Significant soil acidification caused by grazing exclusion across China's grasslands

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Abstract

Soil pH is strongly associated with soil biogeochemical cycles and biodiversity in terrestrial ecosystems. GE has been widely adopted as an effective practice to restore degraded grasslands. However, the effect of GE on soil pH is still poorly understood and remains inconclusive. We synthesized data from 63 sites in the literature and 43 additional field sites and investigated the dynamics of soil pH following GE across China's grasslands. Mean pH decreased 0.13 units with GE (mean pH was 8.15 and 8.02 for grazed and GE groups, respectively, $p < 0.001$). The pH of surface soil (0–20 cm) showed greatest decrease rates in GE grasslands, whereas that of deep soil (20–100 cm) had limited responses to GE. In general, the largest decrease in the rates of soil pH occurred after medium-term periods (5–15 years) of GE, whereas a smaller rate of change was found over short- ([?]5 years) and long-term periods ([?]15 years) of GE. Of the factors examined, the rate of soil pH change was negatively correlated to MAP, but had no significant relationship with MAT. The rate of soil pH change decreased linearly with RCC, RNC, RAC and RBC. Sedge-dominated grassland had higher pH decrease rates at 0–10 cm soil depth than grass-dominated grassland, whereas grassland dominated by forbs and shrub species showed the highest decrease in pH at 20–30 cm. Our results indicate that GE causes significant soil acidification, especially in surface soil and humid areas, which provides an important reference for future management of China's grasslands.

The meaning of the abbreviations

GE: grazing exclusion

SOC: soil organic carbon

SOM: soil organic matter

SN: soil nitrogen

MAT: mean annual temperature

MAP: mean annual precipitation

AB: aboveground biomass

AB: belowground biomass

RPC: the rates of soil pH change

RCC: the rates of soil organic carbon change

RNC: the rates of soil nitrogen change

RAC: the rates of aboveground biomass change

RBC: the rates of belowground biomass change

1 Introduction

Soil acidity or alkalinity, described by soil pH, is strongly associated with soil biogeochemical cycles and biodiversity in terrestrial ecosystems. Controlled experiments and field monitoring have revealed that changes in soil pH have strong effects on organic matter accumulation (Evans *et al.* , 2012), microbial activity (Lauber *et al.* , 2009; Li *et al.* , 2017) and greenhouse gas emissions (Wu *et al.* , 2018). In addition, soil acidification has cascading effects on structures and functions of land ecosystems (Hong *et al.* , 2018). In particular, decrease in pH is a major threat to species diversity both at the regional and continental scale with increasing nitrogen deposition (Azevedo *et al.* , 2013). Further soil acidification could result in a large amount of cation nutrient loss (Haynes & Swift, 1986), intensifying the nutrient limitation for plant growth (Weaver & Hamill, 1985), reproduction (Roem *et al.* , 2002; Basto *et al.* , 2015) and productivity (Kallenbach *et al.* , 1996). Accordingly, the changes of soil pH need to be systematically evaluated under anthropogenic changes (Berthrong *et al.* , 2009; Kirk *et al.* , 2010; Riofrío-Dillon *et al.* , 2012; Hong*et al.* , 2018).

GE is considered to be an effective revegetation practice for overgrazed grasslands. Previous studies have mainly focused on restoring the degraded grassland through its self-healing capacities as well as to promoting carbon sequestration (Pineiro *et al.* , 2009; Wu *et al.* , 2010; Hu *et al.* , 2016; Deng *et al.* , 2017). However, despite the importance of GE in vegetation recovery and soil nutrient accumulation, the effects of GE on soil pH has received less attention and considerable uncertainty remains. For example, previous *in situ* studies have found mixed results of GE effects on soil pH, with studies showing negative (Wu *et al.* , 2009; Raiesi & Riahi, 2014), neutral (Shang *et al.* , 2017; Sigcha *et al.* , 2018) or positive (Cheng *et al.* , 2016) effects of GE. Because of this lack of consensus on the effects of GE on soil pH dynamics, there is little knowledge about the trajectory of soil pH dynamics along the age gradient of GE. In addition, most individual studies have focused on comparison of soil pH between the GE and the grazing plots. Therefore, limited knowledge about the effects of GE on soil pH under different climatic conditions restricts our ability to explore the effects of possible anthropogenic changes on soil biogeochemical processes on a broader scale.

Grasslands are an important part of the Eurasian steppe and cover approximately 40% of the total territorial area of China (Wang *et al.* , 2018). Because of the intense grazing pressure, a markedly increasing percentage of grasslands is displaying degradation across China. The Chinese government has invested heavily to restore degraded grasslands over the past several decades. For example, the 'Returning Grazing Land to Grassland' project was implemented to protect grasslands through GE from heavy grazing pressures (Xiong *et al.* , 2016). Through compilation of published data in addition to field samples from grasslands in China, this study aimed to examine the dynamics of soil pH during the ecosystem recovery processes following GE. Our specific objectives were to: 1) explore the effects of GE on soil pH dynamics, and 2) identify factors influencing the effects of GE on soil pH changes. Understanding the soil pH dynamics resulting from GE is crucial for developing control measures to maintain soil quality and enhance the stability of terrestrial ecosystems.

