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Impacts of management practices on soil organic carbon in degraded alpine meadows on the Tibetan Plateau

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Abstract

Grassland soil organic carbon (SOC) is sensitive to anthropogenic activities. Increased anthropogenic disturbance related to overgrazing has led to widespread alpine grassland degradation on the Tibetan Plateau. The degraded grasslands are considered to have great potential for carbon sequestration after adoption of improved management practices. Here, we calibrated and employed the Century model to investigate the effects of overgrazing and improved managements on the SOC dynamics in alpine meadows. We calibrated Century model against plant productivity at Haibei Research Station. SOC stocks for validation were obtained in 2009–2010 from degraded alpine meadows in two communes. We found that Century model can successfully capture grassland SOC changes. Overall, our simulation suggests that degraded alpine meadow SOC significantly increased with the advent of restoration managements from 2011 to 2030. Carbon sequestration rates ranged between 0.04 Mg C $\mathrm{ha^{-1}\,yr^{-1}}$ in lightly degraded winter grasslands and 2.0 Mg C $\mathrm{ha^{-1}\,yr^{-1}}$ in moderately degraded summer grasslands. Our modeling work also predicts that improve management in Tibetan degraded grasslands will contribute to an annual carbon sink of 0.022–0.059 Pg C $\mathrm{yr^{-1}}$. These results imply that restoration of degraded grasslands in Tibetan Plateau has great potential for soil carbon sequestration to mitigate greenhouse gases.

1 Introduction

Grassland soils play a critical role in stabilizing or reducing atmospheric carbon, as they occupy about a quarter of the world's land surface and store 10 % of global carbon storage (Scurlock et al., 2002). It has been documented that extensive areas of grassland have suffered some degradation (Harris, 2010; Kemp et al., 2013). Losses in soil organic carbon (SOC) by degradation have been large, undoubtedly affecting the terrestrial greenhouse gas balance. Alpine grasslands on the Tibetan Plateau, accounting for over 60 % of the total plateau area, have been grazed for millennia (Yang et al., 2008; Harris, 2010). Due to increased disturbance from livestock populations over the last 50 yr (Harris, 2010; Miehe et al., 2008), one third of alpine grasslands were in a degraded state in 1990s (Duan et al., 2013). The degradation of the Tibetan grasslands has led to loss of soil carbon of 1.01 Pg since the 1980s, which is more than twice of potential carbon accumulation due to climate change and elevated CO_2 concentration (Xie et al., 2007). Alternatively, degraded grassland soils may have substantial potential for sequestering carbon through improving management practices, which weaken or even reverse negative effects of overgrazing. Evidence from early observational studies has agreed on the promoted grassland productivity and soil carbon replenishment after adoption of improved management practices (Wang et al., 2011). Guo et al. (2008) estimated that the adoption of improved management practice could potentially sequester 15.24–65.75 $\mathrm{Mg\,C\,ha^{-1}}$ in degraded alpine grassland soils. However, the magnitude of this potential sinks varies markedly among management practices (Wang et al., 2011; Guo et al., 2008). Characterizing management practices on the SOC stock has important implications for mitigation policies designed to absorb anthropogenic CO_2 emissions.

Quantifying the potential of SOC sequestration is a great challenge due to temporal and spatial heterogeneity of soil properties, environmental conditions, management history, and other complex interactions between these components (Yang et al., 2009; Luo and Weng, 2011). Extrapolation of site-specific results to other soil and climate often leads to great uncertainty. However, simulation models are essential to integrate data from long-term experiments and process studies together with information from spatial-scale surveys, which can overcome the extrapolating limitations (Luo and Weng, 2011). Additionally, models have flexibility to simulate various management practices, such as grazing, tillage, and fertilization (Xu et al., 2010; Wang et al., 2008). During the past decades, several types of models have been widely applied to simulate regional carbon cycle on the Tibetan Plateau, such as TEM, Century, BIOME-BGC and LSM (Tan et al., 2010; Zhang et al., 2007; Zhuang et al., 2010). However, application of these generic carbon cycle models suffers from a lack of systematic calibration and validation against observations due to limited filed experiments (Tan et al., 2009). Moreover, these modeling studies evaluated the carbon cycle over the plateau neglected human disturbances and grazing influences (Zhang et al., 2007; Piao et al., 2012). Considering extensive area of degraded grasslands and great potential for carbon sequestration on the Tibetan Plateau, there is a need for understanding the impact of management practices on SOC pools.

