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Changes of soil organic and inorganic carbon in relation to grassland degradation in Northern Tibet

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Abstract The effect of livestock grazing on grassland degradation and the resulting impact on soil carbon concentration is an important factor in carbon estimation. We addressed this issue using field observations and laboratory analysis of samples from Tibetan grassland. Based on the field measurements, we investigated the soil organic carbon (SOC) and soil inorganic carbon (SIC) under two contrasting degradation states: lightly or non-degraded grasslands (LDG) and heavily degraded grasslands (HDG). We assessed their relationships with environmental factors using data collected from 99 sites across Northern Tibet during 2011–2012. Data were analyzed using a linear mixed-effects model and one-way ANOVA. The results showed that: (1) SOC concentration decreased and SIC concentration increased following grassland degradation, especially at soil depths in the range of 0–10 cm ($P < 0.05$); (2) the major environmental factors affecting SOC and SIC were soil pH and plant biomass; (3) spatially, the SOC density increased with the mean annual temperature and mean annual precipitation, whereas SIC exhibited the opposite trend; (4) the SOC density increased at first and then decreased with increasing grazing intensity, with an opposite trend in SIC; and (5) soil carbon storage in this region was 0.14 Pg smaller in the HDG than in the LDG. This study suggests that grassland degradation can significantly affect the vertical distribution and

storage of SOC and SIC. The carbon sequestration capacity of the top 100 cm of soil in Northern Tibet was estimated as 0.14 Pg.

Keywords Soil carbon · Grassland degradation · Carbon storage · Northern Tibet

Introduction

Global and regional carbon cycles are one of the key issues in global climate change research (Batjes 1996). Soils contain the largest pool of terrestrial carbon (Jenkinson et al. 1991). The total CO₂ emission from soils is recognized as one of the largest sources of atmospheric CO₂ in the global carbon cycle (Schlesinger and Andrews 2000). Lal (2003) reported that minor changes in soil carbon storage could have significant impacts on the atmospheric CO₂ concentration. Therefore, accurate estimates of soil carbon are required to further understand the role of soil in global carbon dynamics and to mitigate climate change in the near future (Powlson et al. 2011).

A recent study reported that soil carbon was significantly affected by land-use changes and land degradation (Berhongeray et al. 2013). A number of other studies have found changes to soil carbon following forest degradation (Jandl et al. 2007; Chang et al. 2012); however, few studies have considered the impact on carbon in grassland following changes to livestock density. The vast areas and wide distribution of Chinese grasslands suggest that they may have significant effects on regional climate and continental carbon cycles (Ni 2002). During the past two decades, large-scale grassland degradation has occurred across approximately 40% of the total land area of China (Chen and Fischer 1998). Grassland degradation can lead to the emission of CO₂ from the soil to the atmosphere, and therefore the reduction of soil carbon (Lal 2004). This is of major concern given ongoing global warming (Liu et al. 2008). Soil carbon can be divided into two components: soil

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organic carbon (SOC) and soil inorganic carbon (SIC). Both SOC and SIC are crucial for assessing regional, continental, and global soil C stores, and for predicting the consequences of global change (Wang et al. 2010). Numerous studies have assessed the impact of land degradation on soil organic carbon stocks (Dlamini et al. 2016). Dlamini et al. (2014) revealed a sigmoidal decrease in topsoil SOC stocks under increasing grassland degradation, with depletion rates of up to 89%. However, there is little knowledge regarding soil inorganic carbon and soil carbon components in relation to grassland degradation. The Northern Tibetan region is the source of the Yellow, the Yangtze, and the Lancang rivers, and has 23.27×10^6 hm² of grassland (Liu et al. 2008). The grasslands in this area are suffering from serious degeneration due to overgrazing over recent years (Feng et al. 2005). However, the potential of grazing land to sequester carbon is important in reducing greenhouse-gas emissions and, therefore, in mitigating climate change (Powlson et al. 2011). The effect of grazing on carbon storage is uncertain. Some studies have shown a decrease in carbon with grazing. For example, Martinsen et al. (2011) found that carbon stocks declined by 14% after 7 years of grazing in Norway, reaching 0.64 kg C m⁻² in heavily grazed grasslands compared with 0.76 kg C m⁻² in ungrazed sites. Steffens et al. (2008) found that 30 years of grazing in semi-arid Mongolian grasslands resulted in a 45% decrease in C stocks, with 0.64 kg C m⁻² in the grazed compared with 1.17 kg C m⁻² in the ungrazed grasslands. However, in some cases, the degradation of grassland was not due to overgrazing, but to misuse, such as free grazing by unpacked herds. In these cases C-storage can recover once land management is changed to controlled-grazing (Chaplot et al. 2016). Müller-Nedebock et al. (2016) reported that the loss of soil carbon stocks was mostly due to water erosion, which has certainly contributed to grassland degradation. Therefore, the changes in soil carbon storage under different grazing conditions in this area must be understood to develop effective soil conservation measures and to ensure sustainable livestock production.

In this study, to address how grassland degradation affects soil carbon concentration and storage, we compared soil carbon concentrations in lightly or non-degraded grassland (LDG) with heavily degraded grasslands (HDG) in the Northern Tibetan region.

Materials and method

Site description

The study was conducted in Northern Tibet, which is located in the hinterland of the Qinghai-Tibet Plateau, China, with an average altitude of 4200 m. The mean annual temperature and precipitation in this area ranged between -5.4 and 4.2 °C, and between 260 and 770 mm,

respectively, from 1971 to 2010 (Cao and Long 2009). The region has 16 counties and one township. We collected soil and plant samples from each county. The parent material in this area is loess, and the geomorphology is mountainous. The soil type is mountain meadow soil (Cao et al. 2004) and the main vegetation type is alpine grassland. Based on the vegetation classification system of China, we divided the alpine grasslands in this region into two types: alpine steppe and alpine meadow (Hou 2001). The vegetation database was composed of 99 sites (locations are shown in Fig. 1), of which 36 sites were LDG and 63 sites were HDG. For each site, information on the geographical location, altitude, soil horizon depth, vegetation type, parent material, and land-use pattern were recorded, and an area of 100 × 10 m was delimited and divided into ten plots of 10 × 10 m. A quadrat of 1 × 1 m from each plot was then selected for biomass and soil sample collection.

Selection of grassland

The typical vegetation in the region is predominantly alpine steppe and alpine meadow. According to the indicators of grassland degradation in the studies of Liu et al. (2003) and Liu et al. (2004), we considered areas with >70% plant cover and sites with >70% of palatable herbage as LDG. Areas with <40% plant cover and <40% of palatable herbage were classified as HDG. We did not consider the intermediate grasslands between these two extremes. The plant community characteristics of the two types of grasslands are listed in Table 1. The data were obtained from field investigations and laboratory analysis.

Soil and biomass sampling

The field sampling was conducted from July to August in 2011 and 2012. We first recorded the altitude, longitude, and latitude of each site using GPS (Global Positioning System: Canada 210).

