderate and heavy grazing (Zhou et al., 2017). Therefore, in view of the fragility and sensitivity of alpine grassland, it is suggested that the grazing intensity of alpine grassland should be controlled within the range of light grazing, which may be more conducive to soil organic carbon sequestration.

The restoration of vegetation can increase soil organic carbon sequestration, and the current restoration measures in alpine grasslands are mainly to establish artificial grasslands on severely degraded grasslands (Dong et al., 2020). However, our results show that this restoration measure presents as a carbon sink in the early stage but as a carbon source in the later stage. In order to avoid becoming a carbon source, the self-recovery of degraded grassland can be promoted by fertilizing, forage clipping and controlling toxic weeds after 3–5 years of the establishment of artificial grassland (Dong et al., 2020; Zhang et al., 2010). Additionally, appropriate grazing is conducive to enhance the stability of vegetation. For example, it was recommended that the grazing intensity of about 10 head/hm^2 yak on the artificial grassland (*Elymus nutans/Puccinellia tenuiflora)* was beneficial to increase vegetation stability (Dong et al., 2020). Compared with natural alpine grassland, the species structure of artificial alpine grassland is relatively simple, and the system stability is relatively low. In view of the close relationship between vegetation and soil organic carbon, therefore, it's very important to explore the stabilization mechanism of artificial alpine grassland and the succession mechanism of its transformation to natural grassland to promote the soil carbon sequestration of alpine grassland.

4.2. *Main driving factors of SOC stock changes*

The initial SOC stock (I) was the strongest factor affecting SOC stock changes (ΔC) during the total and temperate grassland transformation (Table 3). The larger the initial SOC stock, the greater the SOC stocks loss, revealing the vulnerability of soil with large C stocks, which has also been found in other studies (e.g., Bellamy et al., 2005; Goidts and van Wesemael, 2007; Meyer et al., 2017). Similarly, van Straaten et al. (2015) have shown that the key variable to predict SOC changes across plantations was the initial SOC, and the higher the initial SOC, the higher the SOC loss. Because the capacity of soil to store and protect C is limited, and once the limit is exceeded, soil C will reach saturation due to the inability to protect the extra C (Hassink, 1997; Meyer et al., 2017). Meyer et al. (2017) had reported that SOC losses occur especially at sites with large SOC contents but low protection capacity, i.e., at sites which are close to C saturation. According to the concept of C saturation, the higher the soil carbon stock, the closer the soil C is likely to saturation. Although we do not have enough data to prove that the larger the soil carbon storage, the closer the soil C is saturated, it is certain that unreasonable grassland utilization will significantly interfere with vegetation and soil, thereby reducing the ability of soil to protect and store C. Therefore, the degree of soil C saturation is likely to be another cause of the vulnerability of soils with large C. For C sink transformation, the SOC changes of total grasslands affected by initial SOC stock and