In this study, we applied the widely used process–based Century model to evaluate the SOC response to human disturbances and grazing influences in Tibetan alpine grasslands. The model parameterizations were calibrated using plant productivity measurements at an alpine meadow site. Soil profile data sampled from Tangde and Xiala communes in Zeku County was used to validate the simulated soil carbon at depleted state due to overgrazing. We then used the verified Century model to conduct simulations on SOC response to typical restoration managements on the Tibetan Plateau, and to quantify the uncertainty of SOC sequestration.

2 Materials and methods

2.1 Study area

The study area spread over approximately 1.9 × 10^4 ha in the boundaries of Tangde and Xiala villages in Zeku County, Qinghai province, China. The altitude varies from 3400 to 4100 m. The mean annual temperature is about $-2 \sim 2.3\,^{\circ}$C. The mean annual precipitation is 460 mm (Table 1). Alpine meadow was the dominant vegetation types, which consists of *Kobresia pygmaea* (C.B. Clarke), *K. humilis* (C.A. Mey) Serg., and *K. tibetica* Maxim. The growing season normally starts in mid-May and lasts until mid-September. The soil is classified as alpine meadow soil or Mat Cry-gelic Cambisols (The Chinese soil taxonomy). Pastoralism is the dominant land use in this area for several centuries. Livestock numbers have increased during the last 50–60 yr. At the same time, alpine meadow in this area has degraded, with characteristics of vegetation coverage and productivity decrease, soil fertility change, and soil loss.

2.2 Soil sampling and analyses

Soil samples were collected in late August through early September of 2009 and 2010, with 591, 204, 121 and 280 sites for lightly, moderately, heavily and extremely degraded summer grassland, respectively. At each sampling sites, five cores were extracted for depth intervals of 10 cm to a depth of 20 cm, and pooled in the field by depth. The soil samples were air-dried, processed to remove visible plant visible plant residue and then sieved (2 mm mesh) for further analysis. Soil bulk density was determined with core cutters (100 cm^3, diameter 5.3 cm). SOC concentration was measured using a Shimadzu SOC-5000 analyzer (Shimadzu corp., Kyoto, Japan). Soil texture was determined by a particle size analyzer (MasterSizer, 2000). Soil pH was measured using a pH meter in soil water suspension, with a soil: water ratio of 1 : 2.5. Soil carbon concentrations were converted to areal estimates for 0–20 cm depth using soil bulk density for each site.

2.3 Century model simulations

2.3.1 Century model

Century model is a highly integrated process-based ecosystem model that calculates plant growth and variations of carbon and nutrient on monthly basis. The model consists of three major coupled modules for vegetation process, exchange of water and energy and terrestrial carbon cycle. It partitions soil organic matter into active pool, slow pool and passive pool with turnover times of 1–15 yr, 20–40 yr and 200–15 000 yr, respectively. Century model has been used extensively to simulate the fluxes and storage of carbon in various terrestrial ecosystems that driven by multiple natural and anthropogenic perturbations (e.g. climate change, CO_2 concentration, and land use and management practices).

Grazing event can be realistically simulated in Century model by removing defined fraction of aboveground live and standing dead plant material each month. The model has three options as proxy of grazing influences (Feng and Zhao, 2011): option 1, there are no direct impacts of grazing on plant production; option 2 refers to light grazing with a constant root: shoot ratio and a linear decrease in potential plant production with increasing grazing intensity; option 3 represents moderate and heavy grazing where aboveground plant production increases for moderate grazing and decreases sharply for heavy grazing. The root: shoot ratio is constant for low to moderate grazing and sharp decreases for heavy grazing. The century model could also simulate other human disturbances such as fertilization and tillage. More detailed information about the model structure and processes can be found in previous studies (Feng and Zhao, 2011; Zhang et al., 2007).

2.3.2 Model calibration

Model calibration was performed on an alpine meadow field at the Haibei Research Station, Chinese Academy of Science. The sample field has been fenced since 1980, which had been used for winter free grazing (November–May). Climate change and vegetation dynamics then have been monitored each year. Monthly precipitation, maximum and minimum temperature were measured with an automatic weather station (Table 1). Aboveground plants were cut in 10–20 quadrats of 50 × 50 cm during the growing season and aboveground biomass was measured using the weighing method. Aboveground biomass of sample field was the average value of the quadrats. In calibration, aboveground biomass dynamic and monthly meteorological data were provided by the Haibei Research Station. Century was calibrated by iteratively running the model to equilibrium for 5000 yr (from 3020 BC to 1980) with the initial grazing intensity of 50 % (50 % of live shoots was removed by grazing event per month). Starting from this equilibrium state, the model was integrated for 1998–2007, forced by observed weather data. We then inspected the simulated outputs and altered the vegetation parameters until the aboveground biomass matched the measured values.

