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Simulating effects of grazing on soil organic carbon stocks in Mongolian grasslands

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ABSTRACT

Grassland degradation is a major issue in many parts of the world. Rehabilitation of areas that have been degraded by overgrazing can potentially accumulate soil carbon, but there have been few studies in the vast grasslands of Mongolia. Here, we calibrated and validated Century model with 618 measurements from a soil inventory covering four grassland types in a forest steppe region of Mongolia. Soil organic carbon (SOC) simulated by Century largely agreed with the observational dataset and the sign of SOC response to intensive grazing. We employed the calibrated model to assess SOC accumulation under reduced grazing intensity scenarios, and the projected accumulation rates were 22.0–36.9 g C m^{-2} yr^{-1} in the near term (2012–2035). These results imply that reducing the intensity of grazing may be an effective strategy for restoration of degraded grasslands, which can be implemented by reducing livestock numbers and/or by changing the timing and duration of grazing events. Moreover, the simulated SOC accumulation was mainly determined by a conceptual slow pool, which was not supported by experimental observations in similar soils. Therefore, evaluating the long-term climate mitigation through soil carbon accumulation in degraded grasslands still warrants further attention.

1. Introduction

Concerns about the steady increase in atmospheric carbon dioxide (CO_2) have sparked worldwide interest in the global carbon cycle and the role of various potential carbon sinks (Houghton, 2007). Grasslands cover approximately 50 million km^2, and contain the largest share (39%) of terrestrial soil carbon stocks (White et al., 2000). Any change in storage in this large grassland soil carbon reserve would have a substantial and long-lived effect on global carbon cycles (McSherry and Ritchie, 2013). Management and land use change will be key drivers expected to affect soil carbon in the coming decades, and estimates of changes in grassland soil carbon stocks over the long term are of critical importance (Conant and Paustian, 2002; Wang et al., 2011). However, despite considerable research over the past 40 years, much uncertainty exists regarding the effects of grazing on soil organic carbon (SOC) (McSherry and Ritchie, 2013). Previous studies found both strong positive and negative grazing effects on SOC (Conant and Paustian, 2002; McSherry and Ritchie, 2013). In semi-arid regions, intensive grazing leads to grassland degradation and SOC losses, as observed in Northern China (He et al., 2011), America (Neff et al., 2005) and the world (Conant, 2009). Curtailing grazing intensity has been recommended to promote SOC sequestration. An accumulation of SOC after reducing grazing

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has already been documented for many regions of the world (Conant et al., 2001). However, despite strong hints in these scientific studies, broad-scale implementation has been limited by uncertainties in the magnitude, duration, soil texture and grazing regime (McSherry and Ritchie, 2013). For example, estimates of the global mitigation potential of grasslands vary considerably, ranging between 0.15 and 1.3 Gt CO_2 yr^{-1} (Lal, 2004; Follett and Schuman, 2005; Smith et al., 2007; Henderson et al., 2015). The uncertainty of global sequestration estimates is exacerbated by the severe lack of studies in developing countries (Conant et al., 2001; Follett and Schuman, 2005). Reports about the carbon sequestration rates were particularly rare in the vast Eurasian steppe with the exception of China (Wang et al., 2011).

The Mongolian steppe, spanning an area of about 1.15 million km^2 (ALAGC, 2012), is part of the Eurasian steppe. These grasslands have been grazed by wild and then domestic livestock for millennia (Hilker et al., 2014). In the period of Soviet influence, the national livestock population was relatively constant at about 23 million head (Olonbayar, 2010), and Mongolian steppe was sustainably grazed. Since the transition to a market economy and privatization of formerly state-owned livestock in 1992, the number of livestock has steeply increased to 45 million by the end of 2013 (NSO, 2014). During this time, long-term trends of reduced grassland biomass or production were documented over much of Mongolia (Liu et al., 2013). Official data suggest that about 22% of the grassland area is degraded (ALAGC, 2011). Another recent national assessment using a new methodology suggests that about 90% is in an 'altered state', much of which can be rehabilitated through improved management (NAMEM, 2015). Several studies have attempted to use analysis of remote sensing imagery to differentiate the effects of climate change from the effects of grazing, suggesting that overgrazing is the main driver of grassland degradation in much of the central and northern parts of the country where average precipitation is higher (Hilker et al., 2014; Liu et al., 2013). This is consistent with other research suggesting that equilibrium grasslands are more vulnerable to degradation due to inappropriate management (von Wehrden et al., 2012). The presence of degradation in equilibrium grasslands may also indicate potential for increasing SOC stocks through changes in management practice (Booker et al., 2013). Considering it large area and potential importance to the regional and global carbon cycle, it is important to assess the soil carbon pools in Mongolian steppe in response to changes in grazing pressures.

This study assessed the impact of grazing on the SOC of Mongolian grasslands using process based modeling approaches combined with inventory data. Conducting soil inventory once cannot reflect changes in soil carbon stocks in response to specific land use and management. To the contrary, the process-based modeling approach can predict detailed effects of land use and management changes, but requires measured data for model calibration and validation (Bortolon et al., 2011). In the past, the Century model has been used in Mongolia to evaluate the effects of climate change on NPP (Dagvadorj et al., 2009), but there have been limited applications to investigating SOC stock changes under different grassland management practices. Here, we developed a SOC inventory for four major grassland types with varying degrees of degradation in a forest steppe area of central Mongolia. We then applied the Century model using historic grazing regimes based on knowledge derived from local grassland managers. Estimations based on the inventory method were compared to the model simulation results. Our objective was to characterize the responses of SOC stocks to changing grazing pressures and assess the size of the accumulated soil carbon in degraded Mongolian steppe.

