Modeling impacts of climate change and grazing effects on plant biomass and soil organic carbon in the Qinghai–Tibetan grasslands

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Abstract:

The Qinghai Province supports over 40% of the human population but occupies about 29% of the land area, and thus it plays an important role in the entire Qinghai–Tibetan Plateau (QTP). The dominant land cover is grassland, which has been severely degraded over the last decade due to a combination of increased human activities and climate change. Numerous studies indicate that the plateau is sensitive to recent global climate change, but the drivers and consequences of grassland ecosystem change are controversial, especially the effects of climate change and grazing patterns on the grassland biomass and soil organic carbon (SOC) storage in this region. In this study, we used the DeNitrification-DeComposition (DNDC) model and two climate change scenarios (representative concentration pathways: RCP4.5 and RCP8.5) to understand how the grassland biomass and SOC pools might respond to different grazing intensities under future climate change scenarios. More than 1400 grassland biomass sampling points and 46 SOC points were used to validate the simulated results. The simulated above ground biomass and SOC concentrations were in good agreement with the measured data (R^2 0.71 and 0.73 for above ground biomass and SOC, respectively). The results showed that climate change may be the major factor that leads to fluctuations in the grassland biomass and SOC, and it explained 26.4% and 47.7% of biomass and SOC variation, respectively.

Meanwhile, the grazing intensity explained 6.4% and 2.3% variation in biomass and SOC, respectively. The project average biomass and SOC between 2015–2044 was significantly smaller than past 30 years (1985–2014), and it was 191.17 g C m^{-2}, 63.44 g C kg^{-1} and 183.62 g C m^{-2}, 63.37 g C kg^{-1} for biomass and SOC under RCP4.5 and RCP8.5, respectively. The RCP8.5 showed the more negative effect on the biomass and SOC compared with RCP4.5. Grazing intensity had a negative relationship with biomass and positive relationship with SOC. Compared with the baseline, the biomass and SOC changed 12.56% and –0.19%, 7.23% and 0.23%, –5.17% and 1.19% for the treatment G_0, G_{-50} and G_{+50}, respectively. In the future, more human activity and management practices should be coupled into the model simulation.

Keywords: Biogeochemical process; DNDC; Grazing intensity; Grassland management; Degradation;

1 Introduction

Grassland is one of the most widespread terrestrial ecosystems and accounts for nearly 33% of the land without ice cover (Ellis and Ramankutty, 2008), where it plays important roles in both the global carbon cycle and terrestrial ecosystem processes (Li et al., 2013c). The Qinghai-Tibetan Plateau (QTP) covers an area of approximately 130 million hectares (ha), 44% of China's total grassland (Li et al., 2013a;Piao et al., 2012). This area plays a vital role for the ecological services of China and Southeast Asian countries (Piao et al., 2012;Wang et al., 2002;Li et al., 2013b;Zeng et al., 2015;Harris, 2010). Qinghai Province supports over 40% of the population but it has about 29% of the total area, and thus it plays an important role in the whole QTP (Li et al., 2013a;Piao et al., 2012). This area is recognized as one of the most ecologically fragile and sensitive areas to global climate change and human disturbance (Piao et al., 2012;Wang et al., 2002;Li et al., 2013b;Zeng et al., 2015;Harris, 2010). Moreover, this area is also the largest animal husbandry production region in China, and it also contains the headwaters of the two major rivers in China, i.e., the Yellow River and the Yangtze River, and thus it plays a vital role in ecological conservation in China (Zeng et al., 2015).

In recent decades, due to climate change, increased human disturbances, the high altitude alpine grassland ecosystems, which are the dominant grassland vegetation type, have been severely degraded (Gao et al., 2010;Miehe et al., 2017;Qiao et al., 2015). The air temperature on the plateau has increased by 0.3°C per decade, which is three times the global average (Li et al., 2008). Warming could significantly increase the net primary productivity of alpine meadows (Fan et al., 2010;Du et al., 2004;Chen et al., 2013). Other studies have found that warming also speeds up the decomposition rate for litter and manure, and increases soil respiration (Xu et al., 2010;Luo et al., 2010), which could cause significant losses of soil organic carbon (SOC) and affect the alpine grassland ecosystem carbon pool balance (Tan et al., 2010;Pei et al., 2009;Babel et al., 2014;Liu et al., 2017). Although the ecological impact of warming on the QTP alpine grassland ecosystem has not been fully elucidated in previous studies, there is no doubt that warming will greatly accelerate the key processes in the alpine grassland ecosystem carbon cycle (Luo et al., 2010). There are reported that both precipitation amount and the number of precipitation days have increased significantly in QTP (Li et al., 2010). As precipitation is another crucial climate factor in controlling the carbon cycle of grassland ecosystems, how the higher variability precipitation impacts the SOC and biomass in QTP need further investigation (Lehnert et al., 2016;Maussion et al., 2014).

Grazing is the most important biotic factor among the ecological processes that affect rapid changes in the vegetation and soil, and it is the main method for deriving ecosystem services from the QTP grassland (Tanentzap and Coomes, 2012). Moreover, grazing is one of the major human disturbances to the grassland in this area. In general, overgrazing is considered to be one of the main causes of carbon and nitrogen losses from the soil, thereby contributing to the unsustainable use of grassland (McIntire and Hik, 2005). Therefore, sustaining a reasonable grazing intensity has an indispensable role in maintaining the turnover of soil nutrients and plant community stability (Klein et al., 2007).

Previous studies have shown that different types of vegetation and soil nutrient pools exhibit significantly different responses to variations in the grazing intensity (Lavado et al., 1996;Ingrisch et al., 2015). However, there is still a lack of robust studies to evaluate the combined effect of grazing and climate change, as well as their impact on the QTP grassland ecosystem at a large scale. Due to the unique geographic characteristics and important ecological functions of the QTP grassland ecosystem, it is necessary to evaluate the impacts of human management and climate change to ensure that it continues to provide these ecosystem services.

In this study, using a well-calibrated DeNitrification-DeComposition (DNDC) model based on long-term vegetation observations, we evaluated the response of the grassland ecosystem in Qinghai Province in terms of both climate change and human management by analyzing the grazing intensity. We also analyzed the interactions between grassland vegetation and soil carbon storage with grazing intensity and climate change disturbances at a large scale in long-term impact assessments.

2 Materials and methods

2.1 Study area

Qinghai Province (89°35′–103°04′ E, 31°39′–39°19′ N) is located in the northeast of QTP in China (Fig. 1). This region has a typical plateau climate, with a mean annual temperature of 8.6°C (from –6°C to 9°C across the study area) and a mean annual precipitation of 424.7 mm (16.7–776.1 mm across the study area). In general, the climate is cold and dry. The altitude of Qinghai province ranges between 1,650–6,860 meters above sea level (masl) and 67% of the land area is in the range of 3,000–5,000 masl. Grassland is the major land cover in the study area where alpine meadow and alpine steppe are the dominant vegetation types, where they account for 60.5% of the total grassland area.

Grazing is the primary human activity in the study area and livestock production is a key industry in this region. Generally, natural grassland is the major food source for the livestock in the QTP. Compared with 1949, the number of livestock has increased by almost three times from 7.49×10^6 (Zhang, 2011) to the peak number 22.19×10^6 head in 2005 at the study area (QPBS, 2005, 2015).