At each site, soil samples were collected to measure the soil carbon and soil pH at depths of 0–5, 5–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm. Soil was sampled with a corer ($\Phi = 6$ cm), with five replications for each depth per site. The soil samples were air-dried and sieved through a 2-mm mesh to remove fine roots. Soil pits were excavated to measure soil bulk density. In each pit, bulk density samples from each layer were obtained using a soil corer (stainless steel cylinder with 100 cm³ volume) and weighed to the nearest 0.1 g. Soil bulk density (Bd) was calculated as the ratio of the oven-dry soil mass to the container volume. The volume percentage of rock fragments >2 mm (GC) was the ratio of the rock volume to the container volume. Soil samples for carbon analysis were air-dried and sieved to 0.25 mm. The total carbon concentration (STCC) was measured by the dry combustion method using an ele-

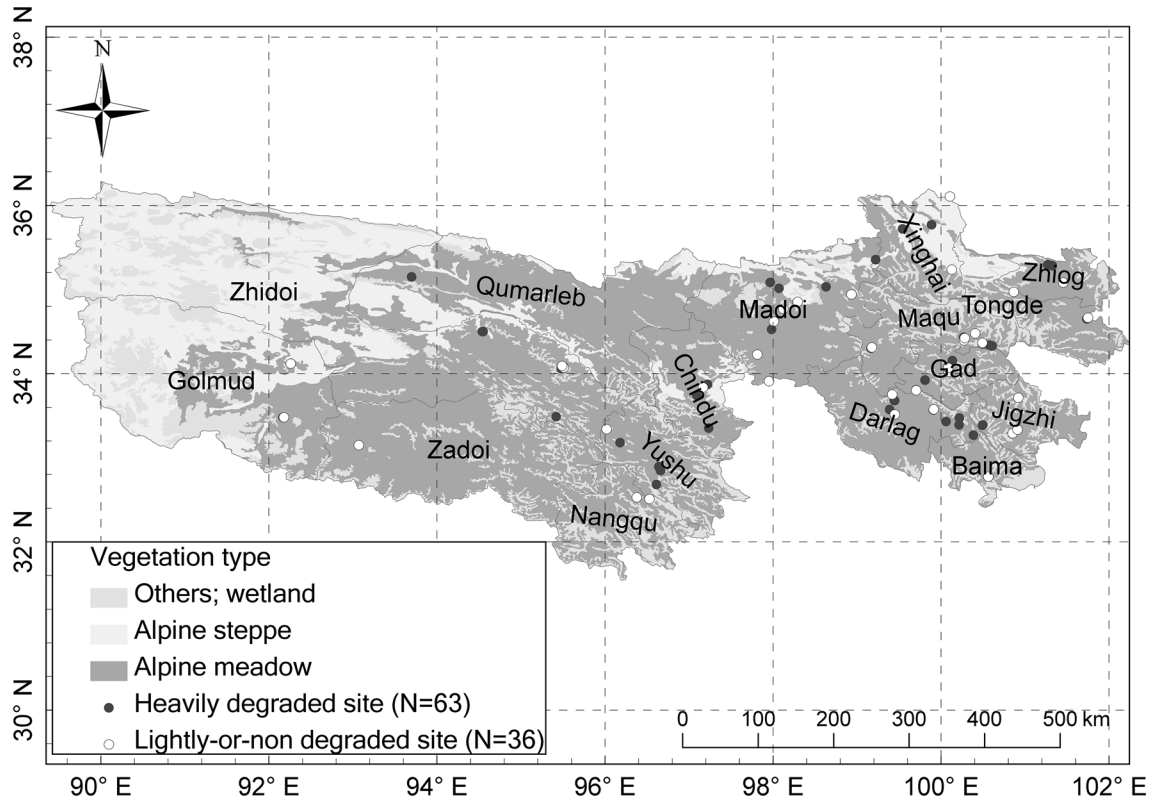


Fig. 1 Field sampling sites in Northern Tibet. *Solid dots* indicate heavily degraded sites and *hollow dots* represent lightly or non-degraded sites. The vegetation types were extracted from the Vegetation Atlas of China (1:1 000 000) (Hou 2001)

Table 1 Plant community characteristics of lightly or non-degraded (LDG) and heavily degraded (HDG) grasslands

Degradation status	LDG	HDG
Alpine steppe	N = 8	N = 14
Common species	Grasses, <i>Stipa purpurea</i> , <i>Poa alpina</i> , <i>Festuca ovina</i> , <i>Koeleria litwinowii</i> .	Forb, <i>Saussurea amara</i> , <i>Ajania tenuifolia</i> , <i>Leontopodium nanum</i> , <i>Microula sikkimensis</i> .
Palatable herbage ^a (%)	73.8 ± 7.3	29.9 ± 7.2
Plant coverage (%)	74.0 ± 6.4	31.3 ± 5.9
Species richness	9.8 ± 0.8	7.4 ± 0.8
Aboveground biomass (g m ⁻²)	109.5 ± 15.3	71.8 ± 15.0
Plant height (cm)	11.6 ± 1.9	6.2 ± 2.0
Alpine meadow	N = 24	N = 53
Common species	Cyperaceae, <i>Elymus nutans</i> , <i>Kobresia pygmaea</i> , <i>Kobresia humilis</i> .	Subordinate, <i>Saussurea pulchra</i> , <i>Potentilla anserina</i> L., <i>Ligularia virgaurea</i> .
Palatable herbage (%);	78.4 ± 6.6	34.2 ± 2.1
Plant coverage (%)	84.5 ± 2.1	39.0 ± 3.8
Species richness	17.2 ± 0.9	11.7 ± 0.6
Aboveground biomass (g m ⁻²)	130.2 ± 16.0	91.0 ± 7.1
Plant height	5.7 ± 0.9	3.6 ± 0.4

^a Data for palatable herbage, plant coverage, species richness, aboveground biomass, and plant height are indicated by the mean ± standard error of all sites for the two grassland types

mental analyzer with a combustion temperature of 950 °C (2400 II CHNS/O, Perkin-Elmer, USA). In this study, SIC refers to the combined content of CaCO₃, MgCO₃, and other carbonate minerals in the soil (Wu et al. 2009). Soil inorganic carbon concentration (SICC) was measured by the modified Pressure-Calcimeter Method, with an Eijkelkamp Calcimeter and short reaction time (Sherrod et al. 2002). The soil organic

carbon concentration (SOCC) was calculated from the difference between STCC and SICC. Soil pH was measured using a PHS-3C meter (Shanghai Dapu Instrument Company, Shanghai, China). Distilled water was used as a solvent, and the soil:water ratio was 1:2.5.

At each site, all plants in the five plots (1 × 1 m²) were harvested by the clipping method to measure aboveground biomass (AGB). To assess underground

biomass (UGB), a soil core (6 cm in diameter) was extracted and divided into seven depth increments (0–5, 5–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm). Five soil samples from each depth interval in the same quadrat were combined and then cleaned under running water to remove soil particles. Roots were passed through a 2-mm sieve to remove fine roots (<2 mm). Live and dead roots could not be distinguished; the UGB values therefore included both live and dead roots. Biomass samples were oven-dried at 65 °C to a constant weight and were weighted.

Mean annual temperature (MAT) and mean annual precipitation (MAP) were compiled from the climate database of Qinghai Province during 1971–2010. Data on grazing density were obtained from the statistical yearbook of Qinghai from 1985 to 2010 (<http://www.tongjinnianjian.com>) and calculated assuming that a yak was equal to 4.5 sheep units, and a horse was equal to 6 sheep units (Agricultural Industry Standard of the People's Republic of China, 2002). The climate and grazing values were averaged by county.

Calculation of SOC and SIC density

We calculated the SOC density (SOCD) of each profile using the stratified cumulative sum calculation (Soil Survey Staff 2011) (1).

$$SOCD = \sum_{i=1}^n SOC_i \times Bd_i \times D_i \times Cm \times 0.01, \quad (1)$$

where SOC_i is the weight of soil organic carbon in the <2 mm particle size fraction (g kg^{-1}); Bd is the bulk density at 33 kpa water content with <2 mm basis (g m^{-3}); D_i is the horizon thickness (cm); Cm is the coarse fragment conversion factor; and 0.01 is a constant conversion factor.