2.3.3 Model validation

We validated the model output with a set of SOC observations obtained from our study area independent of the calibration phase. We kept the model adjustments described as "model calibration" and only modified the model schedule and site variables. Weather data necessary for running the model were obtained from the meteorological station at Zeku County, about 40 km from the study area. A general representative grassland management scenario was developed for the region based on published historical accounts, farm census and farmer interviews. Livestock numbers have increased in the early 1960s in the study area. Thus grassland management practices were divided into two categories, corresponding periods of 0–1960 as summer free grazing (June–October) with 50 % intensity and 1960–2010 as overgrazing with 55, 65, 80, 95 % intensities for lightly, moderately, heavy and extremely grazing, respectively. Soil carbon stocks from the consecutive field surveys during 2009–2010 were averaged and used to assess model performance in 2010.

2.3.4 Simulation protocol

A series of management scenarios related to grazing and restoring were adopted in the modeling. In simulation S1–S4, S5 and S6, grazing intensities were varied for lightly and moderately degraded states; in simulation S7 and S8 for heavily and extremely degraded states, artificial pasture will be established accompanied with fertilization (Table 2). Nitrogen fertilizer amounts used were based on nutrient recommendation in alpine meadow soils. These simulated practices have been adopted since passing the latest Grassland Law in 2002 and will be expanded on the Tibetan Plateau in the future. We also considered two sets of grazing managements, the winter grazing and summer grazing, which are prevalent on the plateau. In the simulations, for purposes of brevity, site variables were averaged for degraded states with broadly similar grazing management.

2.3.5 Modeling uncertainty

The CDM EB approved "*General Guidelines For Sampling And Surveys For Small-Scale CDM Project Activities*"[14] with a view to reducing the uncertainty of model input parameters. As depicted in *Methodology for Sustainable Grassland Management (SGM)*, we estimated uncertainty using the model inputs with the upper and lower limits of the 95 % confidence level. The range of modeling response demonstrates the uncertainty of the soil modeling. First, SOC sequestration estimates were computed using the minimum and maximum values of the model input; then, a percentage uncertainty was estimated based on half of the range divided by the SOC sequestration induced by the mean values of the model input. Following the proposed SGM Methodology, we set tolerable uncertainty of 30 % for carbon sequestration. In this uncertainty analyses, climate and soil model parameters (mean maximum and minimum air temperature, precipitation, soil texture, soil bulk density and pH) were considered simultaneously with the assumption of normal distribution. Finally, projected sequestration was adjusted with the modeling uncertainty. If the modeling uncertainty is 15 % or less, SOC sequestration estimates were reported without any adjustments.

3 Results

3.1 Model calibration and validation

After the model parameters adjustments accomplished by simulating grassland management scenarios according to the conditions of the long-term experiment at Haibei Research Station, we checked the consistency between the modeled evolution of productivity and measurements from 1998 to 2010. A significant linear relationship ($p < 0.001$) was found between measured and modeled aboveground biomass with

r^2 of 0.89 and RMSE of 17.52 %, showing that the model could moderately simulate productivity dynamics of alpine meadow (Fig. 1). As explained earlier, we applied the site-specific SOC inventory in summer grazed grasslands for validation of the optimized model. The simulation of SOC is comparable with the observation, with light, moderate, heavy and extreme degradation RMSE of 10.04, 12.01, 11.20 and 12.01 %, respectively (Fig. 2). We concluded that the model simulated the effect of grazing on soil carbon stocks reasonably well.