Since 2004, the Chinese government has implemented a series of ecological protection projects and policies in Qinghai province, including reducing livestock and prohibiting grazing, building fences to allow natural grassland recovery, as well as providing allowances and awards to local herdsmen families to promote degraded pasture recovery and to balance the livestock rate according to the forage productivity (Zeng et al., 2015). The core objective of these projects and policies is changing the grazing intensity and achieving a balance between the livestock intensity and grassland regenerability in order to construct a sustainable grassland ecosystem. Due to new policies for ecological protection, the livestock numbers have declined in recent years, but they have been maintained at the 2015 level of 19.42×10^6 head (supplementary Table S1) (QPBS, 2015).

2.2 DNDC model

The DNDC 9.5 biogeochemical model, which was downloaded from the official web (http://www.dndc.sr.unh.edu/), was employed in this study (Li et al., 1992;Li et al., 2006). The model has been used widely in more than 20 countries to obtain accurate calibration and verification results in various ecosystems (Abdalla et al., 2009;Chen et al., 2015;Li et al., 2014;Xu et al., 2003;Kariyapperuma et al., 2011;Li et al., 1996;Zhao et al., 2016;Liu et al., 2006;Li et al., 2017;Zhang and Niu, 2016).

The model has two components. The first component can simulate the soil environmental conditions, where it includes soil climate, vegetation growth, and decomposition submodels. The second component includes three submodels for simulating nitrification, denitrification, and fermentation processes, which are used to simulate biogeochemical production, consumption, and emissions of CH_4, N_2O, NO, and NH_3, as well as nitrogen losses due to leaching (Zhang et al., 2015).

The DNDC model simulates vegetation growth by tracking photosynthesis, respiration, water demand, N demand, C allocation, crop yield, and litter production. The model predicts the SOC dynamics mainly by quantifying the SOC input from crop litter incorporation and manure amendment, as well as the SOC output through decomposition. More detailed information about the model was given by Li (1996).

2.3 Regional database

In order to characterize the spatial heterogeneity of natural grasslands in the study area, we collected the following geospatial data as inputs for the DNDC biogeochemical model: grassland type and spatial distribution (Fig. 1), soil properties, and climate data.

Grassland Database

The vegetation parameters in the model were obtained from a grassland field monitoring project implemented during 2005–2014 (ERSMC-b, 2016;ERSMC-a, 2016). This annual monitoring project covered the major types of grassland within the project area. On average, 168 monitoring sites were sampled each year. For each monitoring site, the average value based on 3 replicate sampling points was calculated to determine the aboveground biomass value for the monitoring site. The aboveground biomass harvests used the quadrat method during the plant growing season (July 10–August 20) in a 1 m × 1 m plot. A more detailed description of the sampling method used to obtain the observation data can be found in reports by the Ecological Environment Remote Sensing Monitoring Center of Qinghai Province (ERSMC-a, 2016;ERSMC-b, 2016). The grassland simulation based on the grassland functional group type was categorized according to the grassland type map for the study area (Fig. 1). The detailed grassland parameters used in the model were shown in Supplementary Table S4.

Soil Database

We used a 1:1,000,000 scale soil database developed by the Institute of Soil Science, Chinese Academy of Sciences, which was compiled based on the second national soil survey conducted in 1979–1994 for all the counties in China (Shi et al., 2004). The database had three attributes: locations, soil attributes, and reference systems. It contained multi-layer soil properties (e.g. organic matter, pH, and bulk density), soil texture (e.g. sand, silt and clay proportions), and spatial information (Shi et al., 2004;Yu et al., 2007a;Yu et al., 2007b), which were used in the model simulations.

Climate Database

Daily climate data were obtained from the China Meteorological Network for the study period, and there were 39 stations inside the study areas (http://data.cma.cn/). The daily precipitation and maximum/minimum temperatures between 1985–2014 were interpolated at 1-km resolution grid for our model. Regression kriging and the inverse distance method were employed for air temperature and precipitation interpolation, respectively (Fortin and Dale, 2005;Hengl et al., 2007).

Model implementation

All datasets were processed with ArcGIS version 10.2 (ESRI, Redlands, CA) to the formation a georeferenced DNDC regional simulation database. The data processing flowchart could be found in the supplementary Fig. S1. The county boundary data were overlaid on grassland type maps to form the model simulation unit. Then county-based grazing intensity, soil properties, and climate information were assigned to the model simulation units. The DNDC was running with regional simulation database based on individual model simulation units. The detailed information of how to run the model could be found in Li (2012). The actual climate, soil, grassland type and grazing intensity as the simulation baseline.

2.4 Simulation scenarios

Grazing simulation scenarios

The grazing period is all-year round and cattle (90% yaks), sheep, and goats are major livestock types, while horses are a minor component in the study area. The grazing intensity data were based on the annual national livestock statistical report provided by the National Bureau of Statistics of China and the Bureau of Statistics for Qinghai Province. The detailed grazing data are shown in Supplementary Table S3. In the DNDC model, grazing activity is defined by specifying the grazing parameters, including the livestock type, grazing period, and grazing intensity. The detailed parameters for simulating grass growth are shown in Supplementary Table S4. The grazing intensity is defined according to Eq. 1 based on the grazing area in each administrative region (Li et al., 2014):

$$GI = LP/GA, \qquad \text{(Eq.1)}$$

where GI is the grazing intensity (head ha^{-1}), LP is the livestock unit (head), and GA is the grazing area (ha).

In order to test the responses of the grassland biomass and soil SOC to various grazing intensities, we tested the following treatments: baseline, grazing intensity based on the actual grazing intensity in 2005; G_0, grazing intensity of zero; G_{-50}, 50% of the baseline intensity; and G_{+50}, 50% higher than the baseline.

Climate change scenarios

The Intergovernmental Panel on Climate Change (IPCC) Fifth Report employed new stable concentration-based scenarios in representative concentration pathways (RCPs) to project future climate change (IPCC, 2013). The development of the RCP scenarios used a parallel method, which combined climate, air, and the carbon cycle with emissions and the socio-economic situation to assess the impact of climate change on a study area, as well as adaptation, vulnerability, and mitigation analysis (Moss et al., 2010). The RCPs were named according to their 2100 radiative forcing level and reported by individual modeling teams, i.e., 2.6–8.5 W/m^2. The RCPs comprise four scenarios, i.e., RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (Moss et al., 2010). Each scenario provides a path affected by social and economic conditions and climate, and each projection corresponds to the radiation force value predicted by 2100.

We considered RCP4.5 and RCP8.5 because these two scenarios have been used widely to evaluate the potential impact of climate change on the environment (Di Vittorio et al., 2014;Zhang et al., 2013;Li et al., 2015;van Vuuren et al., 2011). RCP4.5 represents a medium-low RCP with stabilization of CO_2 emissions from 2150 onwards, and RCP8.5 represents a high RCP with stabilizing CO_2 emissions post-2100 (Meinshausen et al., 2011). The projected climate conditions in the present study under RCP4.5 and RCP8.5 were derived from the average values of 25 Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models (Fu and Feng, 2014).