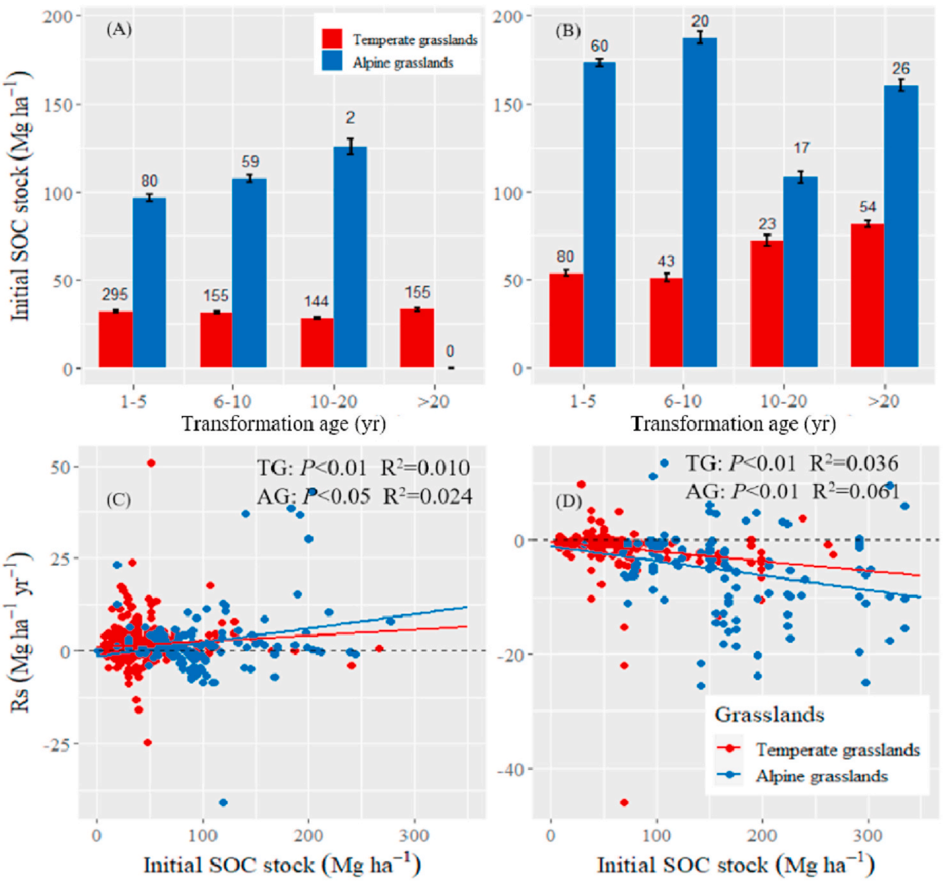

Fig. 4. (A and B), the difference of initial SOC stock (Mg ha^{-1}) between alpine grasslands and temperate grasslands in different transformation age groups (A, in C sink transformation; B, in C source transformation). (C and D), the relationship of SOC change rates (***Rs***, Mg ha^{-1} yr^{-1}) and initial SOC stock (Mg ha^{-1}) (C, in C sink transformation; D, in C source transformation). The dashed line indicates x = 0. TG is temperate grassland and AG is alpine grassland.

environmental factors (*AL*, *MAP* and *MAT*). The results of stepwise regression showed that the initial SOC stock was the main factor for SOC accumulation-the larger the initial SOC stock, the more SOC accumulation. This is probably because soils with larger carbon have a strong ability to store and protect carbon, which has a great relationship with environmental factors. For example, the low temperature in high altitude areas makes the soil difficult to decompose and can be stored for a long time. Ni (2002) has reported that 95% of the carbon of alpine grasslands is stored in soils and accounts for 55.6% of the total carbon storage in China's grassland soils, and the carbon (in both vegetation and soils) of alpine grasslands is about 1.7 times that of temperate grasslands. Additionally, our results showed that the average initial SOC stock of alpine grasslands was about 3 times that of temperate grasslands (Fig. 4A and B).

Moreover, the low-temperature environmental conditions may limit the carbon decomposition and emission in alpine grasslands, but excessive disturbance will destroy the protective effect of low temperature. Crowther et al. (2016) had reported that the high temperature sensitivity of carbon decomposition and the biogeochemical limitations on the processes driving soil C inputs cause the vulnerability of soils with large carbon storage. C source transformation was often accompanied by a decrease in vegetation coverage, which not only promoted surface erosion but also increased surface radiation. The temperature of soil containing large C may rise with the increase of surface radiation, which triggers the high temperature sensitivity of C decomposition, resulting in the rapid decomposition of soil C. These mean that alpine grassland has a high carbon sink potential due to the protection of low temperature (Hobbie et al., 2000; Ni, 2002; Crowther et al., 2016). However, excessive disturbance and climate warming will destroy the protective effect of low temperature, causing greater and faster C loss in alpine grasslands (Qiu, 2008; Yao et al., 2012; Schleuss et al., 2015; Zhang et al., 2015; Crowther et al., 2016). Our findings emphasized the potential and vulnerability of soil carbon sinks in high-altitude areas such as alpine grasslands. Therefore, how to maintain surface low temperature is also important for soil carbon storage capacity during the alpine grassland restoration and reasonable utilization. Especially in the context of climate change, exploring soil carbon protection mechanisms for soils with high carbon content other than low temperature is important for coping with global warming and achieving sustainable grassland development.