3.2 SOC response to improved managements

Significant increases in SOC stocks were noted after adoption of improved managements such as fertilizer application, reduced grazing intensity, altered grazing timing and cultivated pasture from 2011 onwards. Although simulated SOC dynamics showed similar trajectories among degraded grasslands with varying degrees, the magnitude was largely variability (Figs. 3 and 4). Larger increase in soil carbon could be predicted for original summer grassland with more degraded degrees. For example, simulation S1 predicted that annual SOC in summer grassland has increased 0.60 $\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$ in project periods 2011–2030, while it was only 0.04 $\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$ in winter grassland in lightly degraded state (Table 3). Similarly, modeled SOC accrual rate was higher in the summer than in the winter grasslands in moderately, heavily and extremely initial degradation state, respectively, even adopting the same restoration trials (S3, S5 and S6, Table 3). In general, lower SOC sequestration rates were found in less degraded as compared with higher degraded degrees. The simulation S4 in the summer grassland in moderate degradation state had the greatest sequestration rate, whereas the lowest rate was observed in simulation S1 for light degradation of winter grassland. The summer grassland soils were projected (2011–2030) to sequester 12.03–21.44 $\mathrm{Mg\,C\,ha^{-1}}$ for lightly, 38.42–40.08 $\mathrm{Mg\,C\,ha^{-1}}$ for moderately, 37.57 $\mathrm{Mg\,C\,ha^{-1}}$ for heavily and 38.59 $\mathrm{Mg\,C\,ha^{-1}}$ for extreme degradation, respectively, while for the winter grassland these were 0.75–0.99, 3.21–7.51, 6.88 and 8.58 Mg C ha^{-1}, correspondingly. The projected uncertainties were 4.31–28.93 %.

4 Discussion

4.1 Overgrazing causing SOC losses

Our modeling analysis showed a considerable reduction in SOC in the overgrazing periods from 1960 to 2010. Loss of native stocks was approximately 18 %, 37 %, 38 % and 40 % in lightly, moderately, heavily and extremely degraded summer grasslands, respectively. Recently, a meta-analysis of data from alpine grasslands concluded that lightly, moderately and severely degraded pastures lost (27 ± 8) %, (49 ± 4) % and (55 ± 3) %, respectively, of SOC stocks in the non-degraded pasture (Huang et al., 2010). Several field experiments on the Tibetan Plateau revealed that SOC in lightly degraded grasslands was comparable to intact grassland, with its SOC varying from 90 % to 102 % of the SOC in intact grasslands, while moderately and heavily grazed grasslands demonstrated a significantly decrease in SOC content of 77–91 % (Pei, 2004; Wang et al., 2007). The difference in carbon losses between studies may be in part due to the significant differences in soil texture. Coarse, sandy soils are less resistant to wind and rainfall than finer textures soils, so the greater losses being reported for coarse textured soils (Batlle-Bayer et al., 2010; McSherry and Ritchie, 2013). Such SOC loss may also vary according to the local climate. The relatively greater precipitation simulated organic matter decomposition, thus amplified the negative effects of overgrazing (McSherry and Ritchie, 2013).

4.2 SOC sequestration of degraded alpine grasslands

All improved management practices increased soil carbon over the project period (2011–2030). The magnitude of soil carbon sequestration depended on management practices as well as initial seasonal utilization systems (summer or winter grazing) and degraded states. One underlying "carbon saturation" mechanisms may dictate these patterns (Conant et al., 2001). Initial SOC was identified as the predominant environmental variable that negatively influenced SOC sequestration (Zhao et al., 2013). Recent work in grasslands suggests that larger accumulation was found in soils with low initial carbon and less in soils with initial high carbon stocks (Wang et al., 2011). In our study, carbon sequestration in more sever degree of degradation state was larger than in lesser degrees. Overall, the potential SOC sequestration in the summer was greater than in the winter degraded grasslands, even degradation levels and restoration managements were essentially the same. Summer grazing has been shown to reduce the green leaf area and thus carbon uptake, while grazing during the dormant season only alter soil characteristics such as surface hydrology and aggregate stability (Wolf et al., 2010). This suggested that grazing after plant senescence may have less impact on soil carbon stocks than systems grazed while still growing. Therefore, loess of soil carbon in summer grasslands was larger than winter grasslands with the same grazing intensity, on the other hand, the larger sequestration potential if improved management practices were adopted. This also suggested that shifting grassland utilization from summer to winter regime might contribute to soil carbon accumulation.

Our findings regarding the SOC sequestration in degraded grasslands after adoption of improved managements are compatible with studies conducted in the Tibetan Plateau. Shi et al. (2009) and Guo et al. (2008) reported that re-sown pastures reclaimed from degraded grassland sequestered soil carbon at a rate of 1.26 and 1.09 $\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$, respectively. Soil carbon sequestration rate in our modeling study showed similar potential with reported carbon sequestration values in fenced exclosures which grazing have been excluded (Shi et al., 2009; Guo et al., 2008; Wang et al., 2011). However, it has to be kept in mind that adjustment in stocking rates to avoid overgrazing, rather than grazing prohibition, used as a management tool in our simulations. Other management practices may compensate for the negative effect of grazing on SOC such as reduction in C input to soil. Application of fertilizers, adapted stocking rates and introduction of cultivated pastures may be suitable options for Tibetan Plateau, considering economic wellbeing of millions of traditional pastoralists and ecological sustainability.