Compared with 2014, the average temperature and precipitation increased by 0.72°C and 0.80°C, and by 11.81 mm and 12.50 mm under RCP4.5 and RCP8.5 in 2044, respectively, in the study area (Table 1). The changes in the spatial distribution of precipitation are shown in Supplementary Fig. S2. The pattern of increased precipitation was similar using RCP4.5 and RCP8.5 for the period of 2014–2044, where it increased in the whole area and it increased gradually from the north to the south of the study area. However, RCP8.5 obtained a higher increase than RCP4.5 and the southwest part of the research area is projected to have a higher temperature increase than the other regions. Moreover, the annual average temperature had a similar distribution under the two climate change scenarios, where the temperature increase using RCP4.5 (Supplementary Fig. S2c) was lower than that with RCP8.5 (Supplementary Fig. S2d).

Three different periods were considered in the grassland simulations. First, a pretreatment (1961–1984) period was used to initialize the soil climate conditions and SOC composition. The pretreatment period represented the baseline climate with no increases in CO_2 or climate change. The second period represented realistic climate scenarios (1985–2014) based on the most recent climate. The third period comprised future climate scenarios (2015–2044), which represented two future climates (RCP4.5， RCP8.5) scenarios with changes in temperature and precipitation. The future climate database between 2015 to 2044 was obtained through add the projected future climate change to the daily temperature and precipitation in 2014.

2.5 Model validation and sensitivity test

The root mean squared error (RMSE) (Eq.2), coefficient of determination (R^2) (Eq.3) and model efficiency (ME) (Eq.4) were employed for model validation. The RMSE estimates the scatter between the simulated and measured data, where values close to zero indicate excellent agreement and hence the good performance of the model (Araya et al., 2015). R^2 is used to test the agreement between the modeled results and observations, where a value closer to 1 indicates that the model provides a better explanation for the observed values (Willmott, 1982). The positive ME value indicates that the model prediction is better than the mean of observations, and the best model performance has ME value equal to 1 (Miehle, 2006). RMSE, R^2 and ME were calculated as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad \text{(Eq. 2)}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}}\right]^2, \qquad \text{(Eq. 3)}$$

$$ME = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad \text{(Eq. 4)}$$

where P_i and O_i were modeled and observed values, and $\overline{\mathrm{P}}$ and $\overline{\mathrm{O}}$ are their averages. n is the number of values.

The validation dataset included more than 1400 grassland biomass sampling points, which covered the whole of the study area, and the field measurements were also fully representative of the major grassland types in this area. In addition, 46 SOC observation points were sampled between 2011–2012, which were randomly distributed among all of the simulation units (county and grassland types). Maximum biomass in each quadrat was harvested and dried in an oven at 70 °C for 72 h, weighed and ground for analysis. The soil of 0–30 cm depth was sampled at 10-cm intervals with a soil drill (metal cylinder: diameter of 5 cm, length of 20 cm and the total length of the sampler 1.3 m). 3 samples were collected in each replication plot. The ground soil samples passed a 0.15 mm sieve and wet oxidation method was applied to determine SOC (Mebius, 1960). In general, every simulation unit had 1–2 validation points (ERSMC-a, 2016). A series of sensitivity tests were conducted to investigate the responses of the DNDC to variation in climate factors (air temperature, precipitation) and grazing intensity. DNDC was run with a 55-year baseline scenario that was based on the actual climate, soil and grazing conditions of year 2005 in the study area. The ranges of values for alternative scenarios were ±10, ± 20 and ±30% for precipitation, ±1, ± 2 and ±3 °C for air temperature and ±20, ±40, ±60, ±80 and ±100% for grazing intensity, respectively.

2.6 Statistical analysis

Two-way analysis of variance (ANOVA) was used to test the effects of climate and grazing intensity on both the biomass and SOC according to the simulated results. Mean values for the same treatments were compared using Fisher's least significant difference (LSD) test with one-way ANOVA at $P = 0.05$. The statistical analyses, including the test for normality (Shapiro-Wilk) and homogeneity of variance (Levene), were performed using Origin 2016 version b9.3.1.273 (OriginLab Corporation, MA, USA), and the multiple regression analysis was conducted with the Minitab version 17 (Minitab Inc., State College, PA, USA).

3 Results

3.1 Model validation

The biomass simulation showed that the modeled total biomass was in good agreement with the observations (Fig. 2). There was a significant linear relationship ($P < 0.001$) between the measurements and the modeled above ground biomass (R^2 =0.71, ME=0.75, RMSE = 93.11 g C m^{-2}; P < 0.001). The simulated SOC concentrations were in good agreement with the measured data (Fig. 3). The calculated statistical indices indicated that the modeled SOC concentrations were closely correlated with the measured data (R^2 = 0.73, ME=0.69, RMSE = 21.51 g C kg^{-1}; $P < 0.001$).

3.2 Sensitivity analysis

In the sensitivity analysis simulation, increases in precipitation resulted in elevated biomass and SOC, however, the SOC was changed slightly compared to the biomass (Fig. 4A, B); Temperature decrease induced the biomass decrease, and temperature increase could increase the biomass. However, biomass change did not follow a simple linear relationship with change in temperature. The 1°C temperature increase could bring 24% of biomass increase, meanwhile, 1°C temperature decrease could decrease 13% biomass (Fig. 4A) . Biomass was not susceptible to the changes in precipitation. The biomass increased 7% and decreased 6% with precipitation increased and decreased 30%, respectively. SOC had the reverse trend with increased or decreased temperature, but there was a more complex relationship with temperature change. The SOC had less sensitivity to temperature change compared to biomass. With a 1 °C temperature increase, the SOC increased slightly with 0.26%, but when temperature increased over 2 °C, the SOC decreased 0.26–0.83% (Fig. 4B). The modeled biomass was sensitive to grazing intensity and biomass had a reverse trend with increased or decreased grazing intensity (Fig. 4A). When grazing intensity changed from -100 to 100%, SOC increased rate from -0.22 to 0.40% (Fig. 4B).

3.3 Impact of grazing on biomass and SOC

The biomass and SOC were significantly affected by climate change and the grazing intensity. However, there were no significant interaction effects between climate and grazing intensity on biomass and SOC during 1985–2044 throughout the study area (Table 2). The grazing intensity change could significantly influence the biomass, which had a negative relationship with the grazing intensity. The biomass differed significantly under the four grazing intensities. Among the grazing intensity treatments, the biomass followed the order of: G0 > G_{-50} > baseline > G_{+50} (Table 3). Compared with the baseline, the biomass changed 12.56%, 7.23% and –5.17% for the treatment G_0, G_{-50} and G_{+50}, respectively. Grazing could increase the SOC storage. The SOC levels under various grazing intensities followed the order of: $G_0 < G_{-50} <$ baseline $< G_{+50}$ (Table 3). G_0 had the lowest SOC whereas G_{+50} had the highest SOC. Compared with the baseline, the SOC changed –0.19%, 0.23% and 1.19% for the treatment G_0, G_{-50} and G_{+50}, respectively.

3.4 Impact of climate change on biomass and SOC

The biomass exhibited a significant decreasing trend in the future climate scenarios compared with the past 30 years under all the grazing intensities (Fig. 5), although precipitation increased under both RCP4.5 and RCP8.5 (Table 1). Moreover, the biomass was significantly lower in RCP8.5 compared with RCP4.5 (Table 3). Compared with 1985–2014, the simulated biomass decreased –6.29% and –9.99% in 2015–2044 under RCP4.5 and RCP8.5, respectively. This suggests that RCP8.5 had a more negative effect on the biomass compared with RCP4.5 (Fig. 5). The future climate could significantly decrease the SOC, and it was –4.14% and –4.25% lower than that in 2015–2044 for RCP4.5 and RCP8.5, respectively. It suggested that RCP8.5 had a more negative effect than the RCP4.5 on the SOC. SOC exhibited a continuously decreasing trend according to the RCP4.5 and RCP8.5 projections in the research area, where the changes in the SOC were similar under the different grazing treatments (Fig. 6). The SOC was lower under RCP8.5 compared with that under RCP4.5. However, there were no significant differences between RCP4.5 and RCP8.5 (Table 3).