4.3. *Uncertainty statement*

Based on the dataset of 325 published articles, this synthesis provides an assessment of SOC changes of temperate and alpine grasslands due to grassland transformations in China. It is undeniable that the analysis methods of these articles are different, and the research results are contradictory. However, it is precisely because of the differences and contradictions of research on a small scale that it is more necessary to integrate these studies for analysis and evaluation to come up with widely applicable conclusions. And the uncertainty caused by the calculation formula used in the integration process, we will state by the following points. Firstly, although changes in SOC stocks between different grassland utilization types should be based on equivalent soil masses rather than on volume (compaction was considered), it was impossible to correct data for all studies because bulk density was not always provided. Therefore, we did not adjust reported data to a common soil mass, but used mass-corrected SOC stocks when the studies provided the necessary information, which only resulted in a slight bias in the estimation of changes in SOC stocks (Guo and Gifford, 2002; Laganiere et al., 2010; Powers et al., 2011). Secondly, we converted original SOC stock data to 0–30 cm depth by using Eqs. (5) and (6), which may introduce potential uncertainties due to the differences in vertical carbon distribution within the soil profile (Deng et al., 2014a). However, both Yang et al. (2011) and Li et al. (2012) concluded that depth correction did not alter the overall pattern of SOC stock dynamics during vegetation development. Thirdly, it should be mentioned that accuracy bias was also introduced by limited availability on bulk density data. Bulk density was estimated by pedotransfer functions using Eqs. (3) and (4) when not provided in the studies. Bulk density would be significantly different among the different sites, land uses and soil types in reality (Deng et al., 2014a). However, Eqs. (3) and (4) were based on the measurement of 784 samples obtained from the National Soil Survey Office, and were frequently used in earlier studies (Wu et al., 2003; Deng et al., 2014a). In addition, we have performed a new analysis on the observations in the database that do not need to be calculated by formulas (3)-(6) (Appendix Figure S1–S4, Table S2–S3), and the main results are basically consistent with the overall database.

5. Conclusion

Our findings indicate that SOC changes were more sensitive in alpine grasslands than in temperate grasslands during grassland transformation, especially in the C loss process. Environmental conditions (such as low temperature) limit the decomposition of C, causing the soils of alpine grasslands to accumulate C more easily than temperate grasslands. However, excessive disturbance will destroy the protective effect of low temperature, causing greater and faster C loss in alpine grasslands with large soil C. Our findings proposed that soils of alpine grasslands in high-altitude areas have a large carbon sink potential but are also vulnerable and more attention should be paid to alpine grasslands relative to temperate grasslands. Meanwhile, how to maintain surface low temperature is also important for soil carbon storage capacity during the alpine grassland restoration and reasonable utilization. In addition, it is also possible to improve soil carbon protection capacity by exploring the soil carbon protection mechanism of high-carbon soils, thereby reducing carbon emissions into the atmosphere. As a way forward, we recommend future plans for the utilization of grassland ecosystem focus on maintaining of the low-temperature habitat and protecting of the existing soil carbon storage in alpine grasslands, and improving soil carbon sink capacity in temperate grasslands, because improving soil carbon sink capacity during sustainable utilization of grassland ecosystem is of great significance for coping with future reducing carbon emission.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2021.127430.