2 Materials and methods

2.1 Field sampling

In August 2018, we sampled the soils of 43 grasslands including both grazed and GE sites in 20 counties of the Tibet Autonomous Region on the Tibetan Plateau. The sites were grazed by yak and sheep and fences were constructed for GE in degraded pastures, with a duration of GE of less than five years. As a result of the local government's grassland management policy, five years is the maximum GE period for most grasslands in Tibet. The grazed and GE sample plots were selected randomly within 200 m of each other. Thus, all the sample plots had similar climate conditions and parent materials in each site. The geographic location of each site was recorded by a Global Positioning System (GPS, Garmin MAP62CSX, USA). Vegetation types in the sampling regions are dominated by alpine meadow, alpine steppe and alpine desert steppe from semi-humid to arid climate conditions, which covers the major grassland types in Tibet (Fig. 1). The dominant species were recorded in each site. Major soil types are Humic Cambisol for the alpine meadow, Haplic Xerosols for the alpine steppe and alpine desert steppe according to the World Reference Base for Soil Resources (Lu*et al.* , 2004).

At each site, three to five 0.5 m x 0.5 m sampling subplots were located along a random sampling transect at 10 m intervals within each of the grazed and GE plots. On the plateau, since >80% of the roots grow in the top 30 cm of soil (Li *et al.* , 2011), GE-induced changes in soil microbial and root growth processes mainly occur in this horizon and thus the soil was sampled to a depth of 30 cm. Within each subplot, soil samples were collected at fixed intervals of 0–10, 10–20 and 20–30 cm soil depth using a spade. All soil samples were air-dried to constant weight, and handpicked to remove gravel and roots, then sieved through a 2-mm mesh. The air-dried soil was divided into three subsamples for analysing soil pH, SOC and SN concentrations. The soil pH was measured with a glass electrode using a 1:2.5 mixtures of soil and deionized water. SOC concentrations were determined using the wet oxidation method (Nelson & Sommers, 1996). The SN concentrations were analysed using the micro-Kjeldahl digestion method (Coombs *et al.* , 1985). We used the mean value of all replications in each grazed and GE plot at the 43 sites for further analysis.

Meteorological data used in this study were collected from the Meteorology Information Center of the Chinese National Bureau of Meteorology, which included MAT and MAP collected from 268 meteorological observatories during 1981–2010. In addition, the Kriging interpolation method was used to show spatial distribution patterns. For all 43 field sample sites, the MAT ranged from -0.34 to 4.82degC, and MAP ranged from 75.94 to 470.75 mm (supplementary dataset).

2.2 Data compilation

We collected site information and soil data from peer-reviewed literature. Literature searches were performed using the Web of Science, Google Scholar and China National Knowledge Infrastructure with key words relating to grazing exclosure/fencing/exclusion, soil pH, Inner Mongolia, Xinjiang, Qinghai–Tibetan Plateau, temperate grassland/meadow/typical steppe/desert steppe and alpine grassland/meadow/steppe/desert steppe. We selected the papers according to the following criteria: 1) the soil samples and pH data had accurate soil depth; 2) the soil pH value were determined from both GE and free grazing sites, and had to have similar climate and soil conditions; 3) an accurate period of GE had to be recorded; 4) the studies could employ paired sites, chronosequence or retrospective design to analyse the change of soil pH; 5) other interference factors needed to be excluded, such as fertilization and seeding; 6) only field manipulation studies were selected, and model simulation data were not included. If there were several sampling dates in one year, only the growth season (July–August) data were selected because the biomass at this time reaches the maximum for a year and is consistent with most of the previous research. The site information (e.g., location, longitude, latitude, MAP, MAT, dominant species, duration of GE, soil data (e.g., soil sampling depth, pH, SOC and SN concentrations) and biomass (AB and BB) were extracted from the grazed and GE plots. If the exact MAP and MAT data were not available, we extracted the climate data by using the method described above for the field sampling according to their geographical locations. The conversion factor of SOM to SOC is 1.724 (Pribyl, 2010). All data were extracted from tables or figures. Summary information for each site is available in supplementary dataset. The dataset included 63 study sites from 10 provinces (the Xinjiang Uygur Autonomous Region, the Inner Mongolia Autonomous Region, the Ningxia Hui Autonomous Region, the Tibet Autonomous Region, Shaanxi province, Sichuan province, Gansu province, Qinghai province, Shanxi province and Jilin province) reported by 46 peer-reviewed papers published between 2004 and 2019, which together include most of the area of the China's 'Returning Grazing Land to Grassland' project (supplementary dataset).

2.3 Data calculation and analysis

In total, we combined 106 sites both from literature and field sampling ranging from large temperature and precipitation gradients covering the main grassland types in China. We divided the soil layer into four groups, 0–10, 10–20, 20–30 and 30–100 cm. Most root biomass was located in the surface soil (0–10 cm), then decreased along the soil profile (10–20 and 20–30 cm), while only a little root biomass was in the deep soil (30–100 cm). In addition, the soil data from most documents were also collected according to these soil layers. The soil samples belonged to six vegetation types (temperate meadow, temperate typical steppe, temperate desert steppe, alpine meadow, alpine steppe and alpine desert steppe) according to the dominant species, temperature and moisture conditions. According to the duration of GE, we divided all the sites into short- ([?]5 years), medium- (5–15 years) and long-term ([?]15 years) periods. The RPC following GE were calculated with the following formula: RPC (%) = (soil $\mathrm{pH}_{\mathrm{GE}}$ - soil $\mathrm{pH}_{\mathrm{grazing}}$)/soil $\mathrm{pH}_{\mathrm{grazing}}$ x 100%. The rates of RCC, RNC, RAC and RBC changes following GE were calculated by using a similar formula to that of RPC.

We determined the differences in soil pH between grazed and GE grasslands for all samples and in each soil layer using paired$t$ -test. Differences in RPC between soil layers, durations of GE and dominant species were analysed by one-way ANOVA and LSD tests. The relationships of RPC to MAP, MAT, RCC, RNC, RAC and RBC were determined by Pearson correlation analysis.