3.5 The relationship between SOC and biomass change with grazing and climate factors

A multiple linear regression analysis was adopted to each simulation unit to analyze the relationship between the annual changed biomass and SOC with corresponding temperature, precipitation and grazing intensity. The regression analysis indicated precipitation, air temperature and combined with grazing intensity, can explain 33.2% of changes in biomass under the realistic climate scenarios with a linear model. Meanwhile, precipitation, air temperature, and grazing intensity can explain 52.3% of SOC variation (Table 4). Specifically, climate factors explained 26.4% and 47.7% of biomass and SOC variation, respectively. Meanwhile, the grazing intensity explained 6.4% and 2.3% variation in biomass and SOC, respectively. Taking into account the prediction sum of squares (PRESS) value, air temperature is the factor contributing most of variations in biomass and SOC. It's suggested that precipitation and grazing intensity have lower contributes to biomass and SOC change in study region during past thirty years compared to temperature.

3.6 Patterns of regional change in the biomass and SOC

From a spatiotemporal distribution perspective, the distribution of grassland biomass in Qinghai Province is rather distinct due to the different constraints imposed by water and the cumulative temperature. The biomass increased in the central and southwest of the research region but decreased in the eastern and northern regions under RCP4.5 and RCP8.5, respectively. Moreover, the grassland biomass tended to decrease in more regions rather than exhibiting an increasing trend (Fig. 7A). In particular, the vegetation activities are mainly controlled by temperature in the eastern region, which may lead to greater negative effects than the positive effects of increased precipitation (Zhou et al., 2007); therefore, the average regional biomass may exhibit a significant decreasing trend.

In general, the SOC decreased from the low-temperature region to the high-temperature region, where it followed the temperature distribution pattern in Qinghai Province and decreased from the south to the north (Fig. 7B). The cold weather conditions would limit decomposition process and there would be greater carbon storage over the years with accumulation in this area. Furthermore, on the regional scale, although the SOC exhibited a decreasing trend in the whole study area, the rate of change differed with a significant spatial distribution pattern.

4 Discussion

4.1 Effects of climate change on biomass and SOC

Climate change is the main driver of the inter-annual fluctuations in the grassland biomass, as observed in previous studies by Fan et al. (2010) and Gao et al. (2016). The unique climate conditions such as precipitation and temperature on the QTP have a significant impact on the grassland biomass (Fan et al., 2010;Yan et al., 2015). According to this study, the biomass of alpine grassland could increase significantly in the short term as the temperature increases (Fig. 4), as also suggested by Chen et al. (2013) and Gao et al. (2016). However, under long-term constant warming and without considering other meteorological factors, the alpine grassland biomass will probably decrease (Zhu et al., 2016). This may be due to the higher temperature increasing evaporation in the study area, thereby overcoming the benefits of increased precipitation (Xu et al., 2009). The shortage of water will ultimately limit the increase in the grassland biomass with significant warming and drying.

The decline of the SOC in our study indicates that climate warming will have more negative effects and eliminated the positive effect of precipitation increasing in the study area. Riedo et al. (2000) indicated that carbon storage may be lost from grazed grassland as the temperature and precipitation increase. Tan et al. (2010) suggested that after a 2°C increase in temperature in the QTP, the grassland ecosystem's net primary productivity will increase by 9%, but the SOC will decrease by 10%. Temperature and precipitation are the main factors that affect the SOC pools (Jobbagy and Jackson, 2000). Many studies have shown that sustained warming will lead to increases in the SOC decomposition rate (Xu et al., 2012;Tan et al., 2010), especially in the QTP region with high carbon storage at a low temperature in the high latitudes. Thus, the SOC could be released by climate warming and become a more obvious carbon source (Kirschbaum, 1995;Kvenvolden, 1993;Yang et al., 2008;Wang et al., 2008;Qin et al., 2014). However, the effects of warming and precipitation on SOC storage remain a relatively complex problem (Cao and Woodward, 1998;Schuur, 2003).

4.2 Effects of grazing intensity on biomass and SOC

The grazing intensity is most importance for the outcomes of grazing and it is the main external factor that controls the grassland vegetation dynamics, as reported in the previous studies (Zeng et al., 2015;Veen et al., 2012;Guevara et al., 1996;McIntire and Hik, 2005;Pei et al., 2008). Indeed, an increase in the grazing intensity implies that more plants would be removed by animals, which could eventually lead to a decline in the aboveground biomass of the grassland (Yan et al., 2013).

Small differences in the SOC concentrations were observed after the grazing intensity increased. However, there was a positive correlation between the grazing intensity and SOC. There is a lack of consistent conclusions regarding the impact of grazing on the SOC concentration according to previous studies. Thus, some studies showed that the grazing intensity and SOC had a negative correlation (Derner et al., 1997;Bagchi and Ritchie, 2010;Wu et al., 2009) or no relationship (Milchunas and Lauenroth, 1993;Holt, 1997). By contrast, many other studies showed that grazing can increase the SOC (Schuman et al., 1999;Wienhold et al., 2001;Li et al., 2011). This is partly because moderate grazing can increase the grassland below-ground biomass, which is beneficial for the accumulation of SOC (López-Ma̍rsico et al., 2015;Hafner et al., 2012). Some studies have shown that increasing the plant root/shoot ratio and allocating more carbon to the root system could induce SOC increase (Derner et al., 1997). Nevertheless, the main reason for the increase in the SOC in our study was the increasing number of grazing animals, and thus the increased amount of manure returned after grazing on grassland (Hu et al., 2015). Furthermore, the fertilizing effects of livestock excrement can increase the SOC (Conant et al., 2001), especially in alpine grassland where the low temperature leads to the relatively slow decomposition of litter (Davidson and Janssens, 2006). Moreover, increases in the effects of hoof activity can accelerate the decomposition of litter and decaying roots, and improve the contact with the soil, thereby accelerating the transfer of carbon to the soil to increase the SOC concentration (Naeth et al., 1991;Luo et al., 2010).

4.3 Uncertainty analysis

Models are ideal tools for assessing the details of environment processes under various grazing intensity. Furthermore, they can provide projections regarding the variations in grassland biomass and SOC under alternative climate change scenarios. However, the uncertainty of the data sources could be incorporated into the model outputs. The CMIP5 RCP scenarios were used to provide the possible changes in climate in this study, but as a long-term climate projection, the uncertainty of the projected climate will increase with time span increase (Moss et al., 2010). The precipitation seasonal distribution pattern is critical to grassland growth (Shen et al., 2011). In the present study, the precipitation distribution pattern of RCP scenarios was derived from the year of 2014; this assumption may cause uncertainty for long-term study.