SOC_i was calculated by:

$$SOC_i = STC_i - SIC_i = STC_i - CaCO_3 \times 0.12, \quad (2)$$

where STC_i is the weight of soil total carbon on a <2 mm basis estimated by PE 2400; SIC_i is the weight of soil inorganic carbon on a <2 mm basis; $CaCO_3$ is the calcium carbonate content measured by CO_2 evolution with HCl treatment; and 0.12 is a constant to account for the fact that carbon is 12% of $CaCO_3$ by mass. Next,

$$CaCO_3 = 1000 \times \frac{M_2(V_1 - V_3)}{M_1(V_2 - V_3)}, \quad (3)$$

where M_1 is the sample weight (g); M_2 is the reference standard weight (g); V_1 is the CO_2 volume produced by the sample (ml); V_2 is the CO_2 volume produced by the reference standard (ml); and V_3 is the CO_2 volume produced by a blank (ml).

Bulk density is given by:

$$Bd = WFE/VolFE = (WTotal - WG)/(VolTotal - VolG), \quad (4)$$

where WFE is the weight of fine earth; and VolFE is the volume of fine earth. The coarse fragment conversion factor is

$$Cm = (\%FE/BdFE)/((\%FE/BdFE) + (\%G/BdG)), \quad (5)$$

where FE is fine earth (<2 mm size fraction); $BdFE$ is the bulk density of fine earth; G is the soil gravel content; and BdG is the bulk density of gravel.

We estimated the SOC stock as follows:

$$SOCS = \sum_{j=1}^n SOCD_j \times Area_j, \quad (6)$$

where SOCS is the SOC stock (kg C), SOCD is the SOC density (kg m^{-2}), and Area is the grassland degraded area (m^2), based on the report of Liu et al. (2008). SIC density (SICD) and SIC storage (SICS) were calculated using the same method as SOC.

Statistical analysis

Paired comparison was conducted to analyze the difference between the means of LDG and HDG. We performed linear mixed-effects model (LME) analysis using the degree of degradation and grassland types as fixed factors, and site as the random factor. To investigate whether the degree of degradation differed depending on the grassland type, we performed separate analyses for the two grassland types. For each type, LME analysis was applied using the degree of degradation as the fixed factor and site as the random factor, to examine the differences in SOCD and SICD between LDG and HDG. One-way ANOVA was used to examine the difference in the soil carbon concentration between LDG and HDG. Stepwise regression analysis was conducted to evaluate the factors influencing SOCC and SICC. Ordinary least squares (OLS) regression was used to evaluate the relationships between SOC and SIC density, and MAT, MAP, and grazing density. All statistical analyses were performed in R 2.15.1 software (R Core Team 2012).

Results

Profile differentiation of soil carbon in LDG and HDG

The SOC concentration showed a progressive decrease with soil depth in both LDG and HDG (Fig. 2a). The SOC concentration in LDG soil reached 79.53 g kg^{-1} in the upper 0–5 cm and dropped to 15.77 g kg^{-1} in the 70–100 cm layer, while it measured 47.06 and 13.24 g kg^{-1} in the HDG for the two respective soil depths. The SOC concentration in LDG tended to be higher than

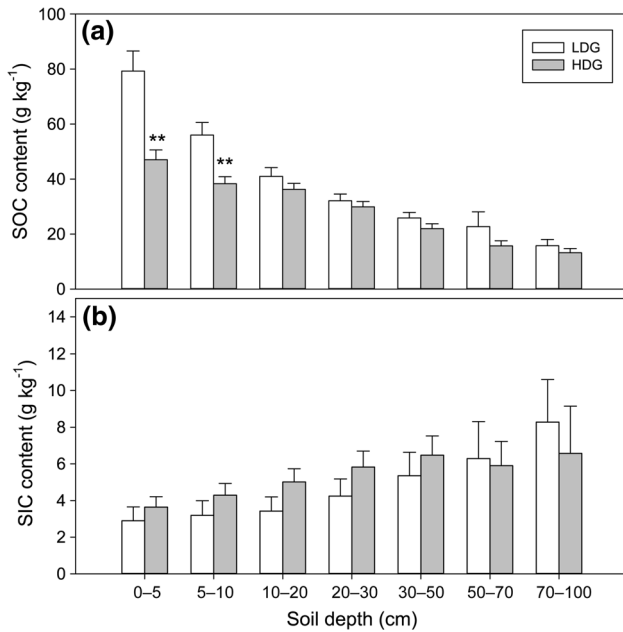


Fig. 2 Vertical distribution of soil organic carbon (SOC, **a**) and soil inorganic carbon (SIC, **b**) in the lightly or non-degraded (LDG) and heavily degraded (HDG) grassland. Error bars indicate standard errors. The asterisks denote significant differences in the average between the two types of grassland with different degradation statuses ($P < 0.05$)

that in HDG at each depth, while the SOC concentrations at 0–5 and 5–10 cm depths in the LDG were significantly higher than those in HDG ($P < 0.05$). The SIC concentration increased with soil depth in LDG and HDG, and increased from 2.89 g kg⁻¹ in the 0–5 cm layer to 8.28 g kg⁻¹ in the 70–100 cm layer in LDG (Fig. 2b). In the upper five layers, the SIC concentration in LDG was less than that in HDG; however, this pattern was reversed in the bottom two layers. No significant difference in SIC was found between LDG and HDG at any depth.

Paired comparison results showed that the averages of SOCD, soil bulk density (Bd), The volume percentage of rock fragments >2 mm (GC), AGB, and UGB of LDG differed significantly from those in HDG, while

SICD and soil pH showed no significant difference between LDG and HDG (Table 2).

The SOCD of HDG was significantly lower than that of LDG in alpine grassland (Tables 2, 3). However, when considering alpine meadow and alpine steppe separately, the SOCD of alpine meadow varied significantly between the grasslands with different degradations, whereas the alpine steppe showed no significant change (Table 3).

Environmental and biological factors influencing soil carbon

Four parameters (soil pH, AGB, UGB, and altitude, ALT) were used to establish a stepwise regression model explaining the SOCD and SICD of the 0–30 cm layer in LDG and HDG (Table 4). The results indicate that pH was related to the SOCD in LDG, while SOCD was mainly determined by UGB in HDG. However, soil pH and AGB were the main factors influencing SICD in LDG and HDG, and they explained 65.8 and 54.4% of the variance of SIC in the LDG and HDG, respectively.

The SOC density in the top 30 cm showed a significant increase with increasing mean annual temperature (MAT, $R^2 = 0.37$, $P < 0.05$), while SIC tended to decrease in grasslands with a higher MAT ($R^2 = 0.15$, $P = 0.16$; Fig. 3a). The SOC density increased with MAP ($R^2 = 0.28$, $P < 0.05$); however, SIC decreased significantly with increasing MAP ($R^2 = 0.44$, $P < 0.05$; Fig. 3b).

The SOC density increased with increasing livestock numbers, but then decreased in heavily grazed grassland ($R^2 = 0.66$, $P = 0.07$). The relationship between SIC density and livestock numbers was the reverse of that for SOC density, but was not significant ($R^2 = 0.27$, $P = 0.45$; Fig. 4).