2. Materials and methods

2.1. Soil and biomass survey

We conducted a field survey in Tariat soum, Arkhangai aimag, in central Mongolia during the summers (July and August) of 2011–2012 (Fig. 1). The climate in Tariat soum has a mean annual temperature range of −5.7 to −1.9 °C, with mean annual precipitation ranging from 82.0 to 350.3 mm (Fig. 2). The soil and biomass survey covered more than 47,000 ha of summer grassland in Tariat, which is about 30% of the total grassland area in the soum. The vegetation is dominated by four grassland types: mountain meadow (MM), riparian meadow (M), riparian meadow and marsh (MWM), and mountain steppe (MS). Each vegetation

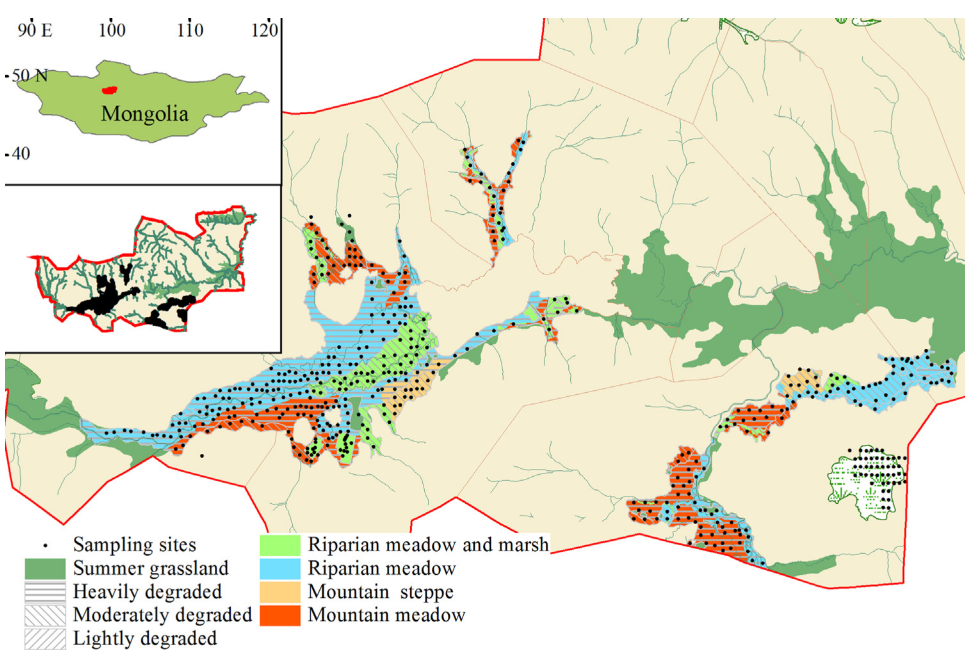

Fig. 1. Distribution of sampling sites and study area in Mongolia.

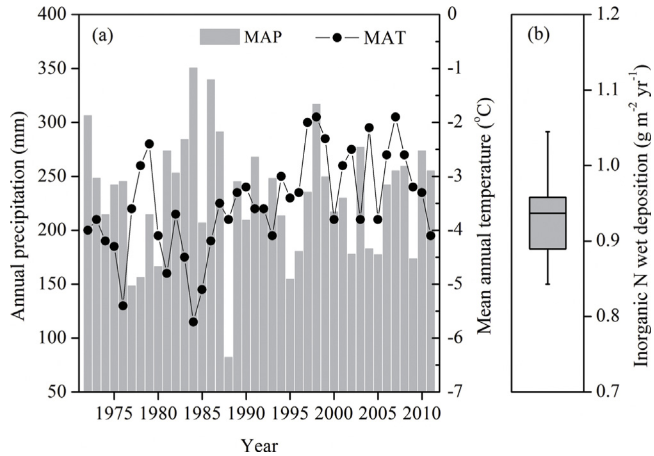

Fig. 2. Annual temperature and precipitation (a), and N deposition (b) at Tariat from 1972 to 2011. The median and error bars in box-and-whisker plot indicate data range within 5th and 95th percentiles. The N deposition was modeled based on the relationship between wet deposition and precipitation across China (Jia et al., 2014).

type was further categorized as non-degraded, or lightly, moderately, or heavily degraded based on the characteristics of ground cover, plant community composition and biomass production. We sampled 618 sites across the study area, including 285 in MM, 86 in MWM, 208 in M and 39 in MS. At each site, a typical quadrat of $0.5 \times 0.5\ m^2$ was randomly selected. Within the selected quadrat, all plants were harvested to measure aboveground biomass. Then we collected three soil cores using a 5-cm corer from 0 to 20 cm depth. Bulk density samples were obtained using a standard container of 100 cm^3 in volume, and weighed after being oven dried at 105 °C for 24 h. Soil samples were sieved (2 mm), air-dried and ground to a powder. SOC of ground soil samples were determined by combustion in a TOC analyzer (Shimadzu TOC-5000, Kyoto, Japan) after phosphoric acid treatment to remove carbonates. Soil texture was determined by a particle size analyzer (MasterSizer 2000, Malvern, Worcestershire, UK). Aboveground biomass samples were oven dried at 65 °C for 48 h and weighed.