In the present study, we assumed that the grassland type was the same in the scenarios. As the grassland community structure could be altered under both grazing and climate change (Koerner and Collins, 2014). Therefore, the assumption of grassland community structure keeps stable in the simulation could induce the uncertainty. Due to a lack of mechanisms regarding the response of grassland soil to animal trampling in the DNDC model, we ignored the trampling effect of the animals on the soil structure, which may have led to some errors in the results.

The grazing rate can be another potential source of uncertainty. In most of the natural grassland regions of the QTP, transhumance is usually practiced, which requires the transfer of livestock from one pasture to another during different seasons, and staying in the same pasture for the whole season. However, this grassland management practice was simplified in the present study because we could not find specific statistical data to address this issue. Thus, we assumed that livestock stayed in the same pasture for the whole year with 24 h d^{-1} of grazing and the stocking rates were the same throughout the simulation unit and without yak dung remove (Zhang et al., 2016). Furthermore, we assumed that all grasslands were useable. These assumptions could have induced uncertainties in the simulation results.

5 Conclusions

In this study, we used the DNDC model to study the grassland biomass and SOC dynamics under different climate change and grazing management scenarios. We found that climate change may be the major factor that leads to fluctuations in the grassland biomass and SOC compare to grazing intensity, and it could explain 26.4% and 47.7% of biomass and SOC variation, respectively. Meanwhile, the grazing intensity explained 6.4% and 2.3% variation in biomass and SOC, respectively. The total grassland biomass and average SOC in the study area were reduced significantly under both the RCP4.5 and RCP8.5 future climate change scenarios. Compared with 1985–2014, the simulated biomass and SOC decreased –6.29%, –4.14% and –9.99%, –4.25% under RCP4.5 and RCP8.5, respectively. There were significant differences in the spatial distribution of the changing trends in the biomass and SOC. In the eastern and northern regions of the study area, the biomass decreased, whereas it exhibited an increasing trend in the southwest part of the research area. Meanwhile, the SOC exhibited a decreasing trend in the whole study area, and SOC change rate decreased from the south to the north. The biomass had a negative relationship with the grazing intensity and it differed significantly under the four grazing intensities. Compared with the baseline, the biomass changed 12.56%, 7.23% and –5.17% for the treatment G_0, G_{-50} and G_{+50}, respectively. Grazing could increase the SOC storage. G_0 had the lowest SOC whereas G_{+50} had the highest SOC. Compared with the baseline, the SOC changed –0.19%, 0.23% and 1.19% for the treatment G_0, G_{-50} and G_{+50}, respectively. Overall, grassland management should be adapted to potential climate change to ensure sustainable grassland development in the study area.

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Table 1. Projected climatic changes (precipitation and maximum, minimum, and mean air temperature) under the RCP4.5 and RCP8.5 scenarios in 2044 compared with the corresponding values in the baseline data (2014).

Scenarios	Air temperature (°C)			Precipitation(mm)
	T_{max}	T_{min}	T_{mean}	
Baseline	3.63	-16.88	-3.56	279.24
RCP4.5	+0.99	+0.44	+0.72	+11.81
RCP8.5	+1.09	+0.51	+0.80	+12.50

Table 2. Summary of two-way analysis of variance for biomass and SOC relative to the climate, grazing intensity, and their interactions during 1985–2044. Degrees of freedom (d.f.), mean squares (M.S.), variance ratio (*F*-value), and level of significance (*P*-value) are shown.

Source of variation	d.f.	Biomass			SOC		
		M.S.	*F*-value	*P*-value	M.S.	*F*-value	*P*-value
Climate	2	16827.91	54.27	**	468.16	723.54	**
Grazing Intensity	3	22132.64	71.37	**	17.29	26.72	**
Climate*Grazing Intensity	6	2.63	0.01	n.s.	0.28	0.28	n.s.

** Indicate the population means of the treatment are significantly different at 0.05 level; n.s., the means no significant different.

Table 3. The simulated SOC concentrations and total biomass under climate and grazing scenarios.

Scenarios		**Total biomass ($g\ C\ m^{-2}$)**	**SOC (0–20 cm) concentrations ($g\ C\ kg^{-1}$)**
Climate	Realistic (1985–2014)	204.01	66.18
	RCP4.5 (2015–2044)	191.17	63.44
	RCP8.5 (2015–2044)	183.62	63.37
	$LSD_{0.05}$	3.87	0.09
Grazing	Baseline	187.83	64.49
	G0	211.42	64.37
	G–50	201.41	64.64
	G+50	178.11	65.26
	$LSD_{0.05}$	4.47	0.10

$LSD_{0.05}$: Least significant difference at 0.05 level.

Table 4. Multiple linear regression analysis of grassland biomass and SOC change with relative factors.

	Variables numbers	R-square	PRESS	Temperature	Precipitation	Grazing Intensity
Biomass	1	26. 4	273067.7	X		
	1	6.4	370402.4			X
	1	0.4	349337.6		X	
	2	26.4	287817.3	X	X	
	2	26.4	301908.4	X		X
	2	8.6	383224.5		X	X
	3	26.4	326183.5	X	X	X
SOC	1	47.6	179.2		X	
	1	2.3	310.9			X
	1	0.4	322.9	X		
	2	47.9	185.5		X	X
	2	47.7	189.5	X	X	
	2	4.7	328.8	X		X
	3	48.6	199.1	X	X	X

PRESS: The prediction sum of squares. The smaller the PRESS value, the better the model´s predictive ability.

X: Indicates variable applied in the regression.