Our local level simulations could be severe as a reference when estimating possible SOC gains of Tibetan degraded grassland at the regional scale. Duan et al. (2013) reported that towards the end of last century about 33 % of Tibetan grasslands were degraded to different degrees, of which ca. 16.54 % was extremely degraded. We predicted roughly an annual carbon sink in Tibetan degraded grassland soils of 0.022 to 0.059 $\mathrm{Pg\,C\,yr^{-1}}$ in the 0–20 cm depth layer, assuming half of the total degraded area was summer grasslands, which is similar to net carbon sequestration in Tibetan forests (0.024 $\mathrm{Pg\,C\,yr^{-1}}$) over the 1980s and 1990s (Fang et al., 2007). This sequestration would be equivalent to 1–4 % of fossil fuel $\mathrm{CO_2}$ emissions in China in 2006 (Gregg et al., 2008). However, the magnitude of soil carbon sequestration may be potentially underestimated when considering topsoil only, in view of sequestration capacities in deeper soil depth (Wang et al., 2011).

4.3 Uncertainties

Although the parameterizations of Century model were improved and calibrated against temporal observations of plant growth of a long-term alpine meadow experiment, large uncertainties still remain in our simulation of the soil carbon dynamics due to the uncertainty of forcing data. The climate forcing extrapolated from meteorological station about 40 km away from our study area may not well represent the spatial change of climate over the small mountainous region with a large range of elevation (from 3100 to 4200 m). In addition, averaging soil characteristics by degradation-level obscured the complexities of landscapes. Similarly, the scale of the historic grassland management scenarios utilized contains implicit generalizations that oversimplified the field-specific herder's activities because herders often shared limited information about history of fields, especially grazing intensity (Tornquist et al., 2009). Without considering these nuances, uniform grassland management practices could lead to large uncertainty in

SOC sequestration at site scale. A spatially explicit simulation of management history in future studies where information about past management is available would help improve SOC modeling (Tornquist et al., 2009).

Another source of uncertainty is related to the propagation of “adjusted” model parameters. Although soil carbon simulations for winter grasslands were conducted, we must emphasize that the model inputs for winter grasslands were based on extrapolation from summer grasslands inputs applied. This may have also contributed to some modeling errors. Nevertheless, the similarity between these winter and summer grasslands (e.g., plant composition and soil type), which provides a base for our modeling work, may lead to small uncertainty derived from the propagation of model inputs.

Besides above mentioned, climate change could also influence the soil carbon balance of the grasslands through altering plant growth and organic matter decomposition (Yang et al., 2009). There is general agreement that the Qinghai-Tibetan Plateau is particularly sensitive to global climate change (Tan et al., 2007; Piao et al., 2012). Sources provided statistical evidence of a general warming trend on the Qinghai-Tibetan Plateau over the past decades (Liu et al., 2006; Piao et al., 2012). For Zeku county, precipitation trends displayed no discernible change, while temperature has significantly increased over the past three decades (from 1960 to 1990). Small increases in summer temperatures will improve vegetation growth in this region where growing seasons are short and cold to begin with (Zhang et al., 2013). This resulting increase in carbon inputs may override the temperature-induced rise in soil decomposition rates, and consequently SOC would tend to increase (Qi et al., 2011). Considering that short-term climate warming is most likely to benefit SOC accumulation, we speculated that our estimates of carbon sequestration over the period 2010 to 2030 were conservative.

5 Conclusions

We concluded that the Century model well described the behavior of alpine meadow SOC stocks in 2010 after being calibrated against field data 1998–2004 of Haibei Research Station. Simulation of overgrazing implemented by 1960 and extended to 2010 showed a SOC stock depletion. Improved grassland management, such like application of fertilizers, adapted stocking rates, shift of grazing season, establishment of cultivated pasture, led to the considerable soil carbon sequestration by 2030. The predicted SOC sequestration rates were in accordance with the general sequestration rates given in the literature for Tibetan alpine meadow. Grazing regime adjustment (including grazing intensity and grazing season) and cultivated pasture establishment are potential effective strategies to increase SOC in Tibetan grasslands and could subsequently offset anthropogenic CO_2 emissions.

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Table 1. Site parameters at Haibei Research Station and the study area.