2.2. Century model description, calibration and validation

Century is an ecosystem model that simulates biogeochemical fluxes on a monthly time step. In the model, soil organic matter is divided into three pools (active, slow and passive) depending on turnover rates. In the plant submodel, the maximum plant growth is calculated according to the genetic potential of the plant, temperature, and availability of moisture and nutrients. The plant module also determines the timing of net primary production and its proportional allocation to roots or foliage. The grazing event can be specified by defining the fractions of aboveground biomass consumption and excrement export to folds (urine and dung). Grazing effects were determined based on relationships of grazing to biomass production changes as grazing intensity increases (Evans et al., 2010). This approach has been used to simulate grazing in other studies (Wang et al., 2008; Chang et al., 2014).

To represent the long history of grazing on Mongolian grasslands, we simulated an equilibrium period for 5000 years with a perennial grass system under moderate grazing (50% of live shoots removed by grazing event per month) in summer (June–October). From 1990 to 2012, the model was run with higher removal of plant production by heavy grazing. The modeled biomass removal rates for degraded grassland strata during this period were 80%, which was determined on the basis of an inventory of livestock herds and grazing patterns among households using grasslands in the study area. For non-degraded mountain meadow sites, moderate grazing was kept constant during entire period. The climatic data used in the Century model consisted of monthly precipitation, monthly maximum and minimum air temperature provided by Tariat meteorology station. Because the geospatial N deposition data were unavailable, we set the two N deposition parameters (EPNFA(1) and EPNFA(2)) based on the relationship between wet deposition and precipitation over the neighboring country, China (Jia et al., 2014). The basic site-specific parameters, such as soil texture, bulk density and rock fragments, were obtained from analysis of soil samples. Drainage conditions were also predefined according to local topography. Potential aboveground production (PRDX) parameter was adjusted so that the modeled carbon stock accurately matched the measured values from 309 sampling sites taken randomly from our sampling campaign (Fig. S1). Once the model had been calibrated, the modeled SOC was validated against another dataset comprised of data from the field campaign that had not been used in calibration.

2.3. Grazing management scenarios

Once the model calculations are optimized, we assessed carbon dynamics according to the different grazing scenarios. Grazing management scenarios for the degraded grasslands were projected based on ‘rule of thumb’ sustainable biomass removal rates applied to each degradation stratum within each vegetation type: 50% biomass removal for non-degraded grasslands, 45% for lightly degraded, 40% for moderately degraded and 35% for heavily degraded grasslands. The timing of grazing events simulated in the summer grasslands followed local common practice, with grazing beginning on June 1 and ending on October 31 of each year

Table 1
Mean particle size distribution, bulk density, plant biomass and SOC stocks (0–20 cm) for Mongolian grasslands at different degrees of degradation.

Grassland type	Status	Clay (%)	Silt (%)	Sand (%)	Bulk density ($g\,cm^{-3}$)	Above-ground biomass ($g\,m^{-2}$)	SOC stock ($kg\,C\,m^{-2}$)
MM	Non-degraded	25.4	50.0	24.6	0.9	135.3	5.60
	Light	32.3	42.0	25.7	0.9	125.8	4.73
	Moderate	23.5	42.1	34.5	1.1	126.2	3.47
	Heavy	10.2	28.7	61.1	1.1	106.5	1.56
MWM	Light	29.6	44.8	25.7	0.9	188.4	4.50
	Moderate	21.5	41.7	36.8	1.1	118.9	3.84
	Heavy	8.9	24.7	66.3	0.9	50.4	1.38
M	Moderate	18.9	42.1	39.0	1.0	104.6	3.45
	Heavy	10.3	28.7	61.0	1.0	106.8	1.70
MS	Moderate	21.3	38.3	40.5	1.1	112.2	3.10
	Heavy	8.0	31.8	60.2	1.0	87.8	1.09

MM: mountain meadow; MWM: riparian meadow with marsh; M: riparian meadow; MS: mountain steppe.

modeled. A 23 years (2012–2035) spin-up was applied on the basis of average historical climate data.

2.4. Model performance and uncertainty assessment

Performance of the Century model was assessed using the methodology described by Cheng et al. (2014). According to Methodology for Sustainable Grassland Management (SGM) depicted in CDM EB- approved General Guidelines For Sampling And Surveys For Small-Scale CDM Project Activities, we assessed the parametric uncertainty using the key parameters with a given error. The range of estimated changes in SOC stock demonstrates the model parameter uncertainty, which is expressed as follows:

$$\text{Uncertainty}(\%) = \frac{|S_{max} - S_{min}|}{2 \times S} \times 100 \quad (1)$$

$$S_{max} = \text{Model}(P_{max}, \text{Temperature}_{min}, \text{Precipitation}_{min}, \text{Clay}_{max}) \quad (2)$$

$$S_{min} = \text{Model}(P_{min}, \text{Temperature}_{max}, \text{Precipitation}_{max}, \text{Clay}_{min}) \quad (3)$$

where S_{max} and S_{min} denote the upper and lower values of soil carbon accumulation corresponding to the parameters at the 95% confidence level, and S is the modeled SOC accumulation with the mean of parameters. P_{min} and P_{max} are the minimum and maximum value of parameter at the 95% confidence level, respectively. This is clearly a very limited way to assess many possible uncertainties, but was the best we could do given the limitations in data availability.

3. Results

3.1. Effects of degradation

Our field inventory revealed that variations of plant and soil variables were significantly across a degradation gradient (Table 1). Grassland degradation coincided with an increase in sand content and decreases in clay and silt content. The differences in bulk density among degradation classes were negligible. Above-ground biomass generally decreased as degradation increased. SOC stock decreased markedly with degradation. SOC in lightly degraded MM grasslands were 18.7% lower than that in non-degraded grasslands. The SOC further declined by about 20% and 50% in moderately and heavily degraded grasslands, respectively.