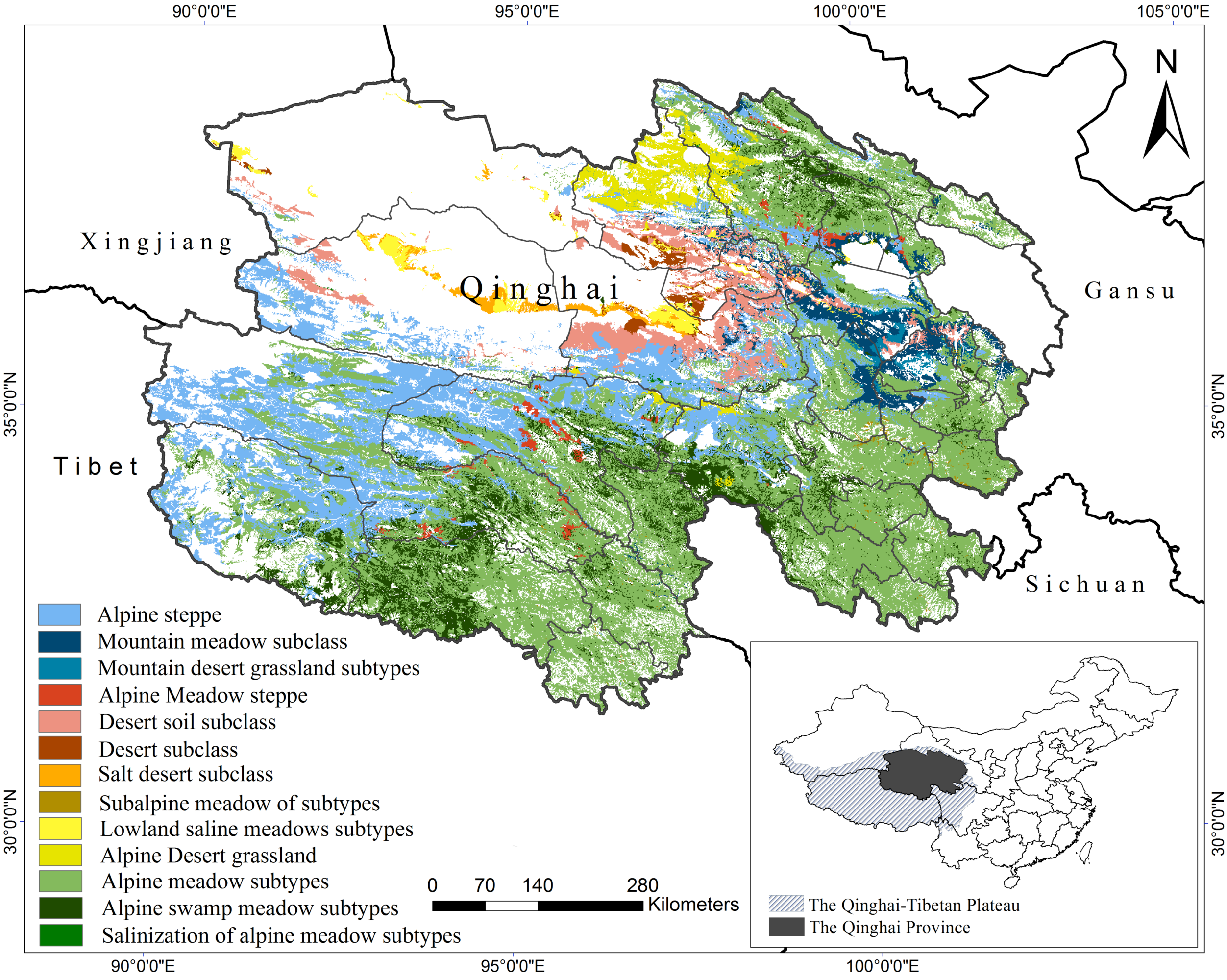

Fig. 1. Location of the study area and spatial distribution of the main grassland types. White areas are not covered by grassland.

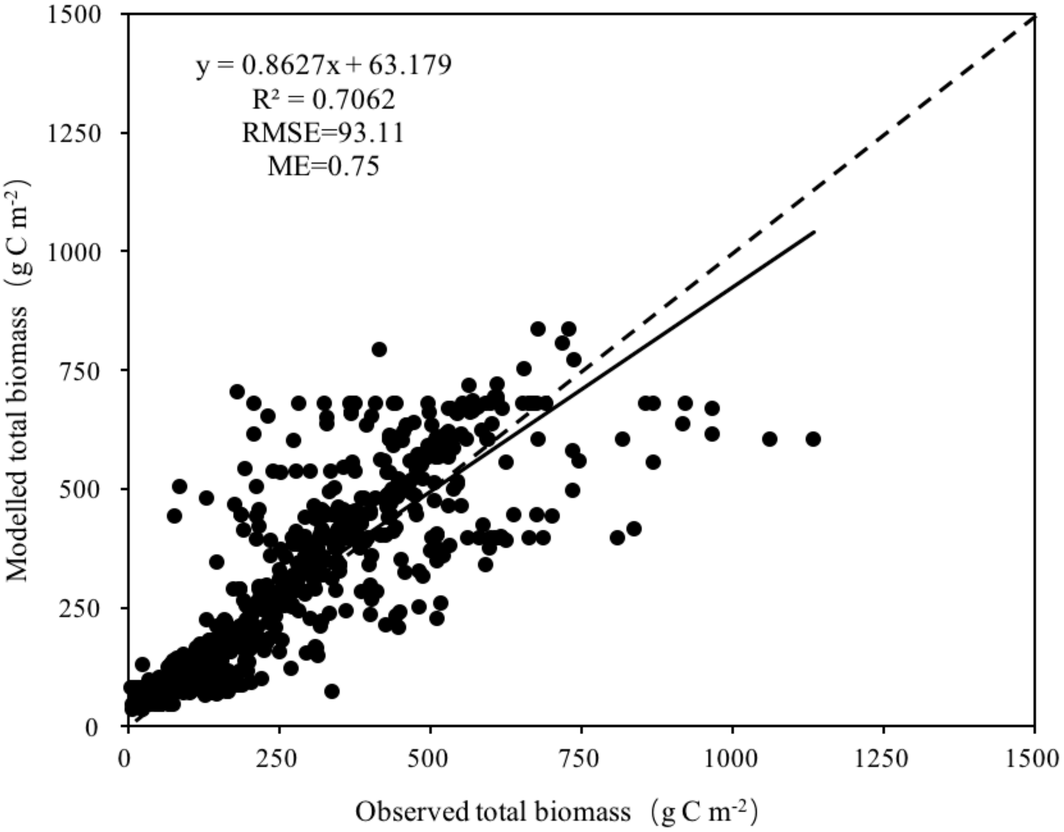

Fig. 2. Comparison of the modeled and observed total biomass values.

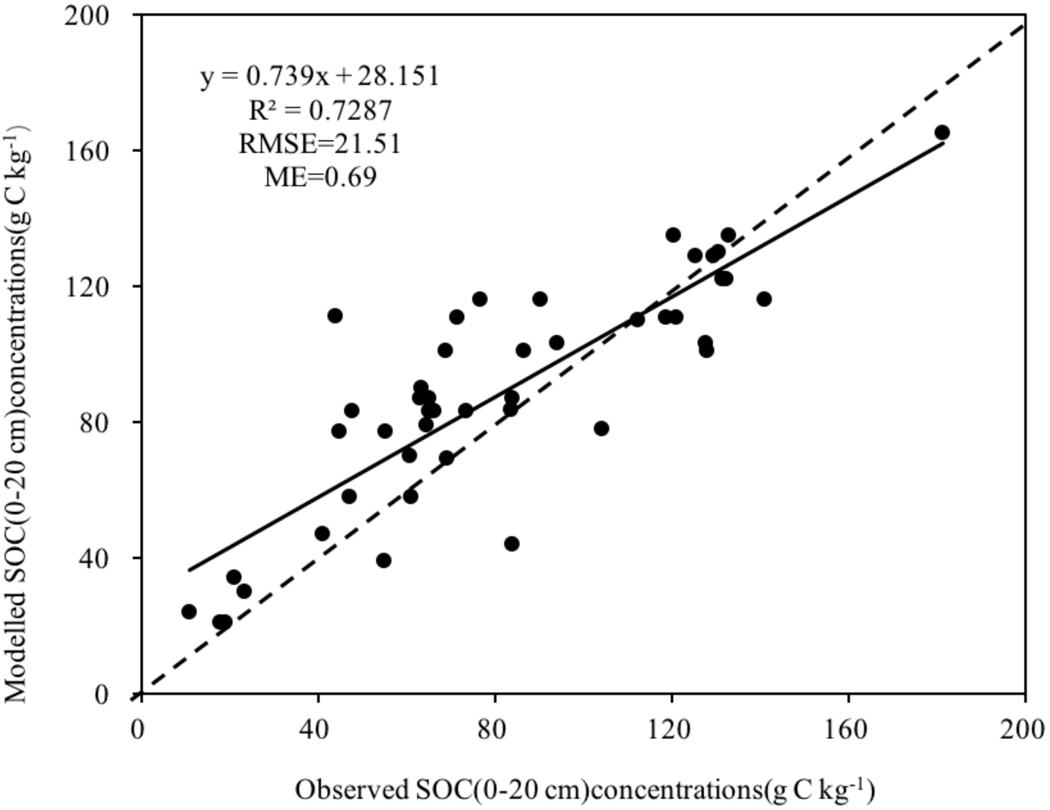

Fig. 3. Comparison of the modeled and observed SOC concentrations (0–20 cm).