Site parameter	Haibei Station	Zeku County
Location	37°36′ N, 101°18′ E	35°14′ N, 101°15′ E
Altitude (m a.s.l.)	3200	3680
Soil texture (clay, silt, sand) (%)	0.24, 0.39, 0.37	0.27, 0.38, 0.35
Bulk density (g cm^{-3})	0.93	0.89
Soil pH	7.5	7.0
Minimum mean monthly temperature (°C)	−6.0	−8.0
Maximum mean monthly temperature (°C)	9.5	6.7
Mean precipitation (mm)	522.2	448.8
Vegetation type	Alpine meadow	
Soil type	Mat-Cryic Cambisols	

Climate parameters were averaged from 1960 to 2005, and from 1991 to 2000 in Haibei Research station and study area, respectively.

Table 2. Scheduling of management practices in Century in Zeku County.

Scenario	Period	Management practice
S1	2011–2020	Graz: Jun–Oct; 45 %
	2021–2030	Graz: Jun–Oct; 50 %
S2	2011–2030	Graz: Nov–Apr; 50 %
S3	2011–2020	Graz: Jun–Oct; 30 %
	2021–2030	Graz: Jun–Oct; 50 %
S4	2011–2020	Graz: Nov–Apr; 40 %
	2021–2030	Graz: Nov–Apr; 50 %
S5	2011	Cultivation: No-till-drill
		Graz: Nov–Apr; 50 %
	2012–2014	Graz: Nov–Apr; 50 %
	2015	Fertilizer: 15 g N/m2 in Jul
		Graz: Nov–Apr; 50 %
	2016–2024	Graz: Nov–Apr; 50 %
	2025	Fertilizer: 15 g N m^{-2} in Jul
		Graz: Nov–Apr; 50 %
	2026–2030	Graz: Nov–Apr; 50 %
S6	2011	Cultivation: Plowing; Cultivator
		Fertilizer: 15 g N m^{-2} in May
	2012–2014	Graz: Nov–Apr; 50 %
	2015	Fertilizer: 15 g N m^{-2} in Jul
		Graz: Nov–Apr; 50 %
	2016–2020	Graz: Nov–Apr; 50 %
	2021	Cultivation: Plowing; Cultivator
		Fertilizer: 15 g N m^{-2} in May
	2022–2024	Graz: Nov–Apr; 50 %
	2025	Fertilizer: 15 g N m^{-2} in Jul
		Graz: Nov–Apr; 50 %
	2026–2030	Graz: Nov–Apr; 50 %
S7	2011–2020	Graz: Nov–Apr; 45 %
	2021–2030	Graz: Nov–Apr; 50 %
S8	2011–2020	Graz: Nov–Apr; 40 %
	2021–2030	Graz: Nov–Apr; 50 %

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Table 3. Soil carbon sequestration of degraded grasslands under different management practices.

Present condition		Management practice	SOC_{2010} ($kg\,C\,m^{-2}$)	SOC_{2030} ($kg\,C\,m^{-2}$)	SOC sequestration ($Mg\,C\,ha^{-1}$)	Modeling uncertainty (%)	Modified SOC sequestration ($Mg\,C\,ha^{-1}$)	SOC sequestration rate ($Mg\,C\,ha^{-1}\,yr^{-1}$)
Summer grassland	L	S1	10.97	12.17	12.03	4.31	12.03	0.60
		S2	10.97	13.11	21.44	5.24	21.44	1.07
	M	S3	8.43	12.89	44.63	28.93	38.42	1.92
		S4	8.43	12.95	45.26	26.43	40.08	2.00
	H	S5	8.30	12.45	41.47	24.41	37.57	1.88
	S	S6	8.02	12.47	44.57	28.42	38.59	1.93
Winter grassland	L	S7	13.08	13.18	0.99	8.92	0.99	0.05
		S1	13.09	13.16	0.75	10.25	0.75	0.04
	M	S8	11.58	12.35	7.70	17.42	7.51	0.38
		S3	11.58	11.92	3.37	19.53	3.21	0.16
	H	S5	11.12	11.82	7.05	17.35	6.88	0.34
	S	S6	11.08	11.98	9.03	19.94	8.58	0.43

L, M, H and S represent the lightly, moderately, heavily and severely degraded alpine meadows, respectively. SOC_{2010}, SOC_{2030}: SOC stocks in 2010 and 2030. SOC sequestration was calculated by difference between SOC_{2030} and SOC_{2010}. Modified SOC sequestration was an adjusted estimate of SOC sequestration based on SAGM methodology. S1–S8 were demonstrated in detail in Table 2.