3.2. SOC response to grazing

The model predicted a marked decrease in SOC stock in the period of high grazing intensity (1990–2012). The modeled SOC stocks corresponded well with measured values (Fig. 3; Table S1). Although grazing scenarios were set for each grassland stratum on the basis of rule of thumb biomass removal rates, reducing grazing intensity on the Mongolian grasslands showed substantial carbon accumulation potential, except for a marginal gain in non-degraded MM (Fig. 4). In addition, lower SOC accumulation was predicted in heavily degraded compared to moderately degraded grasslands. The annual accumulation rates were 33.2–36.9 and 22.0–29.5 g C m^{-2} yr^{-1} for moderately and heavily degraded grassland strata, respectively. The lightly degraded grassland strata had moderate SOC accumulation rates, ranging from 27.3 to 31.8 g C m^{-2} yr^{-1}. Simulations to 2035 indicated that reducing grazing intensity would allow SOC stocks to recover from 31.2 to 41.4% of the intact stocks in heavily degraded grassland

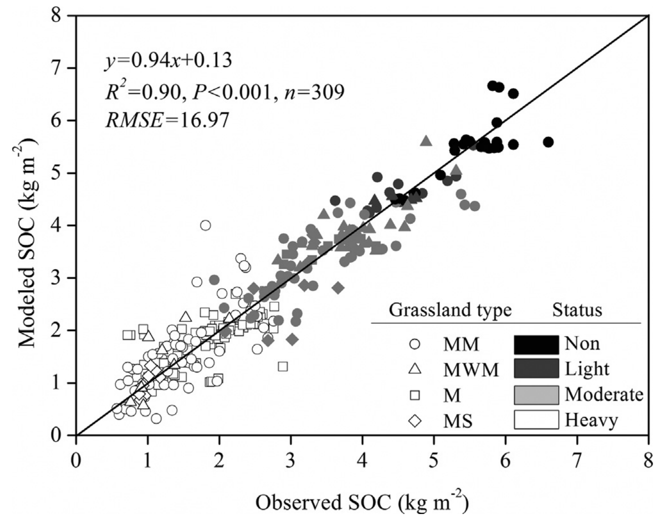

Fig. 3. Comparison observed and modeled soil organic carbon (SOC) for non-degraded, light, moderate and heavy degraded Mongolian grassland soils on the Tariat soum. MM, mountain meadow; MWM, riparian meadow with mash; M, riparian meadow; MS, mountain steppe.

strata, and from 73.4 to 90.3% in moderately degraded strata. However, the grasslands did not reach a steady-state SOC level in the near term, as shown by the continuing accumulation trends.

4. Discussion

4.1. SOC loss from grassland degradation

The Century simulations revealed an evident negative impact of grassland degradation on SOC stocks. This patter is consistent with our geospatial soil inventory, and several findings of experimental studies from other grassland ecosystems with similar soils and climates (Huang et al., 2010; Zhang et al., 2011). SOC depletion could partly be attributed to the reduction in grass biomass production. Studies have shown that overgrazing can often lead to an amount of plant photosynthetic tissue consumption and community composition shifts that lower plant production, and thereby limit potential litter inputs to the soil (Bagchi and Ritchie, 2010; Gao et al., 2008; Wang et al., 2012). A gradient decrease in aboveground biomass and soil carbon stocks from intact soils towards the heavily degraded soils has also observed in other semi-arid grasslands, confirming a close connection between soil carbon and grass biomass production, and suggesting that overgrazing could restrict soil carbon sequestration (He et al., 2011; Wen et al., 2013; Zhang et al., 2011). In addition, the SOC loss may be likely driven by increasing erosion due to a decrease in vegetation cover associated with continuous, heavy grazing (Hoffmann et al., 2008). Erosion can amplify the negative effects of heavy grazing on SOC, and potentially even further coarsening the soil and reducing its capacity to hold SOC (McSherry and Ritchie, 2013). Another possible reason for SOC depletion may be the impact of animal trampling. Animal trampling generally leads to a deterioration of soil structure, particularly to destruction of soil aggregates followed by a release of physically protected soil organic matter which then mineralized (Steffens et al., 2008). In Century, soil erosion is treated in a simplified form. Erosion events are uncoupled from precipitation and only flat monthly soil loss rates can be entered as input variables (Tornquist et al., 2009). Furthermore, information regarding soil erosion was unavailable in our study area. Thus we have not explored soil erosion here. Although it was in fact posited as a potential mechanism for SOC depletion in several studies (Wiesmeier et al., 2012; Steffens et al.,