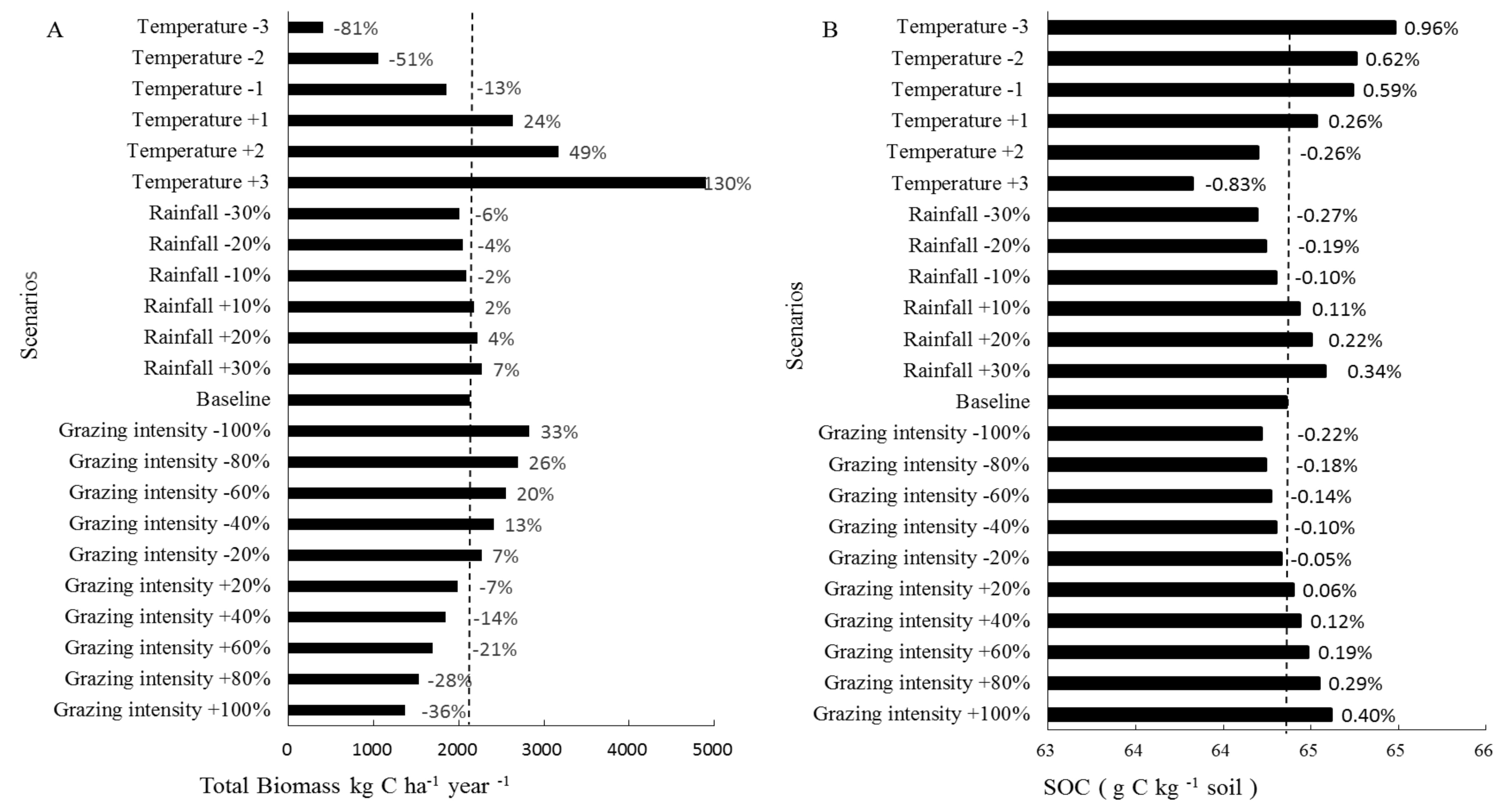

Fig. 4. Sensitivity analysis of model response to climate and grazing intensity change. The baseline biomass and SOC were the average value of a 55-year (1961-2014) simulation based on the actual climate and grazing conditions in the study area.

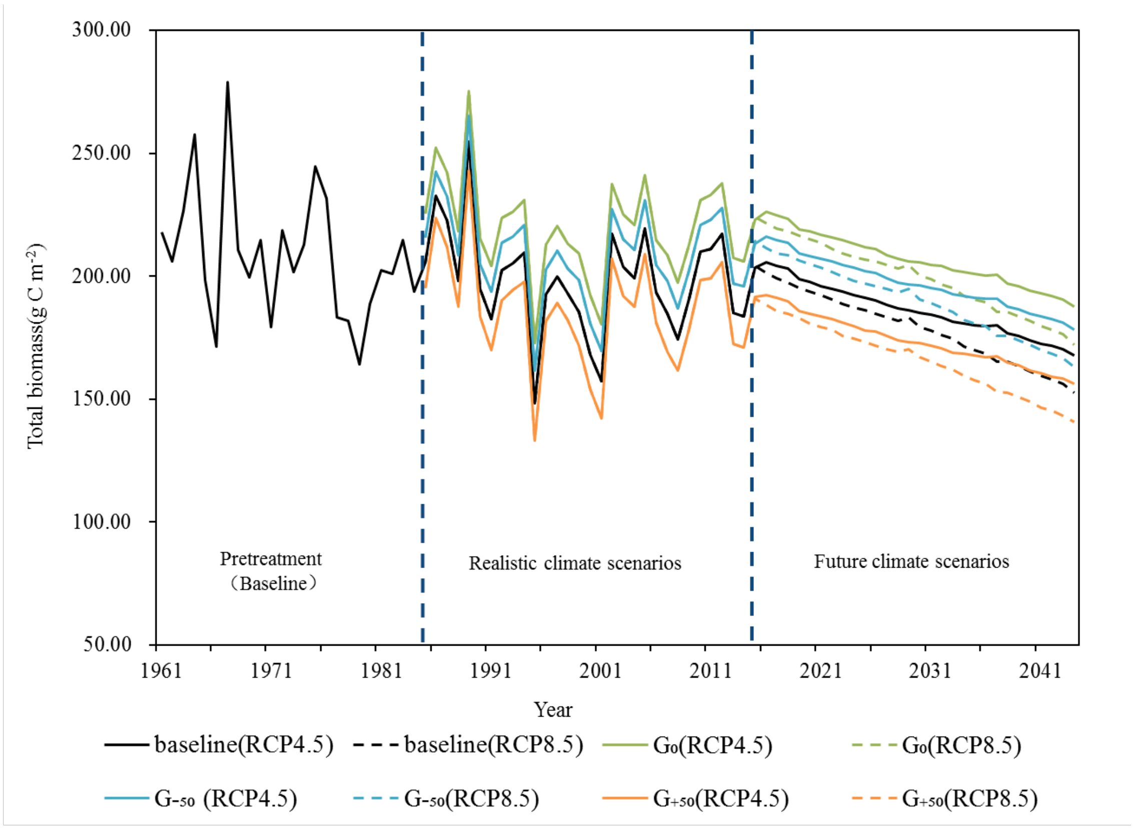

Fig. 5. Variations in the area-weighted mean biomass value under different scenarios. The stage on the left represents the preprocessing period from 1961 to 1984. The stage in the middle represents the realistic climate scenarios. The stage on the right represents future climate scenarios.