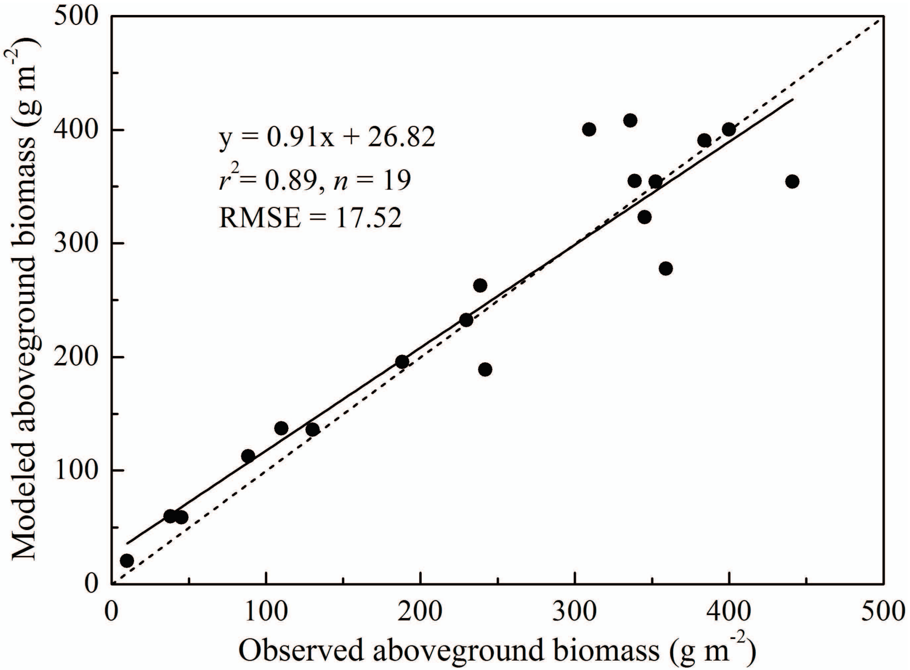

Fig. 1. Comparison of observed and modeled above ground biomass of alpine meadow at Haibei Research Station in Tibetan Plateau for 1998–2010.

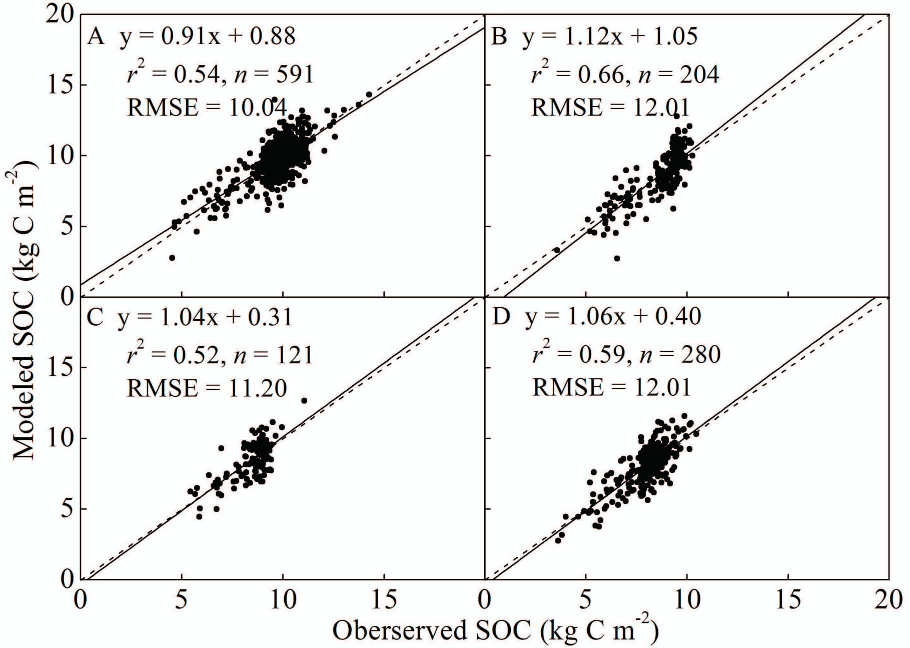

Fig. 2. Comparisons of observed and modeled grassland SOC stocks for **(A)** lightly, **(B)** moderately, **(C)** heavily **(D)** and extremely degraded states, respectivily.

