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RESEARCH ARTICLE

Soil organic carbon dynamics in Xilingol grassland of northern China induced by the Beijing-Tianjin Sand Source Control Program

Liangxia ZHANG[1,2], Wei CAO[2], Jiangwen FAN (✉)[2]

1 Jiangsu Key Laboratory of Agricultural Meteorology, and College of Applied Meteorology, Nanjing University of Information Science and Technology, Nanjing 210044, China
2 Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

Abstract To mitigate impacts of sandstorms on northern China, the Chinese government launched the Beijing–Tianjin Sand Source Control Program (BTSSCP) in 2000. The associated practices (i.e., cultivation, enclosure, and aerial seeding) were expected to greatly enhance grassland carbon sequestration. However, the BTSSCP-induced soil organic carbon (SOC) dynamics remain elusive at a regional level. Using the Xilingol League in Inner Mongolia for a case study, we examined the impacts from 2000 to 2006 of the BTSSCP on SOC stocks using the IPCC carbon budget inventory method. Results indicated that over all practices SOC storage increased by 1.7%, but there were large differences between practices. SOC increased most rapidly at the rate of 0.3 Mg C$\cdot$ha$^{-1}\cdot$yr^{-1} under cultivation, but decreased significantly under aerial seeding with moderate or heavy grazing (0.3 vs.0.6 Mg C$\cdot$ha$^{-1}\cdot$yr^{-1}). SOC increases varied slightly for grassland types, ranging from 0.10 Mg C$\cdot$ha$^{-1}\cdot$yr^{-1} for temperate desert steppe to 0.16 Mg C$\cdot$ha$^{-1}\cdot$yr^{-1} for temperate meadow steppe and lowland meadow. The overall economic benefits of the SOC sink were estimated to be 4.0 million CNY. Aerial seeding with no grazing was found to be the most cost-effective practice. Finally, we indicated that at least 55.5 years (shortest for cultivation) were needed for the grasslands to reach their potential carbon stocks. Our findings highlight the importance and effectiveness of BTSSCP in promoting terrestrial carbon sequestration which may help mitigate climate change, and further stress the need for more attention to the effectiveness of specific practices.

Keywords grassland carbon sequestration, ecological restoration, Beijing-Tianjin Sand Source Control Program (BTSSCP), IPCC carbon budget inventory method

1 Introduction

Grasslands cover 41.7% of China's total land area and mostly occur in the northern arid and semiarid regions of China (DAHV and CISNR, 1996). They are of key value in servicing local ecological functions and socio-economics (Kang et al., 2007). However, about 90% of the grasslands in the arid and semiarid regions are seriously degraded due to intensive human activities and climate change (Chen and Wang, 2000; Runnström, 2000; Ni, 2003). Deterioration of these grasslands' biodiversity together with ecosystem functions and services have created serious desertification and sandstorms that can affect broad areas beyond their local area (Zhang et al., 2004; Liu, 2006; Wu et al., 2012). Beijing, the capital of China, has long suffered from sandstorms arising from the grasslands, and these seriously affect industrial and agricultural activities, transportation, and daily life (Goudie and Middleton, 1992; Wang et al., 1999; Gao et al., 2002).

To mitigate the impacts of sandstorms and improve the ecological condition of the northern grasslands, the Chinese government launched the Beijing-Tianjin Sand Source Control Program (BTSSCP) in 2000. It covers 75 counties (banners, cities, or districts) of Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia, with a combined area of 46 million ha (Wu et al., 2012; http://www.gov.cn). The BTSSCP includes multiple practices such as grassland management (i.e., cultivation, enclosure, and aerial seeding), returning cropland to forest, and reforestation/afforestation (Wu et al., 2013). About 56.2 billion CNY

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E-mails: fanjw@igsnrr.ac.cn, fanjw@igsnrr.ac.cn

(at present, \$1U.S.= 6.2 CNY) was invested in the program from 2000 to 2010 (http://www.gov.cn). The ecological effects of the program have attracted considerable interest by scientists and decision makers (Zhang et al., 2012; Huang et al., 2013; Wu et al., 2013, 2014b; Zeng et al., 2014).