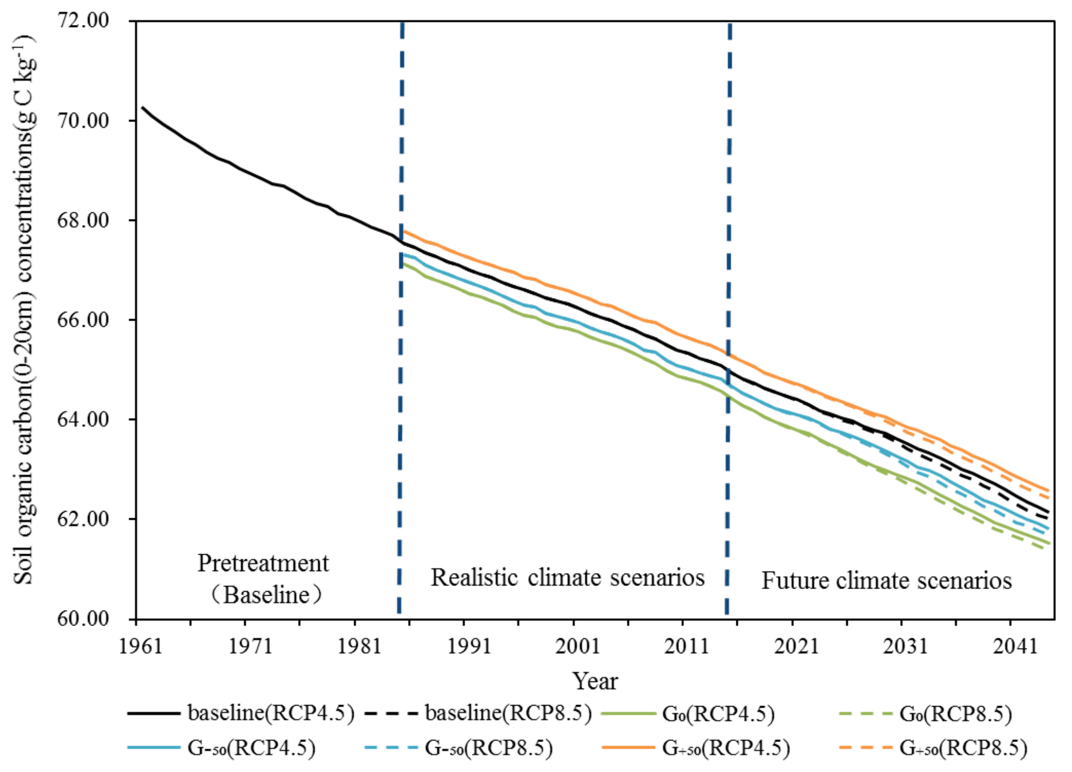

Fig. 6. Variations in the area-weighted mean SOC value under different scenarios. The stage on the left represents the preprocessing period from 1961 to 1984. The stage in the middle represents the realistic climate scenarios. The stage on the right represents future climate scenarios.

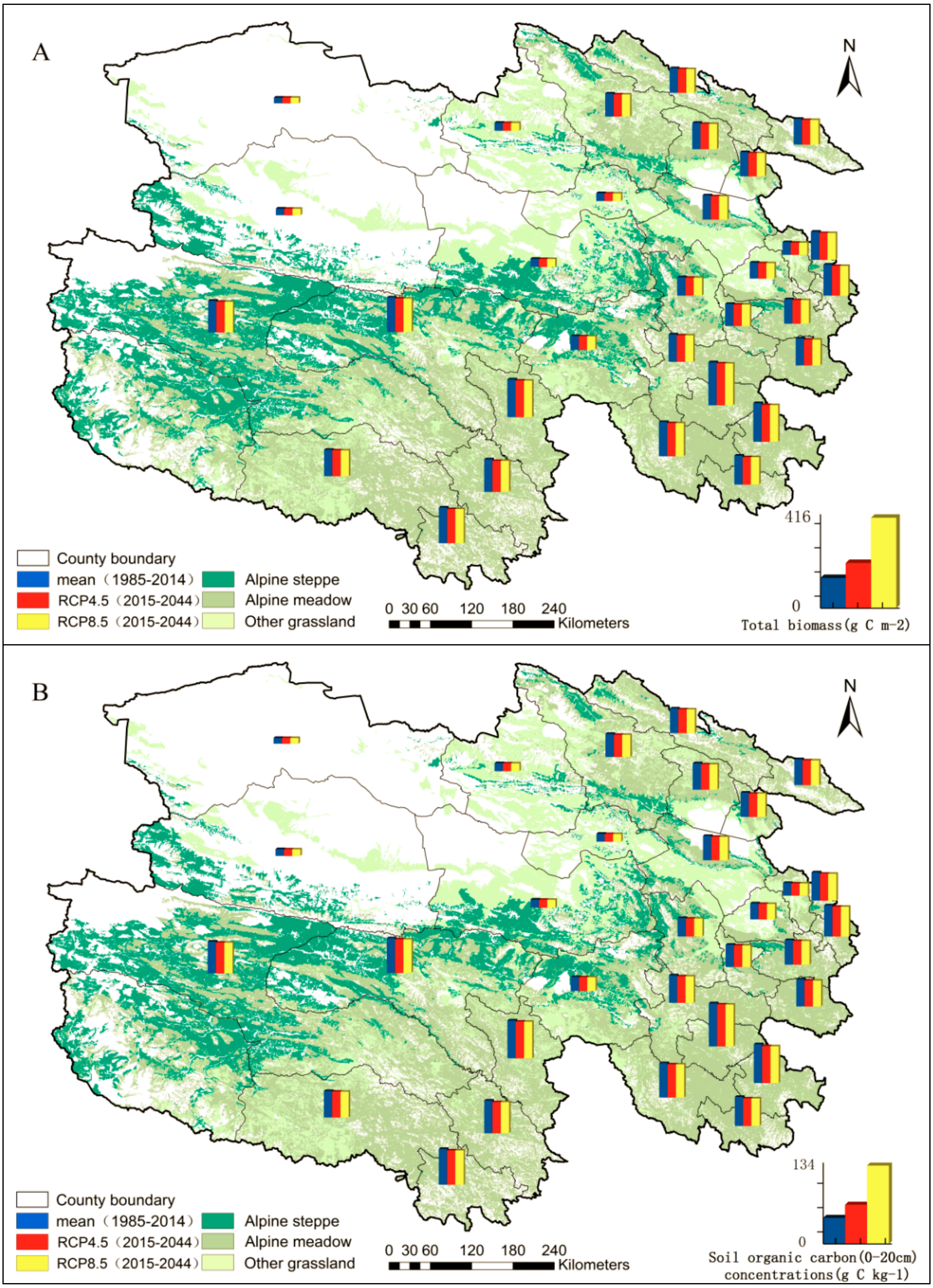

Fig. 7. Responses of the grassland biomass(A) and SOC(B) to climate change at a regional scale.