References

Abdalla, M., Hastings, A., Chadwick, D.R., Jones, D.L., Evans, C.D., Jones, M.B., Rees, R. M., Smith, P., 2018. Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Agric. Ecosyst. Environ. 253, 62–81. https://doi.org/10.1016/j.agee.2017.10.023.

Anderson, J.M., 1991. The effects of climate change on decomposition processes in grassland and coniferous forests. Ecol. Appl. 1, 326–347. https://doi.org/10.2307/1941761.

Bellamy, P.H., Loveland, P.J., Bradley, R.I., Lark, R.M., Kirk, G.J.D., 2005. Carbon losses from all soils across England and Wales 1978–2003. Nature 437, 245–248. https://doi.org/10.1038/nature04038.

Chinese Academy of Sciences, 2001. Vegetation Atlas of China. Science Press, Beijing.

Conant, R.T., Paustian, K., Elliott, E.T., 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecol. Appl. 11, 343–355. https://doi.org/10.2307/3060893.

Connell, J.H., 1978. Diversity in tropical rain forests and coral reefs. Science 199, 1302–1310. https://doi.org/10.1126/science.199.4335.1302.

Crowther, T.W., Todd-Brown, K.E.O., Rowe, C.W., Wieder, W.R., Carey, J.C., Machmuller, M.B., Snoek, B.L., Fang, S., Zhou, G., Allison, S.D., Blair, J.M., Bridgham, S.D., Burton, A.J., Carrillo, Y., Reich, P.B., Clark, J.S., Classen, A.T., Dijkstra, F.A., Elberling, B., Emmett, B.A., Estiarte, M., Frey, S.D., Guo, J., Harte, J., Jiang, L., Johnson, B.R., Kroel-Dulay, G., Larsen, K.S., Laudon, H., Lavallee, J.M., Luo, Y., Lupascu, M., Ma, L.N., Marhan, S., Michelsen, A., Mohan, J., Niu, S., Pendall, E., Penuelas, J., Pfeifer-Meister, L., Poll, C., Reinsch, S., Reynolds, L.L., Schmidt, I.K., Sistla, S., Sokol, N.W., Templer, P.H., Treseder, K.K., Welker, J.M., Bradford, M.A., 2016. Quantifying global soil carbon losses in response to warming. Nature 540, 104–108. https://doi.org/10.1038/nature20150.

Deng, L., Liu, G.B., Shangguan, Z.P., 2014a. Land-use conversion and changing soil carbon stocks in China's 'Grain-for-Green' Program: a synthesis. Global Change Biol. 20, 3544–3556. https://doi.org/10.1111/gcb.12508.

Deng, L., Zhang, Z., Shangguan, Z.P., 2014b. Long-term fencing effects on plant diversity and soil properties in China. Soil Till. Res. 137, 7–15. https://doi.org/10.1016/j.still.2013.11.002.

Deng, L., Zhu, G.Y., Tang, Z.S., Shangguan, Z.P., 2016. Global patterns of the effects of land-use changes on soil carbon stocks. Glob. Ecol. Conserv. 5, 127–138. https://doi.org/10.1016/j.gecco.2015.12.004.

Deng, L., Shangguan, Z.P., Wu, G.L., Chang, X.F., 2017. Effects of grazing exclusion on carbon sequestration in China's grassland. Earth Sci. Rev. 173, 84–95. https://doi.org/10.1016/j.earscirev.2017.08.008.

Derner, J.D., Boutton, T.W., Briske, D.D., 2006. Grazing and ecosystem carbon storage in the north American Great Plains. Plant Soil 280, 77–90. https://doi.org/10.1007/s11104-005-2554-3.

Ding, F., Hu, Y.L., Li, L.J., Li, A., Shi, S., Lian, P.Y., Zeng, D.H., 2013. Changes in soil organic carbon and total nitrogen stocks after conversion of meadow to cropland in Northeast China. Plant Soil 373, 659–672. https://doi.org/10.1007/s11104-013-1827-5.