Although carbon sequestration was not a goal of the BTSSCP, such a large-scale project has great potential for enhancing terrestrial carbon sequestration and thus may help mitigate climate change (Houghton et al., 1999; Ogle et al., 2004; IPCC, 2006; Wang et al., 2011; Liu et al., 2013; Zhou et al., 2014). As the largest organic carbon pool of terrestrial ecosystems (Schimel, 1995), soil organic carbon (SOC) can be considered as one of the key indicators for evaluating the effectiveness of the BTSSCP (Zeng et al., 2014). However, the impacts of the BTSSCP on the grassland SOC pools remains poorly understood at a regional scale. Relatively limited efforts have focused only on vegetation cover and site-scale observations (Su et al., 2003, 2004, 2005; He et al., 2008, 2009; Li et al., 2011; Wang et al., 2011; Li et al., 2012; Liu et al., 2012; Wu et al., 2013, 2014a, b; Hao et al., 2014; Hu et al., 2015). For example, Wu et al. (2013, 2014b) found that the normalized difference vegetation index (NDVI) increased significantly over 45.9% of the BTSSCP region. He et al. (2009) demonstrated that grazing exclusion practices increased the SOC density of the 0 – 10 cm soil layer by 73.3% in the sand fraction in Inner Mongolia. Thus a systematic evaluation of SOC dynamics is urgently needed for better understanding of the carbon sequestration potential and the effectiveness of BTSSCP.

Because SOC cannot be directly observed at the regional or global scale, extrapolating site-scale measurements by a statistical approach has emerged as the common approach for predicting SOC over large areas (Wang et al., 2003; Wu et al., 2003; Holmes et al., 2006; Xie et al., 2007; Meersmans et al., 2008; Piao et al., 2009; Yang et al., 2010). For example, Holmes et al. (2006) examined SOC patterns in the southwestern Amazon basin by using the ordinary kriging interpolation method via a large soil profile database. Piao et al. (2009) scaled up soil carbon inventory data obtained in the 1980s to a national level for China with an empirical regression method. Yang et al. (2010) estimated the SOC stock of northern grasslands in China during 2000s via the relationship between SOC densities and environmental factors. However, the soil carbon inventories extrapolation method is not appropriate to study the rapid SOC dynamics induced by the BTSSCP since the soil inventories are time-consuming and costly. Instead, the IPCC carbon budget inventory method (IPCC, 1997, 2006) can more accurately evaluate the effects of managements on the SOC stocks at a regional scale. It has been successfully used to assess management-induced SOC changes in the United States, Europe, and Russia (IPCC, 1997, 2006; Subak, 2000; Houghton, 2001; Ogle et al., 2004; Somogyi et al., 2007; Dolman et al., 2012).

In this study, we assessed the impacts of the BTSSCP on the grassland SOC pools from 2000 to 2006 in the Xilingol league of Inner Mongolia using the IPCC carbon budget inventory method (IPCC, 2006). The Xilingol grassland is well known for its large area and representativeness of the northern arid and semiarid grassland ecosystem (Bai et al., 2004, 2008; Li et al., 2012). Due to their location and serious environmental problems, all the counties (banners) of Xilingol grassland were set up as pilot areas for the BTSSCP. Assessing the grassland SOC dynamics in Xilingol can therefore provide important scientific and practical bases for the sustainable implementation of the BTSSCP in the arid/semiarid grassland areas of China.

The objectives of this study were to (i) quantify the impacts of the BTSSCP on SOC stocks, (ii) assess the economic benefits of SOC sequestration, and (iii) investigate the time needed to reach the potential SOC density of the grassland for the three most commonly grassland management practices (i.e., cultivation, enclosure, and aerial seeding).