3 Results

3.1 The effect of GE on soil pH

Most soil pH both in the grazed and GE grasslands was above 7 across China's grasslands (Fig. 2a, b). The soil pH grazing and GE grasslands showed a significant positive correlation for all soil samples ($p< 0.001$) (Fig. S1). Among the 376 samples after GE, 248, 5 and 123 observations showed a decrease, neutral and increase in soil pH, respectively, along the whole soil layer relative to grazed grasslands (Fig. 2c).

On average, the changes of soil pH across the 376 grazed-GE paired samples were significant (Fig. 3a; mean pH was 8.15 and 8.02 for the grazed group and the GE group, respectively, $p < 0.001$). Among the 122 observations after GE, 86, 4 and 32 observations showed a decrease, neutral and increase, respectively, in soil pH in the 0–10 cm soil layer (supplementary dataset). Among the 91 observations after GE, 60 and 31 observations showed a decrease and increase in the 10–20 cm soil layer, respectively (supplementary dataset). The pH of the 0–10 and 10–20 cm layers decreased by 0.18 ($p < 0.001$) and 0.13 ($p < 0.01$) after GE, respectively (Fig. 3b). The RPC of 0–10 and 10–20 cm was -2.28% and -1.52%, respectively (Fig. 3c). Moreover, 42 of 72 and 16 of 27 observations showed a decrease in soil pH for the 20–30 and 30–100 cm soil layers, respectively (supplementary dataset). However, paired t -test showed that there were no significant differences in soil pH for the deeper soil layers (20–30 and 30–100 cm) between grazed and GE grasslands ($p> 0.05$) (Fig. 3b). The RPC of 20–30 and 30–100 cm was -0.50% and -0.21%, respectively (Fig. 3c).

Short- ([?]5 years) and medium-term (5–15 years) GE caused a significant decrease in soil pH for GE grasslands ($p < 0.001$) (Fig. 4a). Long-term ([?]15 years) GE had no significant influence on soil pH dynamics (Fig. 4a). The RPC of short- ([?]5 years), medium- (5–15 years) and long-term ([?]15 years) periods was -1.08%, -3.23% and -0.16%, respectively (Fig. 4b). The RPC of medium-term (5–15 years) GE resulted in the lowest RPC along the age gradients of GE ($p < 0.05$) (Fig. 4b).

3.2 Factors influencing the effects of GE on soil pH changes

The MAT and MAP had significant influences on soil pH both in grazed and GE grasslands at a large geographic scale ($p < 0.001$) (Fig. S2a–d). The RPC was significantly negatively related to MAP (r = -0.18, $p < 0.001$), but had no significant relationship with MAT ($p > 0.05$) across China's grasslands (Fig. 5a, b). GE caused significant increases in AB and BB across China's grasslands ($p < 0.01$) (Fig. S3a, b). Significant negative relationships were identified between RAC and RBC and RPC (RAC–RPC r = -0.25, $p < 0.05$; RBC–RPCr = -0.39, $p < 0.01$) (Fig. 5c, d). GE caused significant increases in SOC and SN concentrations in grassland ecosystems ($p < 0.05$) (Fig. S3c, d). Both the RCC and RNC were negatively related with RPC (RCC–RPC r = 0.37, $p< 0.001$; RNC–RPC r = 0.28, $p < 0.001$) (Fig. 5e, f). In addition, strong negative relationships of RCC–RPC and RNC–RPC were observed in the upper soil layers ($p < 0.05$) (Fig. S4a), but not in the deeper soil layers ($p> 0.05$) (Fig. S4b).

Dominant species significantly affected the RPC in grasslands following GE (Table 1). Sedge-dominated grassland had higher pH decrease rates at 0–10 cm soil depth than grass-dominated grassland ($p < 0.05$), whereas grassland dominated by forbs and shrub species showed the highest decrease in pH at 20–30 cm (-6.39%) ($p < 0.05$) (Table 1) .

4 Discussion

This study is a combined analysis using data both from field sampling and literature to explore effects of GE on soil pH dynamics across China's grasslands. Significant soil acidification caused by GE was found in grassland ecosystems. Surface soil showed greater soil acidification rates than those of subsoil layers in GE grasslands. The largest decrease of pH was in the medium-term period (5–15 years) following GE. MAP, RAC, RBC, RCC, RNC and dominant species were identified as important factors controlling the response of soil pH dynamics to GE.

4.1 Change in of soil pH following GE

Mixed results regarding the effects of GE on soil pH have been found in previous studies, with negative (Wu *et al.* , 2009; Raiesi & Riahi, 2014), neutral (Shang *et al.* , 2017; Sigcha *et al.* , 2018) or positive (Cheng *et al.* , 2016) effects. In our study, we found soil pH decreased with GE at most grassland sites across China. This result is consistent with other studies on grasslands of the world (Anderson *et al.* , 2008; Raiesi & Riahi, 2014). GE could lead to soil pH acidification by altering the balance between soil hydrogen ion generation and consumption during the nutrient cycle. GE-induced changes in litter decomposition and rhizospheric processes may play a major role in soil pH dynamics. Firstly, organic matter inputs from aboveground biomass, litter biomass, and root biomass all increased because of the removal of grazing pressure and the amelioration of soil water content (Hu *et al.* , 2016; Xiong *et al.* , 2016; Deng *et al.* , 2017). The addition of plant residues can decrease soil pH through N nitrification in the residue (Binkley & Richter, 1987; Rukshana*et al.* , 2014). Secondly, root exudates (e.g., H^+, OH^- and HCO_3^-) can modify rhizospheric pH to enhance nutrient uptake by plant roots (Dakora & Phillips, 2002). Plants take up more cations than anions in calcareous grassland soils, which reduces the rhizospheric pH as they release $H^+$from their roots to maintain charge balance (Dakora & Phillips, 2002). Thus, the decrease of effective cation exchange capacity in soil and the depletion of soil exchangeable base ions (e.g., calcium ions) accelerate the acidification of grassland soil. Thirdly, higher root biomass was observed in GE grasslands. Consequently, root respiration in the GE grasslands could be expected to exhibit an increasing trend and subsequently the increase in H^+ion inputs from carbonic acid could lead to lower soil pH (Ji *et al.* , 2014).