Dong, S.K., Shang, Z.H., Gao, J.X., Boone, R.B., 2020. Enhancing sustainability of grassland ecosystems through ecological restoration and grazing management in an era of climate change on Qinghai-Tibetan Plateau. Agric. Ecosyst. Environ. 287, 106684. https://doi.org/10.1016/j.agee.2019.106684.

Fan, J.W., Zhong, H.P., Harris, W., Yu, G.R., Wang, S.Q., Hu, Z.M., Yue, Y.Z., 2008. Carbon storage in the grasslands of China based on field measurements of above- and belowground biomass. Climatic Change 86, 375–396. https://doi.org/10.1007/s10584-007-9316-6.

Goidts, E., van Wesemael, B., 2007. Regional assessment of soil organic carbon changes under agriculture in southern Belgium (1955–2005). Geoderma 141, 341–354. https://doi.org/10.1016/j.geoderma.2007.06.013.

Gong, J.R., Wang, Y.H., Liu, M., Huang, Y.M., Yan, X., Zhang, Z.Y., Zhang, W., 2014. Effects of land use on soil respiration in the temperate steppe of Inner Mongolia, China. Soil Till. Res. 144, 20–31. https://doi.org/10.1016/j.still.2014.06.002.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biol. 8, 345–360. https://doi.org/10.1046/j.1354-1013.2002.00486.x.

Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant Soil 191, 77–87. https://doi.org/10.1023/A:1004213929699.

Hobbie, S.E., Schimel, J.P., Trumbore, S.E., Randerson, J.R., 2000. Controls over carbon storage and turnover in high-latitude soils. Global Change Biol. 6 (Suppl. 1), 196–210. https://doi.org/10.1046/j.1365-2486.2000.06021.x.

Hu, Z.M., Li, S., Guo, Q., Niu, S., He, N.P., Li, L., Yu, G.R., 2016. A synthesis of the effect of grazing exclusion on carbon dynamics in grasslands in China. Global Change Biol. 22, 1385–1393. https://doi.org/10.1111/gcb.13133.

Huang, L., Xiao, T., Zhao, Z.P., Sun, C.Y., Liu, J.Y., Shao, Q.Q., Fan, J.W., Wang, J.B., 2013. Effects of grassland restoration programs on ecosystems in arid and semiarid China. J. Environ. Manag. 117, 268–275. https://doi.org/10.1016/j.jenvman.2012.12.040.

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E., Schulze, E.D., 1996. A global analysis of root distributions for terrestrial biomes. Oecologia 108, 389–411. https://doi.org/10.1007/bf00333714.

Jiang, Z.Y., Hu, Z.M., Lai, Derrick Y.F., Han, D.R., Wang, M., Liu, M., Zhang, M., Guo, M. Y., 2020. Light grazing facilitates carbon accumulation in subsoil in Chinese grasslands: a meta-analysis. Global Change Biol. https://doi.org/10.1111/gcb.15326.

Jobbagy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10, 423–436. https://doi.org/10.2307/2641104.

Koga, N., Shimoda, S., Shirato, Y., Kusaba, T., Shima, T., Niimi, H., Yamane, T., Wakabayashi, K., Niwa, K., Kohyama, K., Obara, H., Takata, Y., Kanda, T., Inoue, H., Ishizuka, S., Kaneko, S., Tsuruta, K., Hashimoto, S., Shinomiya, Y., Aizawa, S., Ito, E., Hashimoto, T., Morishita, T., Noguchi, K., Ono, K., Katayanagi, N., Atsumi, K., 2020. Assessing changes in soil carbon stocks after land use conversion from forest land to agricultural land in Japan. Geoderma 377, 114487. https://doi.org/10.1016/j.geoderma.2020.114487.

Laganiere, J., Angers, D.A., Pare, D., 2010. Carbon accumulation in agricultural soils after afforestation: a meta-analysis. Global Change Biol. 16, 439–453. https://doi.org/10.1111/j.1365-2486.2009.01930.x.