2 Materials and methods

2.1 Study area

The Xilingol grassland (41°32′–46°41′N, 111°6′–120°10′E) is located in the central part of Inner Mongolia, China (Fig. 1). It covers a total area of 20×10^6 ha and has a typical semiarid climate, with a mean annual temperature of 2.2°C (varying between –2.3°C and 5.6°C) and a mean annual precipitation of 278 mm (varying between 135 mm and 433 mm). Precipitation and soil fertility decrease gradually from east to west, resulting in three zonal vegetation types of temperate meadow steppe, temperate steppe, and temperate desert steppe (Liu, 1960; Li, 1962, 1979; Wu and Loucks, 1992). The temperate meadow steppe is dominated by *Leymus chinensis* and *Stipa baicalensis*, the temperate steppe by *Leymus chinensis*, *Stipa grandis*, *Stipa krylovii*, *Artemisia frigida,* and the temperate desert steppe by *Stipa klemenzii* and *Cleistogenes songorica*. The "non-zonal" grassland type of lowland meadow (dominated by many species including *Calamagrostis epigejos*, *Sanguisorba officinalis*, and *Potentilla anserina*) also occurs in Xilingol. In addition to these four dominant grassland types, small areas of mountain meadow and temperate steppe desert are found in the east and west margins of the region, respectively.

The Xilingol grassland was set up as the pilot area for the BTSSCP in 2000, and included the three main management practices of cultivation, enclosure, and aerial seeding (http://www.gov.cn). Cultivation includes planting productive forage (i.e., *Medicago sativa*), irrigation, fertilization, and fencing the planting area to keep animals out. The enclosure practice involves enclosure of areas of grassland by post and wire fencing. Two grazing policies

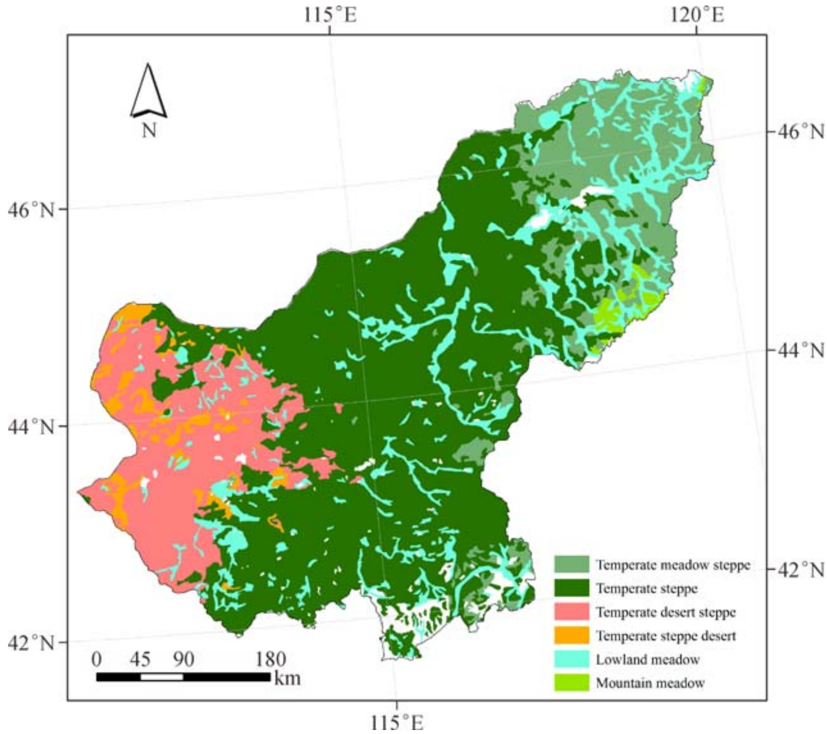

Fig. 1 Location of the study area with background indicating the grassland types.

were implemented under this practice: seasonal controlled grazing and no grazing (Li et al., 2013). The aerial seeding practice involves spreading seeds of forage species over grassland from a plane. By the end of 2006, the management areas covered by the cultivation, enclosure, and aerial seeding practices were 40.2, 669.3, and 34.3 $\times 10^3$ ha, respectively (Table 1).