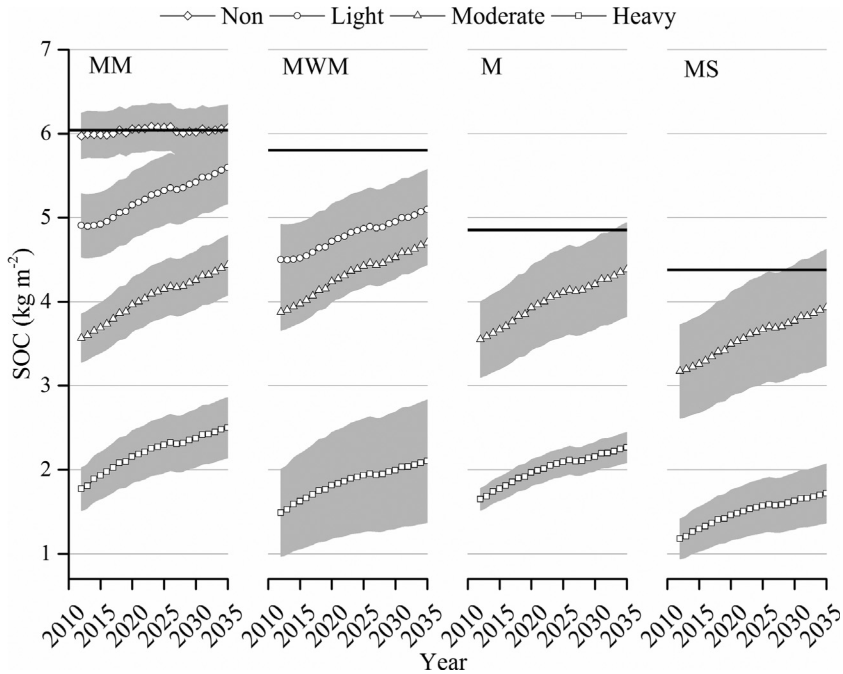

Fig. 4. Trend of SOC change in degraded Mongolian grassland soils in relation to the different simulated grazing managements. Black lines are the SOC equilibrium levles before overgrazing. The shading is the uncertainty range. MM, mountain meadow; MWM, riparian meadow with mash; M, riparian meadow; MS, mountain steppe.

2008), effects of animal trampling on decomposition was not simulated in Century where decomposition are primarily affected by molecular properties of the soil organic matter and are modified by temperature and moisture (Dib et al., 2014). Taken as a whole, Century appears to provide an accurate depiction of SOC responses to grazing events, though still possibly potential for improving the model structure and parameterization to further reduce uncertainties (Tornquist et al., 2009).

4.2. SOC accumulation in response to reduced grazing intensity

With open access or collectively managed grasslands throughout the country (Olonbayar, 2010), it is difficult to implement experiments on the effect of land use and management on SOC stocks in grasslands in Mongolia. However, it is important to fill knowledge gaps to support policy decisions. In this situation, the process-based modeling approach may be capable of providing useful projections of SOC response to a variety of grassland managements (Lugato et al., 2014). In our study, the Century model predicted effective SOC accumulation in degraded Mongolian grassland under reduced grazing intensity, with SOC accumulation rates in the near term (i.e. by 2035) of 21.96–36.91 g C m^{-2} yr^{-1}. If these accrual rates are applied to 90% of Mongolia's total forest steppe grassland area (33.2 million ha), annual accumulation to 2035 would be 7.3–12.3 Mt C yr^{-1} under future grazing recommendations, assuming no climate change. By comparison, in 2006 Mongolia's total net GHG emissions were 4.25 Mt C (MNET, 2012).

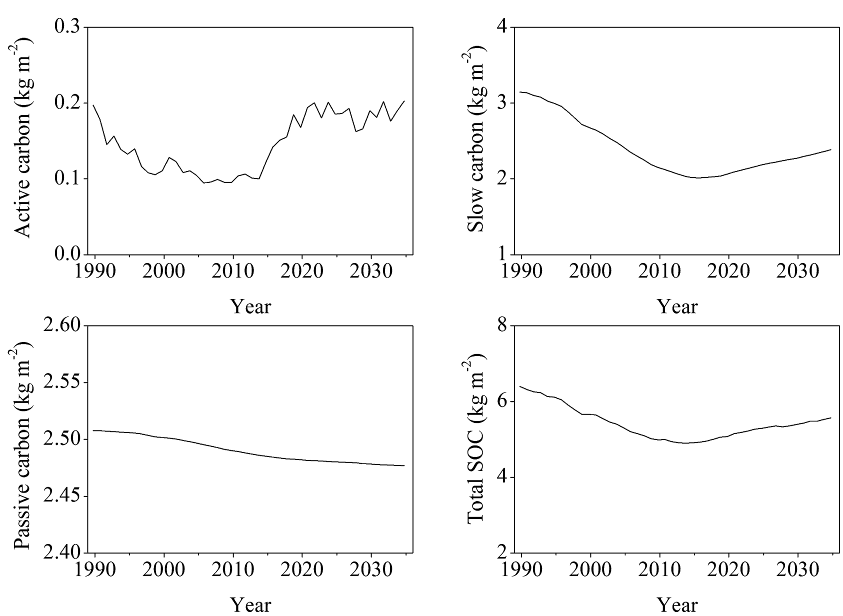

Fig. 5. Predicted changes in active, slow, passive and total SOC in light degraded mountain meadow (other scenarios give similar trends, not shown).

Our estimated accumulation rates were comparable to the reported values (17.0–37.0 g C m^{-2} yr^{-1} for 20 cm) in alpine meadow environments (Fan et al., 2012) with similar vegetation and climate conditions to Tariat, but lower than or within the lower end of the ranges of accumulation rates for grasslands in northern China reported by Wang et al. (2011) (23–330 g C m^{-2} yr^{-1}, 0-20 cm) and Guo et al. (2008) (21.3–73.1 g C m^{-2} yr^{-1}). However, the higher results in that study were obtained through exclusion from grazing, which is not feasible in the Mongolian context, as extensive livestock production remains the source of livelihoods for a considerable proportion of the population (Sankey et al., 2009). In Tariat, surveys of land users suggested that the average household moves their grazing camp just over two times during the summer grazing season. However, since we cannot be sure that each specific plot of grassland is not grazed more than once by different herds in the season, our scenario settings retained the conservative assumption that grazing is continuous in the summer grazing season. If the duration of each grazing event is in fact shorter than we simulated, the accumulation rate would be higher. Given the strong dependence of rural households in Mongolia on livestock for their income, it is likely that the most feasible route to reducing grazing intensity is through changes in the timing and duration of grazing, for example through increased rotation and resting of pastures, which may be supported by strengthening community-based rangeland management institutions (Fernández-Giménez et al., 2015). Efforts to address livestock numbers are likely to require changes in livestock management and marketing to maintain herders' incomes (Kemp et al., 2013), which would depend on longer-term and more systemic changes in the Mongolian livestock economy.