Overall, surface soil showed greater soil acidification rates than deep soil. The soil pH decreased by 0.18 and 0.13 at 0–10 and 10–20 cm soil depth for China's grassland, respectively. However, GE had limited impacts on soil pH dynamics for 20–30 cm and 30–100 cm soil layers. The vertical differentiations of RPC may arise from the plant–soil biological processes, such as litter decomposition, root distribution, rhizospheric processes and microbe activities, are mainly concentrated in topsoil, not in the deep soil. This result is consistent with those of Talore *et al.* (2015), which showed that soil pH was decreased by 0.27 in the top 10 cm following long-term GE in South Africa. Conversely, the pH of deeper soils in GE grasslands increased slightly or remained unchanged.

The largest decrease of soil pH was in the medium-term period after GE. The trends were inconsistent with AB and BB dynamics following GE because the highest biomass accumulation occurred after a short period of GE ([?]5 years) (Hu *et al.* , 2016; Deng *et al.* , 2017), whereas the strongest soil acidification occurred after a medium-term period of GE (5–15 years). The changes in soil pH lag behind changes in vegetation biomass variation. This could be because the decomposition of plant litter takes a certain period of time (Parton *et al.* , 2007), which in turn affects soil microbial activity, N transformation and the proportion of cations and organic anions. GE leads to a limited effect on the decrease of RPC in long-term period ([?]15 years). This result is consistent with the 'dynamic disequilibrium' theory, which states that GE leads to temporal changes in many biogeochemical cycles (e.g., vegetation biomass and soil C and N accumulation) in the short term, but does not affect long-term dynamics (Luo & Weng, 2011). To our knowledge, this is the first study that simultaneously quantifies the large-scale reduction of soil pH in medium-term GE grasslands. Based on this information relating to the relation between the length of GE and soil pH dynamics, the potential soil acidity for GE in grassland ecosystems can be evaluated, which has important implications for soil biogeochemical processes and predicting ecosystem structure and functions in grasslands.

4.2 Factors affecting soil pH

Climate may affect soil pH through physicochemical and biological processes associated with water permeability and leaching processes, productivity of vegetation and decomposition of organic matter, and soil buffering capacity in GE grasslands. This study showed significant negative RPC correlations with the MAP, but there were no significant correlations between RPC and MAT. This indicates that GE can cause soil acidification under wetter climatic conditions and soil pH dynamics are mainly determined by MAP rather than the MAT in China's grasslands. The decrease in RPC responses to GE with MAP may be attributed to the following causes. Firstly, GE decreased soil bulk density and increased the porosity, which can increase the soil water permeability coefficient and leaching effect, thereby resulting in the dissolution of carbonates and larger loss of base cations and nitrate in humid grasslands (Brady & Weil, 2008). Furthermore, increased rainfall may introduce a large amount of acidic substances into the GE soil, such as nitrogenous compounds in humid regions (Guo *et al.* , 2010). Secondly, Hu*et al.* (2016) and Deng *et al.* (2017) found that grassland restoration projects could be more beneficial for biomass accumulation in humid regions. Those stronger biological responses would result in a greater decrease in soil pH by altering litter decomposition, and root exudates and respiration. Thirdly, under humid climate conditions, most soil pH was below 7.0 and such a neutral or slightly acidic environment are not suited to the accumulation of soil carbonates (Yang *et al.* , 2010; Yang *et al.* , 2012). The low amount of carbonates stored in wetter grassland ecosystems may in turn provide a weak buffering capacity for increases in soil acidity (Kirk *et al.* , 2010).

Variations of SOC and SN concentrations were the main factors influencing RPC following GE. The RCC was negatively correlated with RPC, which indicated faster accumulation of SOM leading to lower pH values. This was mainly because the composition of H^+ and Al^{3+} adsorbed to SOM is dependent on various processes such as humification of SOM and microbial decomposition, physical incorporation of SOM and chemical reactions between mineral and organic matter (Skyllberg *et al.* , 2001). In particular, SOM contains a number of acid functional groups from which H^+ ions can dissociate, and thus it is an important source of H^+ ions in soil, and is favorable for maintaining soil acidity (Brady & Weil, 2008). The mechanisms of soil N-induced soil acidification involved the adsorption and desorption of exchangeable basic/acidic cations. Improved soil N significantly reduced the exchangeable basic cations of Ca^{2+}, K^+, Mg^{2+} and Na^+, while increasing free Al^{3+} and Mn^{2+}in soils (Tian & Niu, 2015).