Potential for carbon sequestration

The grassland area of this region measures approximately 2.33×10^{11} m² (Liu et al. 2008). In total, SOC

Table 2 A paired comparison of the main characteristics in lightly or non-degraded (LDG, n = 36) and heavily degraded (HDG, n = 63) grassland at the same location

Source	LDG ^b	HDG	df	t	P
SOCD ^a (kg m ⁻²)	14.87 ± 1.27	11.30 ± 1.13	21	2.89	0.01
SICD (kg m ⁻²)	1.75 ± 0.48	1.99 ± 0.49	21	-0.88	0.39
ρ (g cm ⁻³)	1.07 ± 0.05	1.26 ± 0.05	21	-3.57	0.01
GC (%)	0.15 ± 0.03	0.29 ± 0.06	21	-2.67	0.01
AGB (g m ⁻²)	117.55 ± 17.54	80.85 ± 13.02	21	2.41	0.03
UGB (g m ⁻²)	1152.19 ± 151.75	531.04 ± 163.34	17	3.00	0.01
pH	7.77 ± 0.20	7.90 ± 0.20	21	-1.76	0.09

SICD soil inorganic carbon density, ρ bulk density, GC the volume percent of the rock fraction >2 mm, AGB aboveground biomass, UGB underground biomass

^a SOCD soil organic carbon density

^b Data are indicated by the mean ± standard error of all sites for the two grassland types, P values <0.05

Table 3 Effect of grassland types and degree of degradation on SOCD and SICD in the linear mixed-effects model (LME)

	<i>df</i>	SOCD ^a		SICD	
		<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Alpine grassland					
D	1	18.498	< 0.001	2.995	0.097
G	1	42.421	< 0.001	71.099	< 0.001
D × G	1	1.097	0.298	0.961	0.329
Alpine steppe					
D	1	2.769	0.110	0.364	0.563
Alpine meadow					
D	1	31.495	< 0.001	2.414	0.126

SICD soil inorganic carbon density, D degree of degradation, G grassland type P values < 0.05

^a SOCD soil organic carbon density

Table 4 Regression models between soil carbon and influencing factors

Regression coefficients ^a					Coefficient of determination
	Offset	pH	AGB	UGB	
LDG ^b					
SOCD	41.135	-3.331			0.288**
SICD	-9.548	1.551	-0.008		0.658**
HDG					
SOCD	9.393			0.002	0.097*
SICD	-8.417	1.401	-0.008		0.544**

AGB aboveground biomass, UGB underground biomass, in the top 100 cm of soil, pH average soil pH in the top 100 cm of soil HDG heavily degraded grassland, SOCD soil organic carbon density in the top 100 cm of soil, SICD soil inorganic carbon density in the top 100 cm of soil

* $P < 0.05$, ** $P < 0.01$

^a Stepwise linear regression for SOCD and SICD was conducted for three factors (UGB, AGB, pH), but only one or two variables were selected for the SOCD and SICD

^b LDG lightly or non-degraded grassland

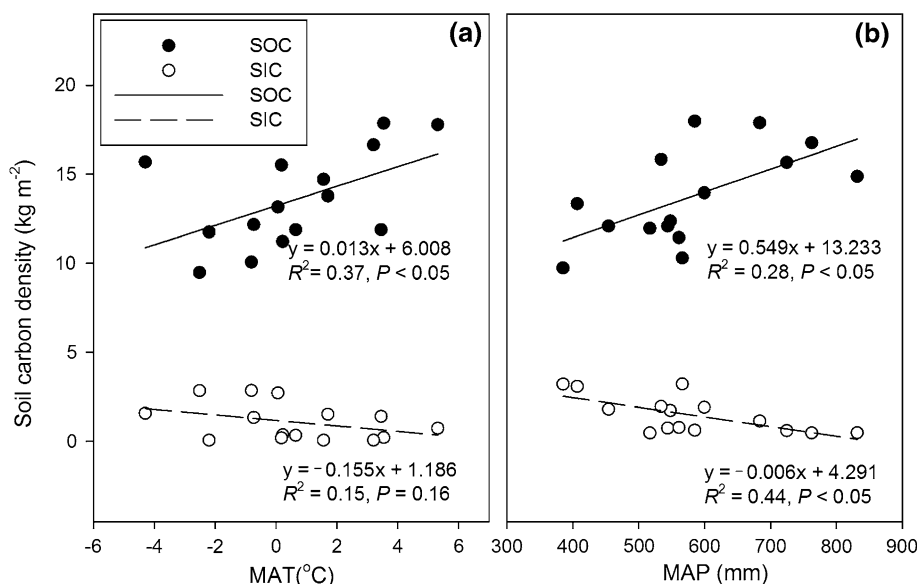


Fig. 3 Relationship between soil organic carbon density (SOCD) and soil inorganic carbon density (SICD) with climate factors in the grassland in the Northern Tibetan region. The mean annual

temperature (MAT) and the mean annual precipitation (MAP) were averaged from 1981 to 2010. Solid line and dash line is the regression line

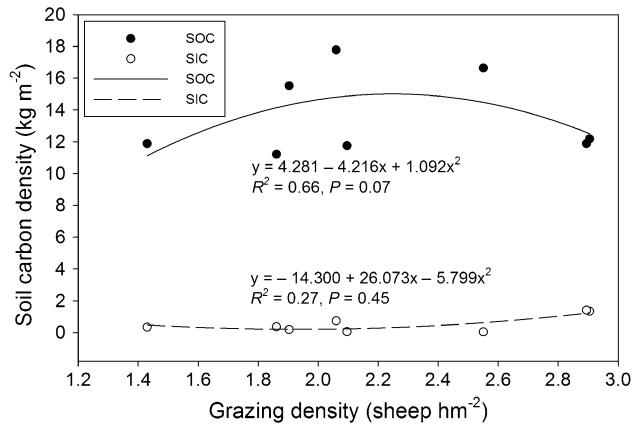


Fig. 4 Grazing disturbance in relation to SOCD and SICD in Northern Tibetan grassland. *Soidl line* and *dash line* is the regression line

and SIC storage in the top 30 cm of the Northern Tibet region was estimated to be between 2.99 and 0.37 Pg, with an average density of 12.83 and 1.61 kg m⁻², respectively. A large area of grassland (8.41×10^{10} m²) has degenerated in this region as a result of overgrazing. Our results show that soil carbon storage in this region was 0.14 Pg smaller in HDG than in LDG. The SOC stock had decreased by 0.22 Pg, while SIC stock had increased by 0.08 Pg (Table 5). These changes demonstrate that this region has a potential carbon sequestration capacity of 0.14 Pg following the rehabilitation of these grasslands to lightly or non-degraded grassland. The SOC density of undegraded grassland in different counties exhibited large variations, with the highest value in Banma (24.01 kg m⁻²) and the lowest in Tanggula (6.55 kg m⁻²). The SOC density in degraded grassland ranged from 18.83 to 4.12 kg m⁻². The SIC density also varied in different counties between undegraded and

Table 5 Changes in soil organic carbon (SOC) and soil inorganic carbon (SIC) from lightly or non-degraded (LDG) to heavily degraded (HDG) grassland in the 0–100 cm soil depth