2.2 Methods and data

2.2.1 SOC stock estimation

We assumed that the cultivation, enclosure, and aerial seeding practices were implemented averagely on the four main grassland types (i.e., temperate meadow steppe, temperate steppe, temperate desert steppe, and lowland meadow) because the spatial distribution of these practices was not available for this study. The SOC stock (soil depth of 40 cm) at the t^{th} year in the entire BTSSCP area (C_t) was calculated as follow:

$$C_t = \sum_{i=1}^{3} C_{it}, \tag{1}$$

where i represents the grassland management practice (i.e., $i = 1$ is cultivation, $i = 2$ is enclosure, and $i = 3$ is aerial seeding), and C_{it} is the SOC stock for the i^{th} practice at the t^{th} year. C_{it} was calculated using the IPCC carbon budget inventory method (IPCC, 1997, 2006). This approach has been successfully used to calculate the management-induced changes of SOC pools in the United States, Europe, and Russia (IPCC, 1997, 2006; Subak, 2000; Houghton, 2001; Ogle et al., 2004; Somogyi et al., 2007; Dolman et al., 2012). The SOC stock over the first 20 years

Table 1 Areas ($\times 10^3$ ha) covered by different management practices from 2000 to 2006 in Xilingol

Year	Cultivation	Enclosure	Aerial seeding	Total
2000	11.1	3.8	1.0	15.9
2001	23.8	72.3	7.3	103.4
2002	28.1	189.5	15.0	232.6
2003	28.1	323.6	25.1	376.8
2004	35.3	456.9	30.8	523.0
2005	39.6	557.4	32.6	629.6
2006	40.2	669.3	34.3	743.8

under certain practices (C_{i20}) was estimated as follow:

$$C_{i20} = D_{soc} \times S_i \times F_i, \tag{2}$$

where D_{soc} is the SOC density at the initial year (Mg C·ha^{-1}), S_i is the area covered by the i^{th} practice (ha), and F_i is the stock change factor. Since our study period (i.e., 2000 to 2006) was shorter than 20 years, and as the area covered by the i^{th} practice increased each year, due to data limitation we assumed the carbon increased equally each year and calculated C_{it} as follow:

$$C_{it} = D_{soc} \times \Delta S_{it} + D_{soc} \times S_{it} \times (F_i - 1)/20, \tag{3}$$

where ΔS_{it} and S_{it} are the increased and total areas (ha) covered by the i^{th} practice in the t^{th} year, respectively. The values of ΔS_{it} and S_{it} were provided by the Inner Mongolia Rangeland Survey Institute (Table 1). The values of D_{soc} for lowland meadow, temperate meadow steppe, temperate steppe, and temperate desert steppe were set to (51.78, 51.11, 40.78, and 31.72) Mg C·ha^{-1}, respectively, which were obtained using China's national soil inventory data (Wang et al., 2003) and the grassland distribution map (ECAGRC, 1993, http://www.geodata.cn/). The value of F_i (Table 2) was established according to "2006 IPCC Guidelines for National Greenhouse Gas Inventories" (Ogle et al., 2004; IPCC, 2006) and previous syntheses of the management-induced SOC changes in China's grasslands (Shi et al., 2009; Lu, 2009; Wang et al., 2011).

Since the grassland under aerial seeding practice was not fenced, we further classified the practice into four types based on the grazing intensities in Xilingol (Liu, 2006): no grazing (AS), light grazing (AS-LG), moderate grazing (AS-MG), and heavy grazing (AS-HG). The SOC stock for aerial seeding under a certain grazing intensity was estimated as

$$C_{3jt} = D_{soc} \times \Delta S_{3jt} + D_{soc} \times (F_{3j} - 1) \times S_{3jt}/20, \tag{4}$$

where j represents grazing activity (i.e., $j = 1$ is no grazing, $j = 2$ is light grazing, $j = 3$ is moderate grazing, and $j = 4$ is heavy grazing), ΔS_{3jt} and S_{3jt} are calculated by the area of aerial seeding and the area ratio of j^{th} grazing activity (Liu, 2006), and F_{3j} was obtained by multiplying the stock change factor of aerial seeding by that of the j^{th} grazing intensity.