4.3. Carbon quality and SOC recovery

Soil carbon is heterogeneous in nature and consists of several SOC pools (Allen et al., 2010). Labile pool accounts for a small fraction of SOC and has a fast turnover rate, while recalcitrant SOC is a large pool and has a slower turnover rate (Davidson and Janssens, 2006). Therefore, sequestration of atmospheric carbon in soils in a stable form is considered to have potential for global CO_2 mitigation. The Century simulations for grazing scenarios showed that the shape of the total SOC time-series is mainly dictated by the changes occurring within the slow pool (Fig. 5). During this period, changes in the active and passive pools are relatively small. However, a previous field soil survey in steppe soils in Northern China founded that labile SOC is preferentially lost in the course of soil degradation under intensive grazing (Wiesmeier et al., 2015). According to observations of experiments with reduced grazing intensity or grazing exclusion, SOC increases mainly resulted from an accumulation of labile SOC, which was sensitive to land use and climate change (Steffens et al., 2011). Therefore, the observed SOC increases after improved grassland management cannot be viewed as contribution to long-term carbon sequestration. The differences between the predicted and measured trajectories of carbon fractions may be attributed to particular features of the Century model. Century has a rapid transfer rate of SOC from active pools into pools with lower decomposition rates (Dib et al., 2014). Some changes in the slow SOC pools are needed to improve model predictions in grassland soils, even if quantitative SOC pools in Century often do not easily correspond to measurable entities. Without such improvements, the magnitude of the predicted SOC sequestration simulated by Century may be amplified.

Even after 23 years of improved grazing management, the SOC storage of the intact grassland cannot be restored completely (Fig. 4). Wind erosion related to intensive grazing should be taken in to account. Evidence gathered in several studies indicated that wind erosion resulted in a loss of silt and clay particles (Steffens et al., 2008; Wiesmeier et al., 2009). Our study also clearly shows the smaller silt and clay contents were found in more degraded grassland soils. The loss of fine soil particles consequently undermines the ability to stabilize SOC, which makes the recovery of the fine mineral fraction SOC largely irreversible (Wiesmeier et al., 2015). Such a wind erosion effect is a contributory reason why the SOC did not recover completely. However, the dynamics and stabilization mechanisms differed between the soil carbon fractions. The physically protected pool may be slow to rebuild past reserves because reassembly of macro- and micro-aggregate structures after disturbance might resume over a long timespan (O'Brien and Jastrow, 2013). This suggests that SOC restoration in the aggregate-protected fraction may require a longer time than our simulations. For active pools, rebuilding past reserves was faster than other fractions. Its recovery dynamics depend on carbon input level and decomposition rate (O'Brien and Jastrow, 2013). Hence, if improved managements fuel long-term grassland productivity, active carbon pools of a new equilibrium may over the past values. The objective was to simulate effects of grazing on total SOC, however, there is also need to further investigate the dynamics of different SOC fractions.

5. Conclusions

Overgrazing has caused widespread degradation in Mongolian steppes. Reducing grazing intensity is a common strategy promoted by government sources to combat grassland degradation. However, few experimental data of the soil carbon recovery are available. This study assessed the impacts of grassland management on SOC stocks using a modeling approach combined with a geospatial inventory dataset. Although there are significant possibilities for future improvement, validation against SOC stocks from inventories confirmed the robustness and accuracy of the modified Century model when simulating the effect of grazing management practices on forest steppe grasslands in Mongolia. The prediction of future SOC accumulation potential was in the range of 21.96–36.91 g C m^{-2} yr^{-1} in near term (by 2035) under decreased grazing intensity. Our results demonstrate that reduction in grazing intensity may provide a near term solution for Mongolian steppe that have experienced soil carbon loss from intensive grazing managements. The reduction in grazing pressures offers a profitable and sustainable solution to our needs for pairing livestock production with SOC recovery.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2015.07.014.

References

Administration for Land Affairs, 2011. Geodesy and Cartography (ALAGC). Annual Report of ALAGC. ALAGC, Ulaanbaatar.