County	Degraded area (10 ⁴ hm ²)	Degraded state	SOCD (kg m ⁻²)	SICD (kg m ⁻²)	Change of SOCS (10 ⁻³ Pg)	Change of SICS (10 ⁻³ Pg)	Changes of STCS (10 ⁻³ Pg)																																																																																																																																																																																			
Boima Xian	6.55	LDG	19.08 ± 0.20	0.06 ± 0.00	-2.51	-0.01	-2.52																																																																																																																																																																																			
		HDG	15.25 ± 0.75	0.05 ± 0.01				Chindu Xian	75.04	LDG	15.34 ± 0.89	1.49 ± 0.26	21.31	-3.23	18.08	HDG	18.18 ± 1.54	1.06 ± 0.74	Darlag Xian	22.01	LDG	13.36 ± 0.44	0.06 ± 0.00	-6.36	0.97	-5.39	HDG	10.47 ± 0.44	0.50 ± 0.21	Gade Xian	10.02	LDG	15.66 ± 1.04	0.04 ± 0.00	-5.28	0.03	-5.25	HDG	10.39 ± 0.68	0.07 ± 0.01	Henan Zizhixian	3.60	LDG	16.01 ± 1.09	0.05 ± 0.01	-0.23	0.05	-0.18	HDG	15.36 ± 2.91	0.18 ± 0.11	Jigzhi Xian	9.38	LDG	18.01 ± 0.71	0.06 ± 0.01	-5.27	-0.01	-5.28	HDG	12.39 ± 0.77	0.05 ± 0.00	Madoi Xian	10.57	LDG	11.80 ± 0.72	2.18 ± 0.33	-34.34	13.42	-20.92	HDG	8.55 ± 0.78	3.45 ± 0.49	Maqen Xian	18.48	LDG	14.32 ± 1.43	0.11 ± 0.02	-4.38	0.17	-4.21	HDG	11.95 ± 0.79	0.20 ± 0.05	Nangqen Xian	40.25	LDG	16.50 ± 1.84	0.45 ± 0.14	8.25	-1.13	7.12	HDG	18.55 ± 0.57	0.17 ± 0.28	Qumarleb Xian	293.22	LDG	8.45 ± 0.87	2.63 ± 0.35	-37.53	8.80	-28.73	HDG	7.17 ± 0.83	2.93 ± 0.20	Tanggula	35.47	LDG	7.20 ± 0.62	5.07 ± 0.17	-7.87	2.59	-5.28	HDG	4.98 ± 0.65	5.80 ± 0.36	Tongde Xian	1.91	LDG	13.80 ± 0.97	0.07 ± 0.02	-0.20	0.11	-0.09	HDG	12.73 ± 1.07	0.63 ± 0.21	Xinghai Xian	8.91	LDG	8.72 ± 1.95	2.65 ± 0.08	-0.33	1.83	1.50	HDG	8.35 ± 0.74	4.70 ± 0.13	Yushu Xian	30.46	LDG	16.50 ± 1.02	0.37 ± 0.16	-0.12	-0.91	-1.03	HDG	16.46 ± 1.77	0.07 ± 0.00	Zadoi Xian	64.90	LDG	12.44 ± 2.61	0.08 ± 0.01	-49.32	19.92	-29.40	HDG	4.84 ± 0.33	3.15 ± 0.54	Zekog Xian	3.83	LDG	16.66 ± 1.51	0.25 ± 0.06	-2.77	0.55	-2.22	HDG	9.43 ± 0.93	1.68 ± 0.25	Zhidoi Xian	111.34	LDG	20.48 ± 0.24	0.07 ± 0.01	-98.31	38.30	-60.01	HDG	11.65 ± 1.80	3.51 ± 0.53	Total	841.03	
Chindu Xian	75.04	LDG	15.34 ± 0.89	1.49 ± 0.26	21.31	-3.23	18.08																																																																																																																																																																																			
		HDG	18.18 ± 1.54	1.06 ± 0.74				Darlag Xian	22.01	LDG	13.36 ± 0.44	0.06 ± 0.00	-6.36	0.97	-5.39	HDG	10.47 ± 0.44	0.50 ± 0.21	Gade Xian	10.02	LDG	15.66 ± 1.04	0.04 ± 0.00	-5.28	0.03	-5.25	HDG	10.39 ± 0.68	0.07 ± 0.01	Henan Zizhixian	3.60	LDG	16.01 ± 1.09	0.05 ± 0.01	-0.23	0.05	-0.18	HDG	15.36 ± 2.91	0.18 ± 0.11	Jigzhi Xian	9.38	LDG	18.01 ± 0.71	0.06 ± 0.01	-5.27	-0.01	-5.28	HDG	12.39 ± 0.77	0.05 ± 0.00	Madoi Xian	10.57	LDG	11.80 ± 0.72	2.18 ± 0.33	-34.34	13.42	-20.92	HDG	8.55 ± 0.78	3.45 ± 0.49	Maqen Xian	18.48	LDG	14.32 ± 1.43	0.11 ± 0.02	-4.38	0.17	-4.21	HDG	11.95 ± 0.79	0.20 ± 0.05	Nangqen Xian	40.25	LDG	16.50 ± 1.84	0.45 ± 0.14	8.25	-1.13	7.12	HDG	18.55 ± 0.57	0.17 ± 0.28	Qumarleb Xian	293.22	LDG	8.45 ± 0.87	2.63 ± 0.35	-37.53	8.80	-28.73	HDG	7.17 ± 0.83	2.93 ± 0.20	Tanggula	35.47	LDG	7.20 ± 0.62	5.07 ± 0.17	-7.87	2.59	-5.28	HDG	4.98 ± 0.65	5.80 ± 0.36	Tongde Xian	1.91	LDG	13.80 ± 0.97	0.07 ± 0.02	-0.20	0.11	-0.09	HDG	12.73 ± 1.07	0.63 ± 0.21	Xinghai Xian	8.91	LDG	8.72 ± 1.95	2.65 ± 0.08	-0.33	1.83	1.50	HDG	8.35 ± 0.74	4.70 ± 0.13	Yushu Xian	30.46	LDG	16.50 ± 1.02	0.37 ± 0.16	-0.12	-0.91	-1.03	HDG	16.46 ± 1.77	0.07 ± 0.00	Zadoi Xian	64.90	LDG	12.44 ± 2.61	0.08 ± 0.01	-49.32	19.92	-29.40	HDG	4.84 ± 0.33	3.15 ± 0.54	Zekog Xian	3.83	LDG	16.66 ± 1.51	0.25 ± 0.06	-2.77	0.55	-2.22	HDG	9.43 ± 0.93	1.68 ± 0.25	Zhidoi Xian	111.34	LDG	20.48 ± 0.24	0.07 ± 0.01	-98.31	38.30	-60.01	HDG	11.65 ± 1.80	3.51 ± 0.53	Total	841.03				-225.26	81.45	-143.81						
Darlag Xian	22.01	LDG	13.36 ± 0.44	0.06 ± 0.00	-6.36	0.97	-5.39																																																																																																																																																																																			