Plant species is a key factor affecting RPCs of grassland ecosystems. Hong *et al.* (2018) reported that the effects of afforestation on soil pH are species-specific through different rhizospheric processes. For example, they found *Pinus tabuliformis* and *Pinus koraiensis* significantly reduced soil pH by 0.18–0.20, whereas other tree species had no detectable effects on soil pH. In our study, we found the grassland dominated by sedge (e.g., *Heleocharis uniglumis* , *Carex enervis* and *Kobresia humilis*) had a higher decrease in soil pH than the grassland dominated by grass species (e.g., *Leymus chinensis* , *Stipa grandis* and *Stipa purpurea*) at 0–10 cm soil depth. This is because the root biomass of sedge species is mainly concentrated in the surface soil and generally shows relatively high absorption rates for $NH_4{}^+$ (Jiang et al., 2016), which could be replaced by H^+, thus decreasing soil pH (Berthrong*et al.* , 2009). In addition, GE had significant decreases in deep soil pH for forb and shrub species (e.g., *Artemisia desertorum*and *Astragalus adsurgens*) in grasslands arise from the deep root allocation. The absorption of a large amount of cations reduced the soil pH by releasing rhizospheric H^+ in deep soil (Dakora & Phillips, 2002).

4.3 Implications of GE for grassland management

Following the implementation of the comprehensive 'Returning Grazing Land to Grassland' project, GE has had a negative effect on soil pH in China's grassland ecosystems. In addition, soil acidification also had lasted for decades and could be maintained for a long periods because of the deposition of atmospheric N and sulfur across China's grasslands (Yang *et al.* , 2012). These two factors may be variably superimposed. Sustained soil acidification could enhance the leaching loss of base cations (e.g., Ca^{2+}, K^{+}, Mg^{2+} and Na^{+}), and the release of mobile forms of Al^{3+} and Mn^{2+}, which influences plant physiological activities (e.g., toxicity) for grassland species (Kochian, 1995; Poschenrieder *et al.* , 2008). Long-term soil acidification could also change structure and function at ecosystem scale, such as C–N transformation processes and plant and microbial diversities (Liu *et al.* , 2011). Similar management recommendations might be applied in other grassland ecosystems with similar histories and patterns of ecological degradation, such as the African savannas (Talore *et al.* , 2015), temperate grassland of north America (Anderson *et al.* , 2008) and Pampas of South America (Pineiro *et al.* , 2009).

4.4 Uncertainty analysis

We combined 106 sites ranging from large temperature and precipitation gradients covering the main grassland types in China, which offers relatively accurate estimates on changes of soil pH following GE across grassland ecosystems. However, there remain some uncertainties and limitations. Uneven distribution of data collected in different types of grassland, soil layers and durations of GE may have some bias on our results. In addition, we were unable to evaluate several other potentially important environmental factors, such as grazing intensities before GE (heavy, moderate or light grazing), type of grazing management (seasonal or perennial grazing) and livestock (e.g., cattle, sheep, horse or yak), because most of these factors were not measured in field sampling and the peer-reviewed literature. Despite these uncertainties, the present study did reveal several interesting and informative patterns, which can provide important references for future management of the ecological environment in China's grassland ecosystems.

5 Conclusion

We found that GE had caused significant soil acidification across China's grasslands. Surface soil pH showed greatest decline rates in GE grasslands, while deeper soil pH showed limited responses to GE. In general, the largest decrease in soil pH occurred after medium-term periods (5–15 years) of GE, whereas soil pH exhibited a smaller response in long-term periods ([?]15 years) of GE. Of the environmental factors examined, MAP, biomass accumulation and soil C and N dynamics were the important factors influencing the RPC following GE. Grassland dominated by sedge species had a higher pH decrease rate in surface soil, whereas forbs and shrubs had the lowest RPC in deeper soil. Our results provide an important reference for future grassland management in China.

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Conflict of interest

The authors declare no conflict of interest.

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Table 1. Effects of grassland types (sedge, grass and forb+shrub) on the RPC following grazing exclusion in different soil layers (0–10, 10–20, 20–30 and 30–100 cm).

Dominant species	Soil layers	Soil layers	Soil layers	Soil layers	Soil layers	Soil layers	Soil layers	Soil layers
	0–10 cm	*SE*	10–20 cm	*SE*	20–30 cm	*SE*	30–100 cm	*SE*
Grass	-1.53a	0.37	-1.32a	0.54	-0.27a	0.40	-0.22	0.58
Sedge	-4.44b	2.18	-1.22a	1.14	0.72a	0.94	0.00	–
Forb+shrub	-2.90ab	1.76	-3.28a	1.93	-6.39b	3.57	–	–

The different letters indicate significant difference among the three grassland types at the 0.05 level ($p < 0.05$, one-way ANOVA, post-hoc *LSD* test).