Liu, S.B., Schleuss, P.M., Kuzyakov, Y., 2018. Responses of degraded Tibetan *Kobresia* pastures to N addition. Land Degrad. Dev. 29 (2), 303–314. https://doi.org/10.1002/ldr.2720.

Li, D., Niu, S., Luo, Y., 2012. Global patterns of the dynamics of soil carbon and nitrogen stocks following afforestation: a meta-analysis. New Phytol. 195, 172–181. https://doi.org/10.1111/j.1469-8137.2012.04150.x.

Li, B.B., Li, P.P., Yang, X.M., Xiao, H.B., Xu, X.M., Liu, G.B., 2020. Land-use conversion changes deep soil organic carbon stock in the Chinese Loess Plateau. Land Degrad. Dev. https://doi.org/10.1002/ldr.3644.

Luo, Y.Q., Field, C.B., Jackson, R.B., 2006. Does nitrogen constrain carbon cycling, or does carbon input stimulate nitrogen cycling? Ecology 87, 3–4. https://doi.org/10.1890/05-0923.

Luo, Z., Viscarra Rossel, R.A., Shi, Z., 2020. Distinct controls over the temporal dynamics of soil carbon fractions after land use change. Global Change Biol. 26, 4614–4625. https://doi.org/10.1111/gcb.15157.

Mann, L.K., 1986. Changes in soil carbon storage after cultivation. Soil Sci. 142, 279–288. https://doi.org/10.3334/CDIAC/tcm.007.

Meyer, N., Bornemann, L., Welp, G., Schiedung, H., Herbst, M., Amelung, W., 2017. Carbon saturation drives spatial patterns of soil organic matter losses under long-term bare fallow. Geoderma 306, 89–98. https://doi.org/10.1016/j.geoderma.2017.07.004.

Ni, J., 2002. Carbon storage in grasslands of China. J. Arid Environ. 50, 205–218. https://doi.org/10.1006/jare.2001.0902.

Niu, K.C., He, J.S., Lechowicz, M.J., 2016. Grazing-induced shifts in community functional composition and soil nutrient availability in Tibetan alpine meadows. J. Appl. Ecol. 53 (5), 1554–1564. https://doi.org/10.1111/1365-2664.12727.

Peng, F., Xue, X., You, Q.G., Sun, J., Zhou, J., Wang, T., Tsunekawa, A., 2020. Change in the trade-off between aboveground and belowground biomass of alpine grassland: implications for the land degradation process. Land Degrad. Dev. 31 (1), 105–117. https://doi.org/10.1002/ldr.3432.

Piao, S.L., Fang, J.Y., Ciais, P., Peylin, P., Huang, Y., Sitch, S., Wang, T., 2009. The carbon balance of terrestrial ecosystems in China. Nature 458, 1009–1014. https://doi.org/10.1038/nature07944.

Powers, J.S., Corre, M.D., Twine, T.E., Veldkamp, E., 2011. Geographic bias of field observations of soil carbon stocks with tropical land-use changes precludes spatial extrapolation. Proc. Natl. Acad. Sci. U.S.A. 108 (15), 6318–6322. https://doi.org/10.1073/pnas.1016774108.

Qiu, J., 2008. The third pole. Nature 454, 393–396. https://doi.org/10.1038/454393a.

Ren, H., Shen, W.J., Lu, H.F., Wen, X.Y., Jian, S.G., 2007. Degraded ecosystems in China: status, causes, and restoration efforts. Landsc. Ecol. Eng. 3, 1–13. https://doi.org/10.1007/s11355-006-0018-4.

Schlesinger, W.H., Bernhardt, E.S., 2013. In: Biogeochemistry: an Analysis of Global Change, third ed. https://doi.org/10.1093/obo/9780199830060-0111

Schleuss, P.M., Heitkamp, F., Sun, Y., Miehe, G., Xu, X., Kuzyakov, Y., 2015. Nitrogen uptake in an alpine Kobresia pasture on the Tibetan Plateau: localization by N-15 labeling and implications for a vulnerable ecosystem. Ecosystems 18, 946–957. https://doi.org/10.1007/s10021-015-9874-9.