Administration for Land Affairs, 2012. Geodesy and Cartography (ALAGC). Unified Land Territory Report. ALAGC, Ulaanbaatar.
Allen, D.E., Pringle, M.J., Page, K.L., Dalal, R.C., 2010. A review of sampling designs for the measurement of soil organic carbon in Australian grazing lands. Rangeland J. 32, 227–246.
Bagchi, S., Ritchie, M.E., 2010. Introduced grazers can restrict potential soil carbon sequestration through impacts on plant community composition. Ecol. Lett. 13, 959–968.
Booker, K., Huntsinger, L., Bartolome, J.W., Sayre, N.F., Stewart, W., 2013. What can ecological science tell us about opportunities for carbon sequestration on arid rangelands in the United States. Global Environ. Change 23 (1), 240–251.
Bortolon, E.S.O., Mielniczuk, J., Tornquist, C.G., Lopes, F., Bergamaschi, H., 2011. Validation of the Century model to estimate the impact of agriculture on soil organic carbon in Southern Brazil. Geoderma 167–168, 156–166.
Chang, X., Wang, S., Zhu, X., Cui, S., Luo, C., Zhang, Z., Wilkes, A., 2014. Impacts of management practices on soil organic carbon in degraded alpine meadows on the Tibetan Plateau. Biogeosciences 11, 3495–3503.
Cheng, K., Ogle, S.M., Parton, W.J., Pan, G., 2014. Simulating greenhouse gas mitigation potentials for Chinese croplands using the DAYCENT ecosystem model. Global Change Biol. 20 (3), 948–962.
Conant, R., 2009. Challenges and Opportunities for Carbon Sequestration in Grassland Systems. FAO technical report, Rome.
Conant, R.T., Paustian, K., 2002. Potential soil carbon sequestration in overgrazed grassland ecosystems. Global Biogeochem. Cycles 16 (4), 1143.
Conant, R.T., Paustian, K., Elliott, E.T., 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecol. Appl. 11, 343–355.
Dib, A.E., Johnson, C.E., Driscoll, C.T., Fahey, T.J., Hayhoe, K., 2014. Simulating effects of changing climate and CO2 emissions on soil carbon pools at the Hubbard Brook experimental forest. Global Change Biol. 20, 1643–1656.
Dagvadorj, D., Natsagdorj, L., Dorjpurev, J., Namkhainyam, B., 2009. MARCC 2009: Mongolia Assessment Report on Climate Change 2009. Ministry of Nature, Environment and Tourism, Mongolia.
Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173.
Evans, S., Burke, I., Lauenroth, W., 2010. Controls on soil organic carbon and nitrogen in Inner Mongolia, China: a cross-continental comparison of temperate grasslands. Global Biogeochem. Cycles 25 (3) doi:http://dx.doi.org/10.1029/2010GB003945 GB3006.
Fan, Y.J., Hou, X.Y., Shi, H.X., Shi, S.L., 2012. The response of carbon reserves of plants and soils to different grassland managements on alpine meadow of three headwater source regions. Grassland Turf 32 (5), 41–46.
Fernández-Giménez, M.E., Batkhishig, B., Batbuyan, B., Ulambayar, T., 2015. Lessons from the Dzud: community-based rangeland management increases the adaptive capacity of mongolian herders to winter disasters. World Dev. 68, 48–65.
Follett, R.F., Schuman, G.E., 2005. Grazing land contributions to carbon sequestration. In: McGilloway, D.A. (Ed.), Grassland: a Global Resource. Wageningen Academic Publishers, Wageningen, the Netherland, pp. 265–277.
Gao, Y.H., Luo, P., Wu, N., Chen, H., Wang, G.X., 2008. Impacts of grazing intensity on nitrogen pools and nitrogen cycle in an alpine meadow on the eastern Tibetan Plateau. Appl. Ecol. Env. Res. 6, 67–77.
Guo, R., Wang, X.K., Lu, F., Duan, X.N., Ouyang, Z.Y., 2008. Soil carbon sequestration and its potential by grassland ecosystems in China. Acta Ecol. Sin. 28, 862–867.
He, N.P., Zhang, Y.H., Yu, Q., Chen, Q.S., Pan, Q.M., Zhang, G.M., Han, X.G., 2011. Grazing intensity impacts soil carbon and nitrogen storage of continental steppe. Ecosphere 2. doi:http://dx.doi.org/10.1890/ES10-00017.1 art8.
Henderson, B., Gerber, P., Hilinski, T., Falcucci, A., Ojima, D., Salvatore, M., Conant, R., 2015. Greenhouse gas mitigation potential of the world's grazing lands: modelling soil carbon and nitrogen fluxes of mitigation practices. Agric. Ecosyst. Environ. 207, 91–100.
Hilker, T., Natsagdorj, E., Waring, R.H., Lyapustin, A., Wang, Y., 2014. Satellite observed widespread decline in Mongolian grasslands largely due to overgrazing. Global Change Biol. 20, 418–428.
Hoffmann, C., Funk, R., Wieland, R., Li, Y., Sommer, M., 2008. Effects of grazing and topography on dust flux and deposition in the Xilingele grassland, Inner Mongolia. J. Arid Environ. 72, 792–807.
Houghton, R.A., 2007. Balancing the global carbon budget. Annu. Rev. Earth Planet. Sci. 35, 313–347.
Huang, Y., Sun, W., Zhang, W., Yu, Y., 2010. Changes in soil organic carbon of terrestrial ecosystems in China: a mini-review. Sci. China Life Sci. 53, 766–775.
Jia, Y., Yu, G., He, N., Zhan, X., Fang, H., Sheng, W., Zuo, Y., Zhang, D., Wang, Q., 2014. Spatial and decadal variations in inorganic nitrogen wet deposition in China induced by human activity. Sci. Rep. 4, 3763. doi:http://dx.doi.org/10.1038/srep03763.