2.2.2 Economic benefits of SOC sequestration

The economic benefit of SOC sequestration (B_c) was calculated as

$$B_c = V_c - C_p, \tag{5}$$

where V_c is the economic value of SOC sequestration, and C_p is the cost of the management practices. We calculated V_c as

$$V_c = \sum_{i=1}^{3} (C_{i2006} - C_{i2000}) \times P_c, \tag{6}$$

where C_{i2006} and C_{i2000} represent the SOC stocks for the i^{th} practice in 2006 and 2000, respectively, and P_c is the carbon sink price (CNY/t CO_2). The value of P_c was set to 136.5 CNY/t CO_2 according to the world's largest emissions trading scheme – the European Union Emission Trading Scheme (Convery and Redmond, 2007).

C_p was calculated as follows:

$$C_p = \sum_{i=1}^{3} (U_i \times S_i), \tag{7}$$

where U_i is the unit cost for the i^{th} practice, and S_i is the total area covered by the i^{th} practice. The value of U_i was set to 2100, 300, and 210 CNY·ha^{-1} for the cultivation, the enclosure, and the aerial seeding practices, respectively, according to the financial investment of BTSSCP and local practices (http://www.ndrc.gov.cn and http://www.forestry.gov.cn).

Moreover, we calculated the cost of SOC sequestration for the ith practice (C_{si}) in order to identify the most cost-effective practice:

$$C_{si} = (V_{ci} - C_{pi})/(C_{i2006} - C_{i2000}). \tag{8}$$

2.2.3 Calculation of the time needed to reach the potential SOC density

The time needed to reach the potential SOC density under a certain practice (T_i) was calculated as:

$$T_i = (D_{soc\max} - D_{soc2006})/\Delta D_i, \tag{9}$$

where $D_{soc\max}$ is the potential SOC density (assumed soil depth was 40 cm), $D_{soc2006}$ is the SOC density in 2006, and ΔD_i is the annual increase of SOC density. Using the space-for-time substitution method, $D_{soc\max}$ was calculated as the average value of the top 10% SOC density for particular grassland types based on the soil inventory data (Wang et al., 2003) and the grassland distribution map (ECAGRC, 1993, http://www.geodata.cn/) of the study area. ΔD_i was calculated as

Table 2 SOC stock change factors for different management practices and grazing intensities

Grassland management			Grazing intensity		
Cultivation	Aerial seeding	Enclosure	Light grazing	Moderate grazing	Heavy grazing
1.16	1.14	1.11	0.95	0.70	0.5

$$\Delta D_i = D_{soc2006} \times S_{i2006} \times (F_i - 1)/20. \quad (10)$$

We assumed that there were two grazing scenarios under aAerial seeding after 2006: no grazing (scenario 1) and grazing at 2000 to 2006 intensity (scenario 2). Consequently, the time needed to reach $D_{soc\max}$ under aerial seeding (T_3) was calculated separately for the two scenarios after 2006. It was calculated according to Eq. (9) in scenario 1 and as follows in scenario 2:

$$T_{3j} = (D_{soc\max} - D_{soc2009})/\Delta D_{3j}, \quad (11)$$

where T_{3j} and ΔD_{3j} represent the time needed to reach $D_{soc\max}$ and the annual increase of SOC density for aerial seeding under the j^{th} grazing intensity, respectively.

3 Results

3.1 Changes of SOC

The SOC stock increased by 1.7% (32.0 Tg C in 2006 and 31.4 Tg C in 2000) after the implementation of the BTSSCP, with a carbon sequestration of 0.1 Mg C·ha^{-2}·yr^{-1} in the study period. Changes of the SOC stocks and densities varied substantially across management practices (Table 3). Specifically, the increase of SOC stock under enclosure (i.e., 0.53 Tg C) was greatest and significantly larger than that under the other practices (less than 0.07 Tg C). SOC density also rapidly increased under cultivation (0.3 Mg C·ha^{-1}·yr^{-1}), followed by AS. Notably, SOC storage and density were obviously reduced under AS-MG and AS-HG.