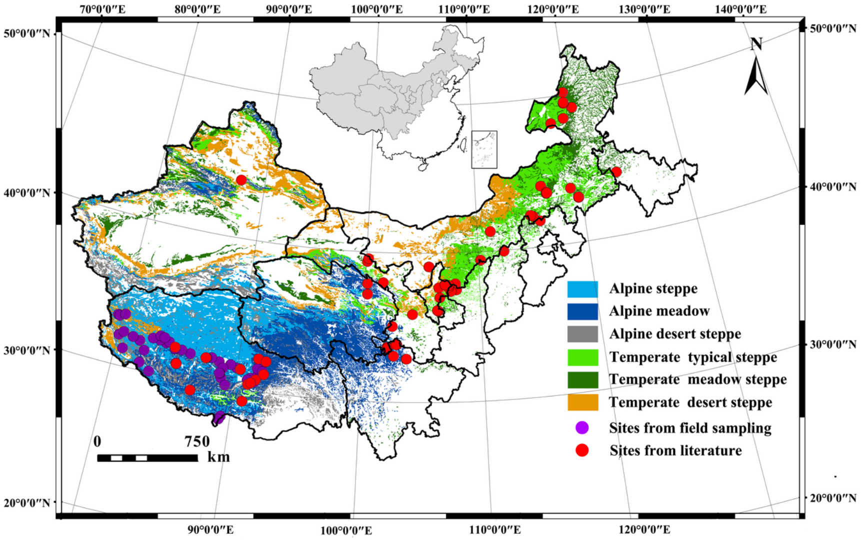
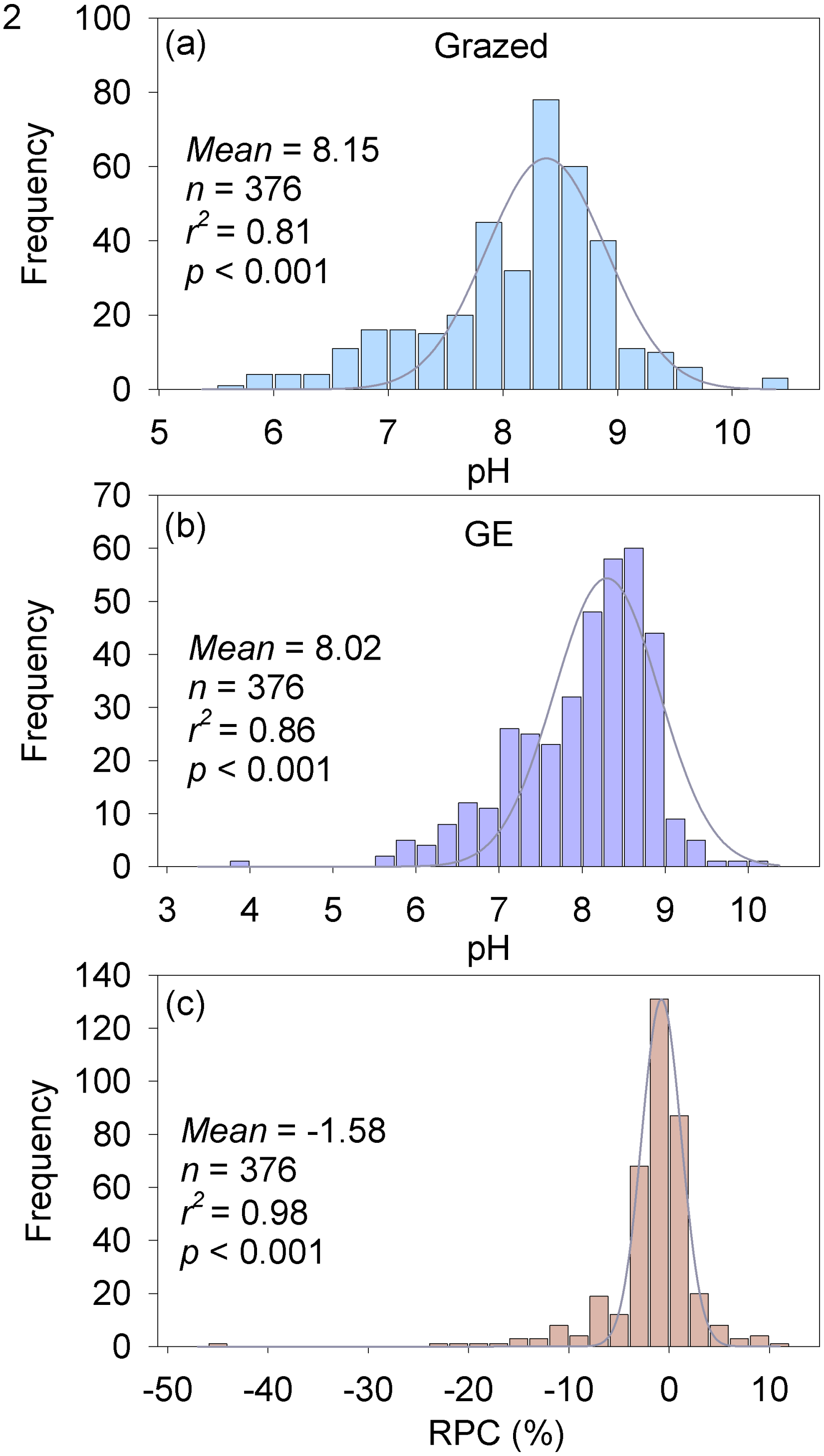


Fig.2



(a)
Grazed
Mean = 8.15
n = 376
r2 = 0.81
p < 0.001
Frequency
0
20
40
60
80
100
5
6
7
8
9
10
pH
(b)
GE
Mean = 8.02
n = 376
r2 = 0.86
p < 0.001
Frequency
0
10
20
30
40
50
60
70
3
4
5
6
7
8
9
10
pH
(c)
Mean = -1.58
n = 376
r2 = 0.98
p < 0.001
Frequency
0
20
40
60
80
100
120
140
-50
-40
-30
-20
-10
0
10
RPC (%)