Kemp, D.R., Han, G.D., Hou, X.Y., Michalk, D.L., Hou, F.J., Wu, J.P., Zhang, Y.J., 2013. Innovative grassland management systems for environmental and livelihood benefits. P. Natl. Acad. Sci. U. S. A. 110, 8369–8374.
Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304 (5677), 1623–1627.
Liu, Y.Y., Evans, J.P., McCabe, M.F., de Jeu, R.A., van Dijk, A.I., Dolman, A.J., Saizen, I., 2013. Changing climate and overgrazing are decimating Mongolian steppes. PloS One 8 (2), e57599. doi:http://dx.doi.org/10.1371/journal.pone.0057599.
Lugato, E., Panagos, P., Bampa, F., Jones, A., Montanarella, L., 2014. A new baseline of organic carbon stock in European agricultural soils using a modelling approach. Global Change Biol. 20, 313–326.
McSherry, M.E., Ritchie, M.E., 2013. Effects of grazing on grassland soil carbon: a global review. Global Change Biol. 19, 1347–1357.
Ministry of Nature, Environment and Tourism (MNET), 2012. Mongolia Second National Communication under the United Nations Framework Convention on Climate Change. Ulaanbaatar.
National Agency for Meteorology and Environmental Monitoring of Mongolia (NAMEM), 2015. Mongolian State of Rangeland Report. Ulaanbaatar.
National Statistical Office of Mongolia (NSO), 2014. Available at: http://www.1212mn/en/contents/stats/contents_stat_fld_tree_html.jsp (accessed 09.1.15.).
Neff, J.C., Reynolds, R.L., Belnap, J., Lamothe, P., 2005. Multi-decadal impacts of grazing on soil physical and biogeochemical properties in southeast Utah. Ecol. Appl. 15, 87–95.
O'Brien, S.L., Jastrow, J.D., 2013. Physical and chemical protection in hierarchical soil aggregates regulates soil carbon and nitrogen recovery in restored perennial grasslands. Soil Biol. Biochem. 61, 1–13.
Livelihood Study of Herders in Mongolia. In: Olonbayar, M. (Ed.), Mongolian Society for Range Management, Ulaanbaatar.
Sankey, T.T., Sankey, J.B., Weber, K.T., Montagne, C., 2009. Geospatial assessment of grazing regime shifts and sociopolitical changes in a Mongolian rangeland. Rangeland Ecol. Manag. 62, 522–530.
Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., 2007. Agriculture. In: Metz, B., Davidson, O.R. (Eds.), Climate Change 2007: Mitigation. Working Group III Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge United Kingdom and New York, NY, USA.
Steffens, M., Kölbl, A., Totsche, K.U., Kögel-Knabner, I., 2008. Grazing effects on soil chemical and physical properties in a semiarid steppe of Inner Mongolia (PR China). Geoderma 143, 63–72.
Steffens, M., Kölbl, A., Schörk, E., Gschrey, B., Kögel-Knabner, I., 2011. Distribution of soil organic matter between fractions and aggregate size classes in grazed semiarid steppe soil profiles. Plant Soil 338, 63–81.
Tornquist, C.G., Mielniczuk, J., Cerri, C.E.P., 2009. Modeling soil organic carbon dynamics in Oxisols of Ibirubá (Brazil) with the Century Model. Soil Till. Res. 105, 33–43.
von Wehrden, H., Hanspach, J., Kaczensky, P., Fischer, J., Wesche, K., 2012. Global assessment of the non-equilibrium concept in rangelands. Ecol. Appl. 22 (2), 393–399.
Wang, Y., Zhou, G., Jia, B., 2008. Modeling SOC and NPP responses of meadow steppe to different grazing intensities in Northeast China. Ecol. Model. 217 (1–2), 72–78.
Wang, S., Wilkes, A., Zhang, Z., Chang, X., Lang, R., Wang, Y., Niu, H., 2011. Management and land use change effects on soil carbon in northern China's grasslands: a synthesis. Agric. Ecosyst. Environ. 42, 329–340.
Wang, S., Duan, J., Xu, G., Wang, Y., Zhang, Z., Rui, Y., Luo, C., Xu, B., Zhu, X., Chang, X., Cui, X., Niu, H., Zhao, X., Wang, W., 2012. Effects of warming and grazing on soil N availability, species composition, and ANPP in an alpine meadow. Ecology 93, 2365–2376.
Wen, L., Dong, S.K., Li, Y.Y., Li, X.Y., Shi, J.J., Wang, Y.L., Liu, D.M., Ma, Y.S., 2013. Effect of degradation intensity on grassland ecosystem services in the alpine region of Qinghai-Tibetan Plateau, China. PloS One 8 (3), e58432. doi:http://dx.doi.org/10.1371/journal.pone.0058432.
White, R.P., Murray, S., Rohweder, M., Prince, S.D., Thompson, K.M., 2000. Grassland Ecosystems. World Resources Institute Washington, DC, USA.
Wiesmeier, M., Steffens, M., Kölbl, A., Kögel-Knabner, I., 2009. Degradation and small-scale spatial homogenization of topsoils in intensively-grazed steppes of Northern China. Soil Till. Res. 104, 299–310.
Wiesmeier, M., Steffens, M., Mueller, C., Kölbl, A., Reszkowska, A., Peth, S., Hor, R., n Kögel-Knabner, I., 2012. Aggregate stability and physical protection of soil organic carbon in semiöarid steppe soils. Eur. J. Soil Sci. 63, 22–31.
Wiesmeier, M., Munro, S., Barthold, F., Steffens, M., Schad, P., Kögel-Knabner, I., 2015. Carbon storage capacity of semiöarid grassland soils and sequestration potentials in Northern China. Global Change Biol. doi:http://dx.doi.org/10.1111/gcb.12957 in press.
Zhang, G., Kang, Y., Han, G., Mei, H., Sakurai, K., 2011. Grassland degradation reduces the carbon sequestration capacity of the vegetation and enhances the soil carbon and nitrogen loss. Acta Agric. Scand. B-S P 61, 356–364.