		HDG	10.47 ± 0.44	0.50 ± 0.21				Gade Xian	10.02	LDG	15.66 ± 1.04	0.04 ± 0.00	-5.28	0.03	-5.25	HDG	10.39 ± 0.68	0.07 ± 0.01	Henan Zizhixian	3.60	LDG	16.01 ± 1.09	0.05 ± 0.01	-0.23	0.05	-0.18	HDG	15.36 ± 2.91	0.18 ± 0.11	Jigzhi Xian	9.38	LDG	18.01 ± 0.71	0.06 ± 0.01	-5.27	-0.01	-5.28	HDG	12.39 ± 0.77	0.05 ± 0.00	Madoi Xian	10.57	LDG	11.80 ± 0.72	2.18 ± 0.33	-34.34	13.42	-20.92	HDG	8.55 ± 0.78	3.45 ± 0.49	Maqen Xian	18.48	LDG	14.32 ± 1.43	0.11 ± 0.02	-4.38	0.17	-4.21	HDG	11.95 ± 0.79	0.20 ± 0.05	Nangqen Xian	40.25	LDG	16.50 ± 1.84	0.45 ± 0.14	8.25	-1.13	7.12	HDG	18.55 ± 0.57	0.17 ± 0.28	Qumarleb Xian	293.22	LDG	8.45 ± 0.87	2.63 ± 0.35	-37.53	8.80	-28.73	HDG	7.17 ± 0.83	2.93 ± 0.20	Tanggula	35.47	LDG	7.20 ± 0.62	5.07 ± 0.17	-7.87	2.59	-5.28	HDG	4.98 ± 0.65	5.80 ± 0.36	Tongde Xian	1.91	LDG	13.80 ± 0.97	0.07 ± 0.02	-0.20	0.11	-0.09	HDG	12.73 ± 1.07	0.63 ± 0.21	Xinghai Xian	8.91	LDG	8.72 ± 1.95	2.65 ± 0.08	-0.33	1.83	1.50	HDG	8.35 ± 0.74	4.70 ± 0.13	Yushu Xian	30.46	LDG	16.50 ± 1.02	0.37 ± 0.16	-0.12	-0.91	-1.03	HDG	16.46 ± 1.77	0.07 ± 0.00	Zadoi Xian	64.90	LDG	12.44 ± 2.61	0.08 ± 0.01	-49.32	19.92	-29.40	HDG	4.84 ± 0.33	3.15 ± 0.54	Zekog Xian	3.83	LDG	16.66 ± 1.51	0.25 ± 0.06	-2.77	0.55	-2.22	HDG	9.43 ± 0.93	1.68 ± 0.25	Zhidoi Xian	111.34	LDG	20.48 ± 0.24	0.07 ± 0.01	-98.31	38.30	-60.01	HDG	11.65 ± 1.80	3.51 ± 0.53	Total	841.03				-225.26	81.45	-143.81																	
Gade Xian	10.02	LDG	15.66 ± 1.04	0.04 ± 0.00	-5.28	0.03	-5.25																																																																																																																																																																																			
		HDG	10.39 ± 0.68	0.07 ± 0.01				Henan Zizhixian	3.60	LDG	16.01 ± 1.09	0.05 ± 0.01	-0.23	0.05	-0.18	HDG	15.36 ± 2.91	0.18 ± 0.11	Jigzhi Xian	9.38	LDG	18.01 ± 0.71	0.06 ± 0.01	-5.27	-0.01	-5.28	HDG	12.39 ± 0.77	0.05 ± 0.00	Madoi Xian	10.57	LDG	11.80 ± 0.72	2.18 ± 0.33	-34.34	13.42	-20.92	HDG	8.55 ± 0.78	3.45 ± 0.49	Maqen Xian	18.48	LDG	14.32 ± 1.43	0.11 ± 0.02	-4.38	0.17	-4.21	HDG	11.95 ± 0.79	0.20 ± 0.05	Nangqen Xian	40.25	LDG	16.50 ± 1.84	0.45 ± 0.14	8.25	-1.13	7.12	HDG	18.55 ± 0.57	0.17 ± 0.28	Qumarleb Xian	293.22	LDG	8.45 ± 0.87	2.63 ± 0.35	-37.53	8.80	-28.73	HDG	7.17 ± 0.83	2.93 ± 0.20	Tanggula	35.47	LDG	7.20 ± 0.62	5.07 ± 0.17	-7.87	2.59	-5.28	HDG	4.98 ± 0.65	5.80 ± 0.36	Tongde Xian	1.91	LDG	13.80 ± 0.97	0.07 ± 0.02	-0.20	0.11	-0.09	HDG	12.73 ± 1.07	0.63 ± 0.21	Xinghai Xian	8.91	LDG	8.72 ± 1.95	2.65 ± 0.08	-0.33	1.83	1.50	HDG	8.35 ± 0.74	4.70 ± 0.13	Yushu Xian	30.46	LDG	16.50 ± 1.02	0.37 ± 0.16	-0.12	-0.91	-1.03	HDG	16.46 ± 1.77	0.07 ± 0.00	Zadoi Xian	64.90	LDG	12.44 ± 2.61	0.08 ± 0.01	-49.32	19.92	-29.40	HDG	4.84 ± 0.33	3.15 ± 0.54	Zekog Xian	3.83	LDG	16.66 ± 1.51	0.25 ± 0.06	-2.77	0.55	-2.22	HDG	9.43 ± 0.93	1.68 ± 0.25	Zhidoi Xian	111.34	LDG	20.48 ± 0.24	0.07 ± 0.01	-98.31	38.30	-60.01	HDG	11.65 ± 1.80	3.51 ± 0.53	Total	841.03				-225.26	81.45	-143.81																												
Henan Zizhixian	3.60	LDG	16.01 ± 1.09	0.05 ± 0.01	-0.23	0.05	-0.18																																																																																																																																																																																			
		HDG	15.36 ± 2.91	0.18 ± 0.11				Jigzhi Xian	9.38	LDG	18.01 ± 0.71	0.06 ± 0.01	-5.27	-0.01	-5.28	HDG	12.39 ± 0.77	0.05 ± 0.00	Madoi Xian	10.57	LDG	11.80 ± 0.72	2.18 ± 0.33	-34.34	13.42	-20.92	HDG	8.55 ± 0.78	3.45 ± 0.49	Maqen Xian	18.48	LDG	14.32 ± 1.43	0.11 ± 0.02	-4.38	0.17	-4.21	HDG	11.95 ± 0.79	0.20 ± 0.05	Nangqen Xian	40.25	LDG	16.50 ± 1.84	0.45 ± 0.14	8.25	-1.13	7.12	HDG	18.55 ± 0.57	0.17 ± 0.28	Qumarleb Xian	293.22	LDG	8.45 ± 0.87	2.63 ± 0.35	-37.53	8.80	-28.73	HDG	7.17 ± 0.83	2.93 ± 0.20	Tanggula	35.47	LDG	7.20 ± 0.62	5.07 ± 0.17	-7.87	2.59	-5.28	HDG	4.98 ± 0.65	5.80 ± 0.36	Tongde Xian	1.91	LDG	13.80 ± 0.97	0.07 ± 0.02	-0.20	0.11	-0.09	HDG	12.73 ± 1.07	0.63 ± 0.21	Xinghai Xian	8.91	LDG	8.72 ± 1.95	2.65 ± 0.08	-0.33	1.83	1.50	HDG	8.35 ± 0.74	4.70 ± 0.13	Yushu Xian	30.46	LDG	16.50 ± 1.02	0.37 ± 0.16	-0.12	-0.91	-1.03	HDG	16.46 ± 1.77	0.07 ± 0.00	Zadoi Xian	64.90	LDG	12.44 ± 2.61	0.08 ± 0.01	-49.32	19.92	-29.40	HDG	4.84 ± 0.33	3.15 ± 0.54	Zekog Xian	3.83	LDG	16.66 ± 1.51	0.25 ± 0.06	-2.77	0.55	-2.22	HDG	9.43 ± 0.93	1.68 ± 0.25	Zhidoi Xian	111.34	LDG	20.48 ± 0.24	0.07 ± 0.01	-98.31	38.30	-60.01	HDG	11.65 ± 1.80	3.51 ± 0.53	Total	841.03				-225.26	81.45	-143.81																																							
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		HDG	12.39 ± 0.77	0.05 ± 0.00				Madoi Xian	10.57	LDG	11.80 ± 0.72	2.18 ± 0.33	-34.34	13.42	-20.92	HDG	8.55 ± 0.78	3.45 ± 0.49	Maqen Xian	18.48	LDG	14.32 ± 1.43	0.11 ± 0.02	-4.38	0.17	-4.21	HDG	11.95 ± 0.79	0.20 ± 0.05	Nangqen Xian	40.25	LDG	16.50 ± 1.84	0.45 ± 0.14	8.25	-1.13	7.12	HDG	18.55 ± 0.57	0.17 ± 0.28	Qumarleb Xian	293.22	LDG	8.45 ± 0.87	2.63 ± 0.35	-37.53	8.80	-28.73	HDG	7.17 ± 0.83	2.93 ± 0.20	Tanggula	35.47	LDG	7.20 ± 0.62	5.07 ± 0.17	-7.87	2.59	-5.28	HDG	4.98 ± 0.65	5.80 ± 0.36	Tongde Xian	1.91	LDG	13.80 ± 0.97	0.07 ± 0.02	-0.20	0.11	-0.09	HDG	12.73 ± 1.07	0.63 ± 0.21	Xinghai Xian	8.91	LDG	8.72 ± 1.95	2.65 ± 0.08	-0.33	1.83	1.50	HDG	8.35 ± 0.74	4.70 ± 0.13	Yushu Xian	30.46	LDG	16.50 ± 1.02	0.37 ± 0.16	-0.12	-0.91	-1.03	HDG	16.46 ± 1.77	0.07 ± 0.00	Zadoi Xian	64.90	LDG	12.44 ± 2.61	0.08 ± 0.01	-49.32	19.92	-29.40	HDG	4.84 ± 0.33	3.15 ± 0.54	Zekog Xian	3.83	LDG	16.66 ± 1.51	0.25 ± 0.06	-2.77	0.55	-2.22	HDG	9.43 ± 0.93	1.68 ± 0.25	Zhidoi Xian	111.34	LDG	20.48 ± 0.24	0.07 ± 0.01	-98.31	38.30	-60.01	HDG	11.65 ± 1.80	3.51 ± 0.53	Total	841.03				-225.26	81.45	-143.81																																																		