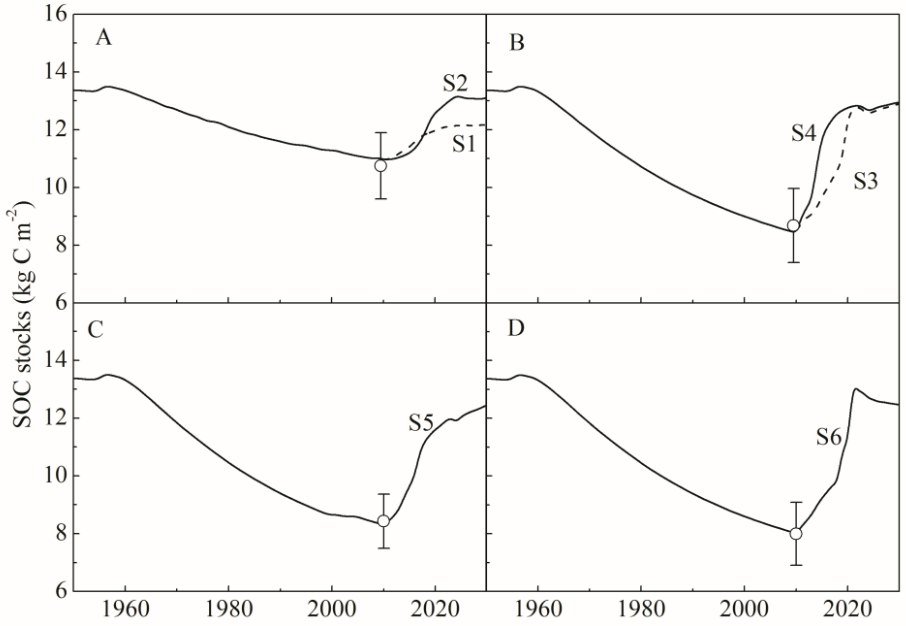

Fig. 3. Soil organic carbon trajectory of the **(A)** lightly, **(B)** moderately, **(C)** heavily and **(D)** extremely degraded summer grasslands as simulated by Century model. Dots represent averaged SOC stocks measuresd in 2009–2010 and bars are standard deviations. Simulations S1–S6 correspond to scenarios from Table 2.

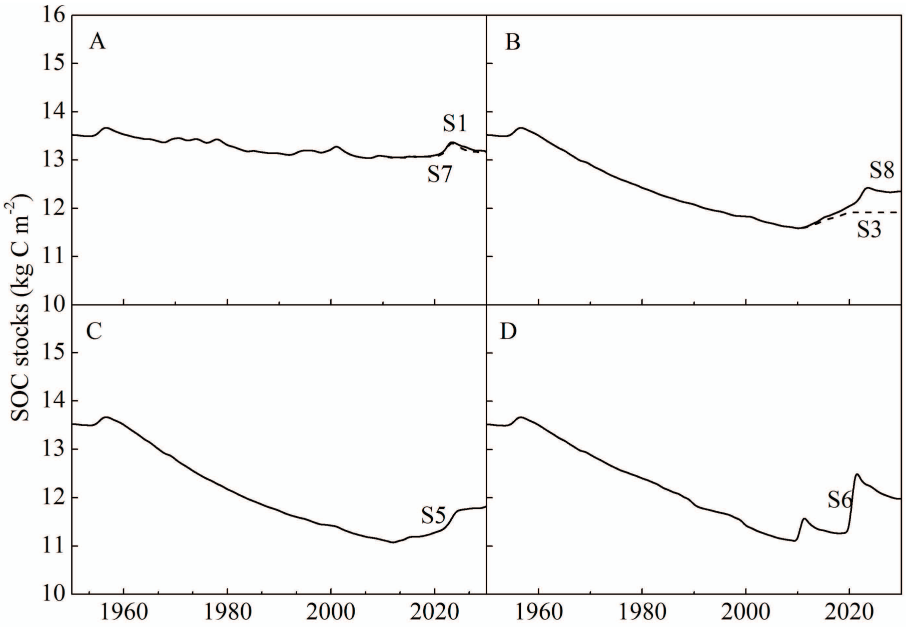

Fig. 4. Soil organic carbon trajectory of the **(A)** lightly, **(B)** moderately, **(C)** heavily and **(D)** extremely degraded winter grasslands as simulated by Century model. Simulations S1, S3 and S5–S8 correspond to scenarios from Table 2.