Fig.3

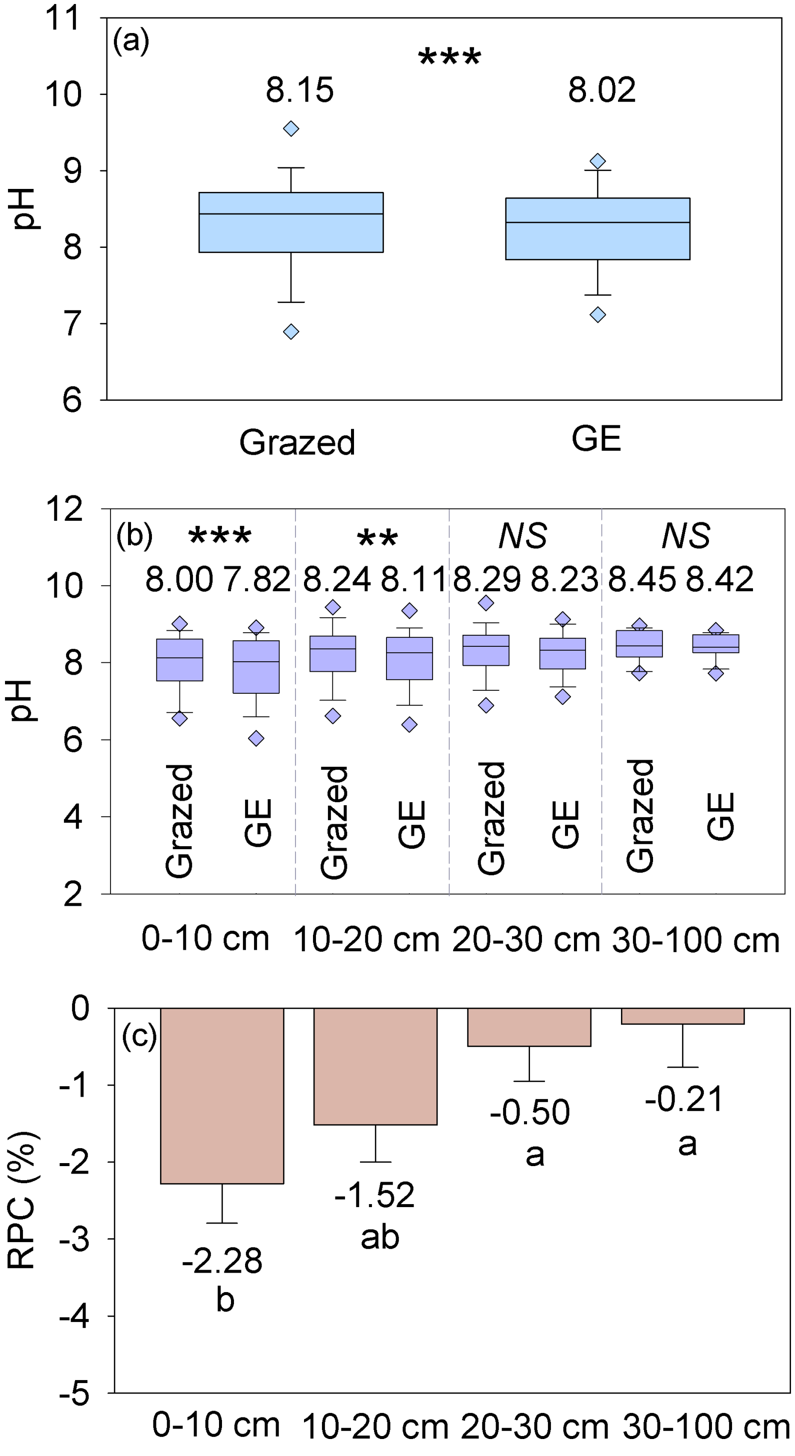

(a)
***
8.15
8.02
pH
11
10
9
8
7
6
Grazed
GE
(b)
***
**
NS
NS
8.00 7.82 8.24 8.11 8.29 8.23 8.45 8.42
pH
12
10
8
6
4
2
Grazed
GE
Grazed
GE
Grazed
GE
Grazed
GE
0-10 cm
10-20 cm
20-30 cm
30-100 cm
(c)
RPC (%)
0
-1
-2
-3
-4
-5
-2.28
b
-1.52
ab
-0.50
a
-0.21
a
0-10 cm
10-20 cm
20-30 cm
30-100 cm