Madoi Xian	10.57	LDG	11.80 ± 0.72	2.18 ± 0.33	-34.34	13.42	-20.92																																																																																																																																																																																			
		HDG	8.55 ± 0.78	3.45 ± 0.49				Maqen Xian	18.48	LDG	14.32 ± 1.43	0.11 ± 0.02	-4.38	0.17	-4.21	HDG	11.95 ± 0.79	0.20 ± 0.05	Nangqen Xian	40.25	LDG	16.50 ± 1.84	0.45 ± 0.14	8.25	-1.13	7.12	HDG	18.55 ± 0.57	0.17 ± 0.28	Qumarleb Xian	293.22	LDG	8.45 ± 0.87	2.63 ± 0.35	-37.53	8.80	-28.73	HDG	7.17 ± 0.83	2.93 ± 0.20	Tanggula	35.47	LDG	7.20 ± 0.62	5.07 ± 0.17	-7.87	2.59	-5.28	HDG	4.98 ± 0.65	5.80 ± 0.36	Tongde Xian	1.91	LDG	13.80 ± 0.97	0.07 ± 0.02	-0.20	0.11	-0.09	HDG	12.73 ± 1.07	0.63 ± 0.21	Xinghai Xian	8.91	LDG	8.72 ± 1.95	2.65 ± 0.08	-0.33	1.83	1.50	HDG	8.35 ± 0.74	4.70 ± 0.13	Yushu Xian	30.46	LDG	16.50 ± 1.02	0.37 ± 0.16	-0.12	-0.91	-1.03	HDG	16.46 ± 1.77	0.07 ± 0.00	Zadoi Xian	64.90	LDG	12.44 ± 2.61	0.08 ± 0.01	-49.32	19.92	-29.40	HDG	4.84 ± 0.33	3.15 ± 0.54	Zekog Xian	3.83	LDG	16.66 ± 1.51	0.25 ± 0.06	-2.77	0.55	-2.22	HDG	9.43 ± 0.93	1.68 ± 0.25	Zhidoi Xian	111.34	LDG	20.48 ± 0.24	0.07 ± 0.01	-98.31	38.30	-60.01	HDG	11.65 ± 1.80	3.51 ± 0.53	Total	841.03				-225.26	81.45	-143.81																																																													
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		HDG	11.95 ± 0.79	0.20 ± 0.05				Nangqen Xian	40.25	LDG	16.50 ± 1.84	0.45 ± 0.14	8.25	-1.13	7.12	HDG	18.55 ± 0.57	0.17 ± 0.28	Qumarleb Xian	293.22	LDG	8.45 ± 0.87	2.63 ± 0.35	-37.53	8.80	-28.73	HDG	7.17 ± 0.83	2.93 ± 0.20	Tanggula	35.47	LDG	7.20 ± 0.62	5.07 ± 0.17	-7.87	2.59	-5.28	HDG	4.98 ± 0.65	5.80 ± 0.36	Tongde Xian	1.91	LDG	13.80 ± 0.97	0.07 ± 0.02	-0.20	0.11	-0.09	HDG	12.73 ± 1.07	0.63 ± 0.21	Xinghai Xian	8.91	LDG	8.72 ± 1.95	2.65 ± 0.08	-0.33	1.83	1.50	HDG	8.35 ± 0.74	4.70 ± 0.13	Yushu Xian	30.46	LDG	16.50 ± 1.02	0.37 ± 0.16	-0.12	-0.91	-1.03	HDG	16.46 ± 1.77	0.07 ± 0.00	Zadoi Xian	64.90	LDG	12.44 ± 2.61	0.08 ± 0.01	-49.32	19.92	-29.40	HDG	4.84 ± 0.33	3.15 ± 0.54	Zekog Xian	3.83	LDG	16.66 ± 1.51	0.25 ± 0.06	-2.77	0.55	-2.22	HDG	9.43 ± 0.93	1.68 ± 0.25	Zhidoi Xian	111.34	LDG	20.48 ± 0.24	0.07 ± 0.01	-98.31	38.30	-60.01	HDG	11.65 ± 1.80	3.51 ± 0.53	Total	841.03				-225.26	81.45	-143.81																																																																								
Nangqen Xian	40.25	LDG	16.50 ± 1.84	0.45 ± 0.14	8.25	-1.13	7.12																																																																																																																																																																																			
		HDG	18.55 ± 0.57	0.17 ± 0.28				Qumarleb Xian	293.22	LDG	8.45 ± 0.87	2.63 ± 0.35	-37.53	8.80	-28.73	HDG	7.17 ± 0.83	2.93 ± 0.20	Tanggula	35.47	LDG	7.20 ± 0.62	5.07 ± 0.17	-7.87	2.59	-5.28	HDG	4.98 ± 0.65	5.80 ± 0.36	Tongde Xian	1.91	LDG	13.80 ± 0.97	0.07 ± 0.02	-0.20	0.11	-0.09	HDG	12.73 ± 1.07	0.63 ± 0.21	Xinghai Xian	8.91	LDG	8.72 ± 1.95	2.65 ± 0.08	-0.33	1.83	1.50	HDG	8.35 ± 0.74	4.70 ± 0.13	Yushu Xian	30.46	LDG	16.50 ± 1.02	0.37 ± 0.16	-0.12	-0.91	-1.03	HDG	16.46 ± 1.77	0.07 ± 0.00	Zadoi Xian	64.90	LDG	12.44 ± 2.61	0.08 ± 0.01	-49.32	19.92	-29.40	HDG	4.84 ± 0.33	3.15 ± 0.54	Zekog Xian	3.83	LDG	16.66 ± 1.51	0.25 ± 0.06	-2.77	0.55	-2.22	HDG	9.43 ± 0.93	1.68 ± 0.25	Zhidoi Xian	111.34	LDG	20.48 ± 0.24	0.07 ± 0.01	-98.31	38.30	-60.01	HDG	11.65 ± 1.80	3.51 ± 0.53	Total	841.03				-225.26	81.45	-143.81																																																																																			
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We calculated the change of soil carbon storage by subtracting the soil carbon for the HDG from that for the LDG. *SOCD* soil organic carbon density, *SICD* soil inorganic carbon density, *SOC* soil organic carbon storage, *SICS* soil inorganic carbon storage, *STCS* soil total carbon storage, *Change of SOCS* the change of SOCS from LDG to HDG, *Change of SICS* the change of SICS from LDG to HDG, *Change of STCS* the change of STCS from LDG to HDG