Further, changes of SOC stock and density differed for grassland types (Table 4). The temperate steppe showed the largest increase in SOC stock of 0.33 Tg C, more than 2.3 times that for the other three grassland types. Interestingly, the increases of SOC density overall varied slightly across grassland types, with the least for temperate desert steppe (0.10 Mg C·ha^{-1}·yr^{-1}), and the largest for both lowland meadow and temperate meadow steppe (i.e., 0.16 Mg C·ha^{-1}·yr^{-1}).

3.2 Economic benefits of SOC sequestration

The total economic benefits of the grassland SOC sequestration was relatively small from 2000 to 2006 (i.e., 4.0×10^6 CNY), with the economic value and cost of 296.6 and 292.6 ×10^6 CNY, respectively (Fig. 2). The economic benefits varied greatly across the management practices. Enclosure had the largest benefits at 63.4 ×10^6 CNY, while cultivation had a loss of 49.7×10^6 CNY. The economic balances for the other practices were relatively small (2.0–8.4×10^6 CNY). Nevertheless, AS had the lowest cost of carbon sequestration (i.e., 0.2 ×10^3 CNY Mg C^{-1}) while cultivation had the highest cost of carbon sequestration (i.e., 1.2×10^3 CNY Mg C^{-1}).

3.3 Time needed to reach the potential SOC density

The time needed to reach the potential SOC density varied across the practices. If there was no grazing after 2006 (i.e., scenario 1), the time was shortest under cultivation (55.5 years), followed by AS (65.6 years), AS-LG (68.1years), AS-MG (81.5 years), and enclosure (86.4 years) (Fig. 3).

Table 3 Changes of grassland SOC stock and density under different management practices in the BTSSCP region from 2000 to 2006. AS: aerial seeding; LG, light grazing; MG, moderate grazing; HG, heavy grazing

Management practice	Year/(Tg C)							SOC stock change /(Tg C)	SOC density change /(Mg C·ha^{-1}·yr^{-1})
	2000	2001	2002	2003	2004	2005	2006		
Cultivation	1.7	1.7	1.7	1.7	1.7	1.8	1.8	0.07	0.3
Enclosure	28.3	28.3	28.3	28.4	28.5	28.6	28.8	0.53	0.1
AS	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.01	0.2
AS-LG	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.01	0.1
AS-MG	0.2	0.2	0.2	0.2	0.2	0.2	0.2	−0.01	−0.3
AS-HG	0.2	0.2	0.2	0.2	0.2	0.2	0.1	−0.02	−0.6
Total	31.4	31.5	31.5	31.6	31.7	31.8	32.0	0.59	0.1

Table 4 Changes of SOC stock and density for different grassland types in the BTSSCP region from 2000 to 2006

Grassland type	SOC storage change/(Tg C)	SOC density change/(Mg C·ha^{-1}·yr^{-1})
Lowland meadow	0.10	0.16
Temperate meadow steppe	0.09	0.16
Temperate steppe	0.33	0.13
Temperate desert steppe	0.07	0.10
Total	0.59	0.13

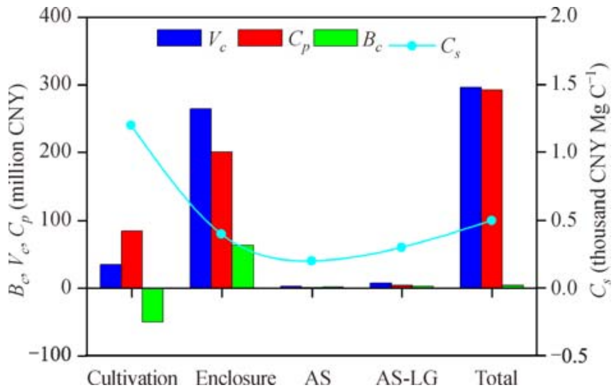

Fig. 2 The economic value of SOC sequestration (V_c), cost of management (C_p), economic benefits of SOC sequestration (B_c), and cost of carbon sequestration (C_s) for grassland management in the BTSSCP region.