Scurlock, J.M.O., Hall, D.O., 1998. The global carbon sink: a grassland perspective. Global Change Biol. 4, 229–233. https://doi.org/10.1046/j.1365-2486.1998.00151.x.

Scurlock, J.M.O., Johnson, K., Olson, R.J., 2002. Estimating net primary productivity from grassland biomass dynamics measurements. Global Change Biol. 8, 736–753. https://doi.org/10.1046/j.1365-2486.2002.00512.x.

Shi, S., Zhang, W., Zhang, P., Yu, Y., Ding, F., 2013. A synthesis of change in deep soil organic carbon stores with afforestation of agricultural soils. For. Ecol. Manag. 296, 53–63. https://doi.org/10.1016/j.foreco.2013.01.026.

Stahlheber, K.A., D'Antonio, C.M., 2013. Using livestock to manage plant composition: a meta-analysis of grazing in California Mediterranean grasslands. Biol. Conserv. 157, 300–308. https://doi.org/10.1016/j.biocon.2012.09.008.

Song, X.D., Yang, F., Ju, B., Li, D.C., Zhao, Y.G., Yang, J.L., Zhang, G.L., 2018. The influence of the conversion of grassland to cropland on changes in soil organic carbon and total nitrogen stocks in the Songnen plain of northeast China. Catena 171, 588–601. https://doi.org/10.1016/j.catena.2018.07.045.

Tang, S.M., Guo, J.X., Li, S.C., Li, J.H., Xie, S., Zhai, X.J., Wang, C.J., Zhang, Y.J., Wang, K., 2019. Synthesis of soil carbon losses in response to conversion of grassland to agriculture land. Soil Till. Res. 185, 29–35. https://doi.org/10.1016/j.still.2018.08.011.

Tarhouni, M., Ben Hmida, W., Neffati, M., 2017. Long-term changes in plant life forms as a consequence of grazing exclusion under arid climatic conditions. Land Degrad. Dev. 28, 1199–1211. https://doi.org/10.1002/ldr.2407.

van Straaten, O., Corre, M.D., Wolf, K., Tchienkoua, M., Cuellar, E., Matthews, R.B., Veldkamp, E., 2015. Conversion of lowland tropical forests to tree cash crop plantations loses up to one-half of stored soil organic carbon. Proc. Natl. Acad. Sci. U.S.A. 112, 9956–9960. https://doi.org/10.1073/pnas.1504628112.

Wang, L., Wiesmeier, M., Zhang, R., Hou, F., Han, G., Gan, Y., Siddique, K.H.M., 2018. Grazing exclusion – a natural approach for restoring degraded grasslands in northern China. Land Degrad. Dev. 29, 4439–4456. https://doi.org/10.1002/ldr.3191.

Wang, S., Wilkes, A., Zhang, Z., Chang, X.F., Lang, R., Wang, Y., Niu, H.S., 2011. Management and land use change effects on soil carbon in northern China's grasslands: a synthesis. Agric. Ecosyst. Environ. 142, 329–340. https://doi.org/10.1016/j.agee.2011.06.002.

Wang, W., Fang, J.Y., 2009. Soil respiration and human effects on global grasslands. Global Planet. Change 67, 20–28. https://doi.org/10.1016/j.gloplacha.2008.12.011.

Wang, X., McConkey, B.G., VandenBygaart, A.J., Fan, J., Iwaasa, A., Schellenberg, M., 2016. Grazing improves C and N cycling in the northern great plains: a meta-analysis. Sci. Rep. 6, 33190. https://doi.org/10.1038/srep33190.