degraded grassland ($0.06\text{--}5.93\text{ kg m}^{-2}$, and $0.05\text{--}5.87\text{ kg m}^{-2}$, respectively). Both SOCD and SICD varied significantly with grassland degradation, but the change in SOC was greater than that in SIC.

The SOC stock decreased with grassland degradation across all counties in the region. The SIC storage increased in most counties with grassland degradation, but little change was observed in SIC. This is because the SIC stock decreased first, and then increased with grassland degradation; however, SIC only increased when grassland was seriously degraded (Liu et al. 2014). The increase in SIC in most counties illustrates that the grassland in these counties has been seriously degraded. Overall, soil total carbon (STC) storage decreased with grassland degradation in all counties, except Xinghai, indicating that most counties in the Northern Tibetan region have a potential carbon sequestration capacity following rehabilitation to lightly or non-degraded grassland.

Discussion

Grassland degradation and soil carbon storage

Some studies have indicated that human activities may have a large influence on SOC and SIC (Post and Kwon 2000; Wu et al. 2009). The impact of human activities on alpine grasslands in the Qinghai-Tibetan region is mainly through livestock grazing (Cao et al. 2004). Long-term overgrazing disrupts of the grassland ecosystem (Brekke et al. 2007) and recent increases in livestock grazing may have led to widespread grassland degradation in the alpine grasslands.

Grassland degradation can influence soil carbon storage because it affects both the carbon inputs from plant production and the carbon outputs through decomposition within the soil (Conant et al. 2001). Hirota et al. (2005) reported that net ecosystem CO_2 uptake and aboveground biomass decreased significantly after a grazing treatment for a period of about 3 months. We found that the aboveground biomass was much smaller in the heavily degraded than in the lightly or non-degraded grasslands. Hopkins et al. (2012) reported that the reduction of aboveground biomass reduced photosynthetic carbon gain and thus led to a decrease in SOC. Conversely, underground biomass with no-grazing control was higher than that in the heavily grazed sites (Guodong and Zhijun 1993). Our study also found that the underground biomass decreased dramatically from LDG to HDG. Soil organic carbon originates from plant residue, soil fauna, and soil microbial activity. Under grassland degradation, rapidly declining soil organic matter content may be mainly due to the lower plant biomass input into the soil (Post and Kwon 2000).

We found that the soil pH was higher in HDG than in LDG. Shi et al. (2012) suggested that low pH condi-

tions promote the decomposition of SIC and lead to a significant loss of carbon from the soil. In addition, SIC accumulates more easily under alkaline conditions (Ahmad et al. 2012). This weakening SOC source may explain why SIC was higher in HDG than in LDG. We also found that the major factor affecting SOC varied under different degradation conditions: soil pH and UGB played a major role in LDG and HDG, respectively. Despite the degradation status, soil pH and AGB appeared to be the critical factors affecting the vertical distribution of SIC.

Soil carbon in relation to climatic factors

Climate change may impact on soil carbon, especially in cooler regions (Gao et al. 2010). An increase in the temperature of the environment could either increase or decrease soil carbon storage, depending on the relative influence of the increase in temperature on ecosystem photosynthesis and respiration (Trumbore and Czimczik 2008; Smith and Fang 2010). Our results suggest that SOC density increases significantly with local temperature in the alpine ecosystems, consistent with the study of Yang et al. (2008). This implies that the ambient temperature in alpine ecosystems limits photosynthesis more than it limits respiration. Further studies are needed to clarify the relative effect of temperature increase on these two processes. In particular, the relationship between ambient temperature and SIC should be considered, as this has long been overlooked.

The relationship between SOC density and MAP can vary with temperature. Our results indicate that SOC increased with local precipitation in the alpine grassland Albaladejo et al. (2013) reported that a reduction in rainfall reduced SOC. These results are consistent with another study showing that SOCD was positively correlated with precipitation (Post et al. 1982). However, the simulations of Alvaro-Fuentes et al. (2012) revealed that decreasing annual precipitation and increasing temperature resulted in SOC gains relative to the baseline conditions. This can be attributed to the key role of precipitation in biomass productivity, where annual precipitation is the main driving force of the alpine grassland NPPP (Bardgett et al. 2008). Also, rooting patterns will change because of altered precipitation (Heimann and Reichstein 2008). However, we found that SIC decreased with increasing MAP. Mi et al. (2008) reported similar results. The correlations between soil carbon and MAT and MAP were very low, owing to the interaction between MAT and MAP. Precipitation has a strong impact on temperature on the Tibetan Plateau.

Potential carbon sequestration

Recently, much effort has been made to mitigate global warming and this can be aided by increasing C seques-

tration in terrestrial ecosystems. Biological approaches are natural and cost-effective, with numerous ancillary benefits (Lal 2003). The restoration of degraded soils and the adoption of recommended management practices on soils can reverse degradation trends and lead to SOC sequestration (Lal 2004). Inorganic C sequestered from land-use changes has little potential to make a significant impact on the concentration of atmospheric CO₂ (Wu et al. 2009). Land-use changes have an immediate effect on the regional rate of C sequestration by incorporating CO₂ in plant biomass (Jandl et al. 2007). Enhancing soil quality through adopting proper management practices and soil restoration may increase SOC concentration and soil productivity, and lead to an increase in SOC sequestration (Lal and Bruce 1999; Conant et al. 2001). Efforts to increase soil carbon storage through conservation management have gained momentum in the past few decades, particularly countering the effects of global warming (Sarkhot et al. 2012). Our data indicate that the SOC density was lower if the grazing intensity was too high or too low. Therefore, proper management can achieve the optimum grassland carbon sequestration. Reduction in grazing pressure, especially during winter, is thought to be critical for the restoration and sustainable use of grassland ecosystems in the Northern Tibetan region (Fan et al. 2010).

The SOC stock in the top 30 cm accounts for 9.1% of the total stock (32.9 Pg) in China (Yang et al. 2007), while SIC in that same layer contributes only 2.4% of the total SIC stock (15.2 Pg). Yang et al. (2010) reported that SOC storage in the surficial 30 cm varied significantly between different regions, reaching a maximum on the Tibetan Plateau. According to the present study, the potential capacity of carbon sequestration in the grassland of this region is estimated as 0.14 Pg. The potential for carbon sequestration in the Northern Tibetan region may vary with livestock conditions, as well as the changes in livestock grazing. Carbon sequestration may be achieved through the restoration of degraded soils, and the adoption of recommended management practices (Lal 2004). Grasslands can act as a significant carbon sink with the implementation of improved management (Conant et al. 2001). The potential capacity of carbon sequestration in the grassland of the Tibetan region is estimated as 0.14 Pg. However, human activities and the harsh environment will hamper recovery.

Conclusions

This study was designed to investigate the response of SOC and SIC to the degradation of grassland in Northern Tibet. A large area of grassland has been degraded in Northern Tibet in recent decades mainly due to overgrazing of livestock. This may have significant and long-term effects on the ecosystem carbon cycle, in particular, on soil carbon. Using soil samples from

grasslands with different degradation states, we show that SOC was significantly lower while SIC was somewhat higher in the heavily degraded grassland compared with the lightly or non-degraded grassland. Degradation also changed the vertical distribution of soil carbon, and other soil properties, such as, soil pH, which in turn may further affect soil carbon accumulation. This study demonstrated that this region has a potential carbon sequestration capacity of 0.14 Pg following rehabilitation to lightly or non-degraded grassland. These results suggest that reducing the intensity of livestock grazing to a moderate level may enhance soil carbon sequestration, which is one of the promising approaches to climate mitigation in the future. This work has established a database of soil carbon sequestration capacity in the Northern Tibetan region. Further studies are required to investigate the rates of carbon sequestration by soil in the Tibetan grasslands.

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