However, if grazing after 2006 remained at the same level as in 2000 to 2006 (i.e., scenario 2), the time was longest under AS-LG (114.9 years). The SOC storage could not be restored for the AS-MG and AS-HG in scenario 2, as they had no SOC gain.

4 Discussion

Although carbon sequestration was not a goal of the BTSSCP, the grassland management practices adopted by the Program can increase SOC storage (Conant et al., 2001; Schuman et al., 2002) and have been proposed as an effective way to sequester carbon and therefore help to mitigate climate change (Follett et al., 2001). To our knowledge, no study has been conducted to explore the effects of the BTSSCP on the SOC pools at a regional scale. Our results show that the SOC stock increased significantly after the initiation of the BTSSCP and were highly consistent with site-scale observations (Wu et al., 2008; He et al., 2008, 2009). The increased carbon sequestration can be mainly attributed to the multiple improvements brought about by the management practices of irrigation, fertilization, seeding, and grazing exclusion (Conant et al., 2001; Ogle et al., 2004). These improvements may increase SOC storage by modifying net primary production, root turnover, and carbon allocation between roots and shoots (Post and Kwon, 2000; Conant et al., 2001; Ogle et al., 2004; Steffens et al., 2008). For example, cultivation practices can increase vegetation production by planting more productive grasses, irrigation, and fertilization (Russell and Williams, 1982; Fisher et al., 1994; Crawford et al., 1996). Enclosure practices can elevate SOC inputs from vegetation biomass and litter accumulation by decreasing that removed by grazing (Su et al., 2005; Bilotta et al., 2007).

We showed that the SOC density increased by 0.1 Mg $C\cdot ha^{-2}$ per year in the Xilingol grasslands, which was much higher than the average rate for the grasslands in northern parts of China or the whole of China during the 1980s and 2000s (i.e., 0.04 Mg $C\cdot ha^{-2}\cdot yr^{-1}$ vs. 0.018 Mg $C\cdot ha^{-2}\cdot yr^{-1}$) (Piao et al., 2009; Yang et al., 2010). At the same time, the evidence is that the BTSSCP can significantly enhance grassland biomass inclusive of both above-ground and below-ground biomass (Wu et al., 2013, 2014b; Hao et al., 2014). For example, Hao et al. (2014) found that the mean above-ground biomass increased by 0.1 – 1.1 Mg $C\cdot ha^{-1}$ from 2004 to 2011 in the Xilingol grasslands due to grazing exclusion. Together these observations suggest that the BTSSCP may play an important role in promoting terrestrial carbon sequestration and therefore help mitigate climate change.

Further, we show that the changes of SOC density varied substantially across management practices with the largest increase under cultivation (Table 3). This can be attributed to the greater management inputs (i.e., seedling, irrigation, and fertilization) made for cultivation than for the other practices (Arnold et al., 1976; Ogle et al., 2004). For example, Ogle et al. (2004) found that the increasing rate of SOC storage under multiple improvements was 1.11 times that made with a single improvement. Notably, consistent with the previous site-scale observations (He et al., 2008; Li et al., 2008; Wu et al., 2008; Wang et al., 2011), SOC decreased significantly under the AS-MG and