Wei, X.R., Shao, M.A., Gale, W., Li, L., 2014. Global pattern of soil carbon losses due to the conversion of forests to agricultural land. Sci. Rep. 4, 4062. https://doi.org/10.1038/srep04062.

Wu, H.B., Guo, Z.T., Peng, C.H., 2003. Land use induced changes of organic carbon storage in soils of China. Global Change Biol. 9, 305–315. https://doi.org/10.1046/j.1365-2486.2003.00590.x.

Xie, Z.B., Zhu, J.G., Liu, G., Cadisch, G., Hasegawa, T., Chen, C.M., Sun, H.F., Tang, H.Y., Zeng, Q., 2007. Soil organic carbon stocks in China and changes from 1980s to 2000s. Global Change Biol. 13, 1989–2007. https://doi.org/10.1111/j.1365-2486.2007.01409.x.

Xiong, D., Shi, P., Zhang, X., Zou, C.B., 2016. Effects of grazing exclusion on carbon sequestration and plant diversity in grasslands of China—a meta-analysis. Ecol. Eng. 94, 647–655. https://doi.org/10.1016/j.ecoleng.2016.06.124.

Yang, Y., Luo, Y., Finzi, A.C., 2011. Carbon and nitrogen dynamics during forest stand development: a global synthesis. New Phytol. 190, 977–989. https://doi.org/10.1111/j.1469-8137.2011.03645.x.

Yan, L., Zhou, G.S., Zhang, F., 2013. Effects of different grazing intensities on grassland production in China: a meta-analysis. PLoS One 8, e81466. https://doi.org/10.1371/journal.pone.0081466.

Yao, T.D., Thompson, L.G., Mosbrugger, V., Zhang, F., Ma, Y.M., Luo, T.X., Xu, B.Q., Yang, X.X., Joswiak, D.R., Wang, W.C., Joswiak, M.E., Devkota, L.P., Tayal, S., Jilani, R., Fayziev, R., 2012. Third pole environment (TPE). Environ. Dev. 3, 52–64. https://doi.org/10.1016/j.envdev.2012.04.002.

Zhang, K., Dang, H., Tan, S., Cheng, X., Zhang, Q., 2010. Change in soil organic carbon following the 'Grain-for-Green' programme in China. Land Degrad. Dev. 21, 13–23. https://doi.org/10.1002/ldr.954.

Zhang, X.L., Wang, S.J., Zhang, J.M., Wang, G., Tang, X.Y., 2015. Temporal and spatial variability in precipitation trends in the southeast Tibetan Plateau during 1961–2012. Clim. Past Discuss 11, 447–487. https://doi.org/10.5194/cpd-11-447-2015.

Zhao, H.L., Zhao, X.Y., Zhao, R.L., Zhang, T.H., Drake, S., 2005. Desertification processes due to heavy grazing in sandy rangeland, Inner Mongolia. J. Arid Environ. 62, 309–319. https://doi.org/10.1016/j.jaridenv.2004.11.009.

Zhou, G.Y., Zhou, X.H., He, Y.H., Shao, J.J., Hu, Z.H., Liu, R.Q., Zhou, H.M., Hosseinibai, S., 2017. Grazing intensity significantly affects belowground carbon and nitrogen cycling in grassland ecosystems: a meta-analysis. Global Change Biol. 23, 1167–1179. https://doi.org/10.1111/gcb.13431.

Zhou, H., Zhao, X., Tang, Y., Gu, S., Zhou, L., 2005. Alpine grassland degradation and its control in the source region of the Yangtze and Yellow Rivers, China. Grassl. Sci. 51, 191–203. https://doi.org/10.1111/j.1744-697X.2005.00028.x.

Zhou, Y., Hartemink, A.E., Shi, Z., Liang, Z., Lu, Y., 2019. Land use and climate change effects on soil organic carbon in North and Northeast China. Sci. Total Environ. 647, 1230–1238. https://doi.org/10.1016/j.scitotenv.2018.08.016.