Fig.4

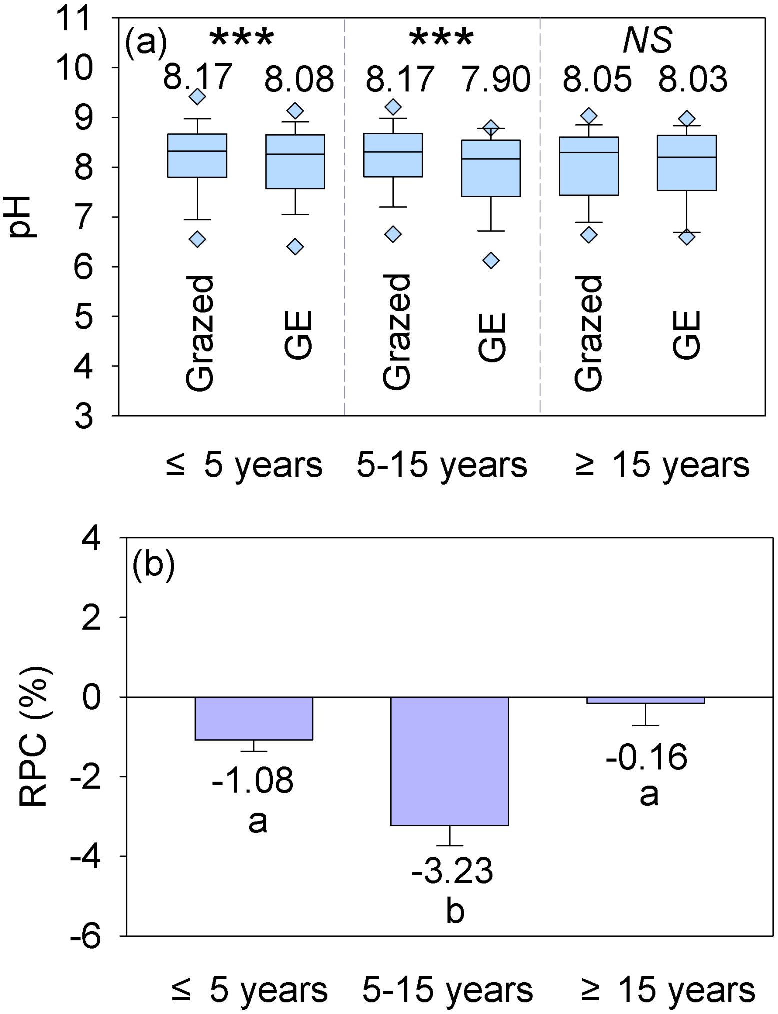
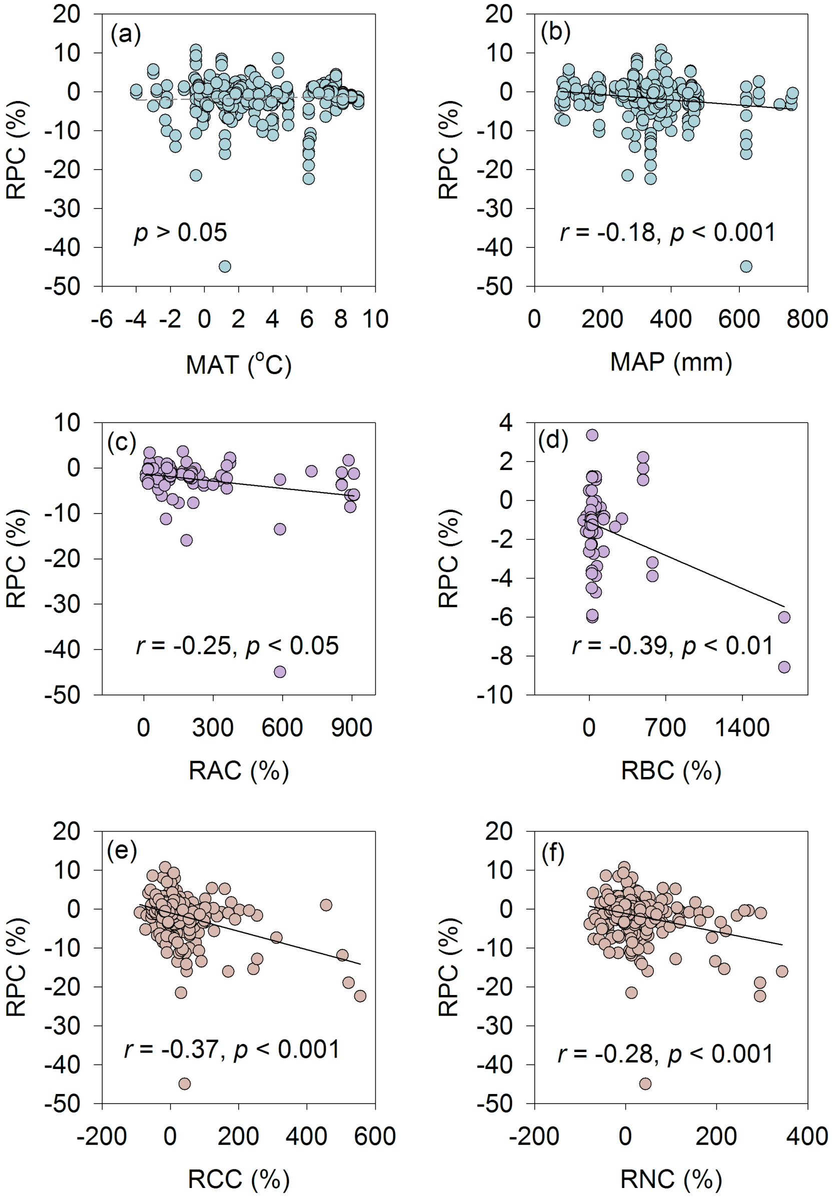

(a)
***
***
NS
8.17
8.08
8.17
7.90
8.05
8.03
pH
11
10
9
8
7
6
5
4
3
Grazed
GE
Grazed
GE
Grazed
GE
≤ 5 years
5-15 years
≥ 15 years
(b)
RPC (%)
4
2
0
-2
-4
-6
-1.08
a
-3.23
b
-0.16
a
≤ 5 years
5-15 years
≥ 15 years

Fig.5


(a)
RPC (%)
p > 0.05
MAT (°C)
20 10 0 -10 -20 -30 -40 -50
-6 -4 -2 0 2 4 6 8 10
(b)
RPC (%)
r = -0.18, p < 0.001
MAP (mm)
20 10 0 -10 -20 -30 -40 -50
0 200 400 600 800
(c)
RPC (%)
r = -0.25, p < 0.05
RAC (%)
10 0 -10 -20 -30 -40 -50
0 300 600 900
(d)
RPC (%)
r = -0.39, p < 0.01
RBC (%)
4 2 0 -2 -4 -6 -8 -10
0 700 1400
(e)
RPC (%)
r = -0.37, p < 0.001
RCC (%)
20 10 0 -10 -20 -30 -40 -50
-200 0 200 400 600
(f)
RPC (%)
r = -0.28, p < 0.001
RNC (%)
20 10 0 -10 -20 -30 -40 -50
-200 0 200 400