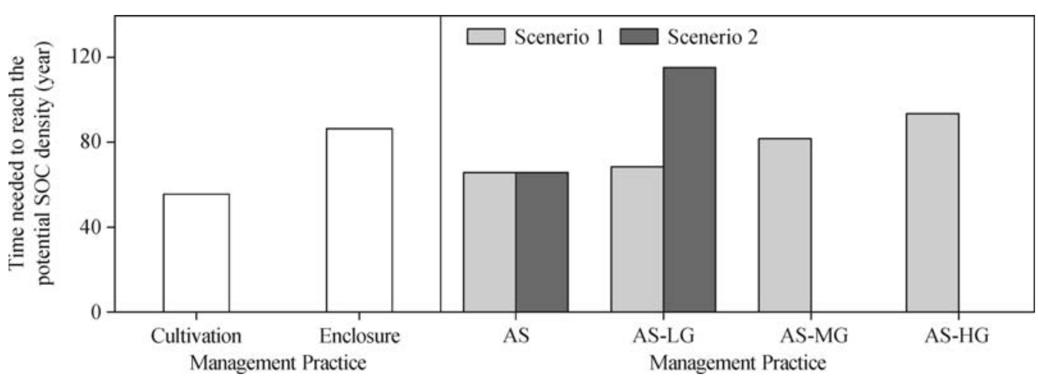

Fig. 3 Time needed to reach the potential SOC density for different grassland management practices in the BTSSCP region. Scenario1 represents no grazing under aerial seeding while scenario 2 represents grazing at 2000 to 2006 intensity under aerial seeding.

AS-HG practices (Table 3). This phenomenon can be largely explained by the decrease of SOC input from aboveground biomass and roots and the enhancement of soil organic matter (SOM) decomposition caused by consumption of biomass by grazing (Johnson and Matchett, 2001; Neff et al., 2005).

Changes of SOC density differed slightly for grassland types. Relatively larger increases were observed in lowland meadows and temperate meadow steppes (Table 4), mainly due to the higher precipitation and background SOC storage of these grassland types (DAHV and CISNR, 1996). Hu et al. (2015) concluded that precipitation was the major driver of SOC changes after grazing exclusion in northern China. Also, SOC change was reported to be positively related to background SOC content (Holmes et al., 2006; Yang et al., 2010). This implies that the implementation of the BTSSCP will be more effective in regions with high precipitation and original carbon storage if viewed in the terms of carbon sequestration.

In general the economic benefits of the SOC sequestration were small but varied significantly with management practices (Fig. 2). Though having the highest increase of SOC density (Table 3), cultivation had the largest benefit loss because its cost was much higher than its economic value (84.6 vs. 34.9 million yuan), and thus was not recommended as the optimal practice (Zhang and Liu, 2005; MacLeod and McIvor, 2006). Aerial seeding was the most cost-effective and economic practice in promoting SOC sequestration.

Importantly, we found that a long time is needed for the degraded grasslands to reach their potential SOC density, with the shortest time of 55.5 years with cultivation (Fig. 3). This was comparable to the estimate by Burke et al. (1995) in Colorado, USA that more than 50 years were required for the semiarid grassland to reach their potential SOC stocks. This value, however, was larger than the estimate (above 20 years) by He et al. (2008) for lightly degraded grasslands in Inner Mongolia to return to their natural state. This is indicative of the more serious grassland degradation of our study area.

There remain uncertainties in our study. First, the SOC stock change factor was established according to global and national field observations (IPCC, 2006; Lu, 2009; Shi et al., 2009; Wang et al., 2011), and these values may be slightly different from the actual situation in the BTSSCP region. Secondly, due to the data limitations, we assumed that the cultivation, enclosure, and aerial seeding practices are distributed evenly over the four grassland types. Further studies are needed to ascertain the location of the BTSSCP-induced SOC sink. Thirdly, we analyzed the SOC dynamics in the first seven years of the implementation of the BTSSCP and assumed that the SOC increased equally each year. Nevertheless, the most recent synthesis indicated that the rate of SOC increase declined linearly with the time from the implementation of grassland management (Hu et al., 2015), suggesting that the soil carbon sink may be under-estimated in our study. We do not consider climatic effects in our analysis, although these effects are documented to be able to alter biomass substantially in the Xilingol grassland (Li et al., 2012; Wu et al., 2013, 2014b; Hao et al., 2014; Tian et al., 2015) and therefore may impact on soil carbon sequestration. For example, Wu et al. (2013, 2014b) indicated that NDVI decreased by more than 20% over most of the Xilingol grasslands in the years of 2007 and 2009 because of summer drought. These considerations stress the necessity for more effort towards understanding the ongoing SOC consequences of the BTSSCP by the combined use of direct observations, remote sensing, inventory data, and ecosystem modelling.

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