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Effects of Grassland Degradation and Re-vegetation on Carbon and Nitrogen Storage in the Soils of the Headwater Area Nature Reserve on the Qinghai-Tibetan Plateau, China

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Abstract: Both overgrazing and climate change contribute to grassland degradation in the alpine regions of China and negatively affect soil carbon and nitrogen pools. We quantified changes in soil organic carbon (SOC) and total nitrogen (TN) in black soil beach (BSB). We measured SOC and TN in severely degraded and non-degraded grasslands to calculate differences in carbon and nitrogen storage, and field survey results were extrapolated to the entire headwaters area of the Qinghai-Tibetan Plateau (36.3×10^5 km^2) to determine SOC and TN losses from these grasslands. We also evaluated changes in SOC and TN in severely degraded grasslands that were artificially re-vegetated five, seven and nine years ago. Totally 92.43 Tg C and 7.08 Tg N were lost from the BSB in the headwater area, which was approximately 50% of the original C and N soil pools. Re-vegetation of the degraded grasslands in the headwater area would result in a gain of 32.71 Tg C in the soil after five years, a loss of 5.52 Tg C after seven years and an increase of 44.15 Tg C after nine years. The TN increased by 53.09% and 59.98% after five and nine years, respectively, while it decreased by 4.92% after seven years of re-vegetation. The results indicate that C and N stocks followed a "V" shaped pattern with re-vegetation time. Understanding plant-soil interactions during succession of artificially planting grassland ecosystems is essential for developing scientifically sound management strategies for the effectively re-vegetated BSB.

Keywords: Black soil beach; Grassland degradation; Soil loss; Revegetation; Alpine grasslands; Soil carbon sequestration; Soil nitrogen sequestration

Introduction

The alpine grasslands around the world are not only habitats for endemic alpine plants and animals, but also important grazing pastures for the indigenous livestock such as yak, indeer and illema (Dong et al. 2011). In addition, the alpine

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grasslands provide important ecosystem functions, such as biodiversity conservation, pasture for grazing livestock and wildlife, flood regulation, biomass production and cover, soil erosion prevention, regulation of nutrient cycles and hydrologic functions, cultural recreation, biogeochemical cycling, and most importantly carbon sequestration and nitrogen cycling (Zhang et al. 2011; Wang et al. 2009). Because of the high production to respiration ratio of these ecosystems, they have the potential to sequester even more carbon and thus the potential to help mitigate global climate change (Tomomichi et al. 2004; Zhao et al. 2005). However, these grasslands have been extensively degraded in recent decades due to numerous driving forces, such as population growth, overgrazing, climate change, management policies and land use changes (Li et al. 2007; Wang et al. 2008). The degradation of the alpine grasslands and consequent loss of productivity have produced serious socioeconomic impacts on the livelihoods of local herders (Martin 1997). Moreover, the land use pattern changes associated with alpine grassland degradation can alter carbon and nitrogen storage in the soil (Dong et al. 2012). It is important to mitigate alpine grassland degradation for maintaining the ecosystem functions such as carbon sequestration and nitrogen cycling.

Grasslands store approximately 12.7% of the total carbon stock of terrestrial ecosystems in China, and the alpine grasslands of the Qinghai–Tibetan Plateau (QTP) account for approximately 54.5% of the total carbon stored in the grassland ecosystems of China (Raich and Schlesinger 1992; Jian 2002). In the Headwater Area Nature Reserve (HWATR) of the QTP, approximately 90% of the alpine grasslands have been degraded, and approximately 26% are severely degraded into "black soil beach (BSB)", which is defined as bare land in the winter and the sparsely covered land with weedy forbs or poisonous plants (such as *Aconitum pendulum*, *Lagotis brachystachya*, *Carum carvi*, *Oxytropis ochrocephala*, *Heteropappus altaicus*) in summer (Zhou et al. 2003; Shang and Long 2007; Dong et al. 2010; Harris 2010). Moreover, the soils of severely degraded grasslands release C and N as greenhouse gases (CO_2, CH_4 and N_2O etc.) to the atmosphere (Kang 1996; Wang and Zhou 1999; Wen et al. 2012), reducing the carbon and nitrogen storage in the soil. With such a large pool of releasable carbon and nitrogen in the soils of the QTP, these grasslands have the potential to become a significant global source of greenhouse gases unless the trend of grassland degradation is reversed.

The continued loss of carbon and nitrogen from the soil will eventually reduce the production capacity of the grasslands limiting its capacity to sequester carbon and thus further exacerbating their greenhouse effect. Management strategies are needed to restore grasslands that can increase the carbon and nitrogen storage capacity of the soils so that they continue to be a net carbon sink. The successful re-vegetation of soils improves the soil water holding capacity and enhances plant-root growth, which leads to improved soil fertility and greater pools of organic carbon and total nitrogen (Feng et al. 2010; Wu et al. 2010). The artificial planting of severely degraded grasslands has been found to be an effective method for restoring alpine grasslands in terms of the vegetation composition and diversity, soil properties, and ecological and economic benefits of alpine grasslands all over the world (Wang et al. 2006; Li et al. 2012). However, few studies have examined the effects of land degradation and artificial re-vegetation on carbon and nitrogen storage in alpine grasslands (Schlesinger et al. 1986; Augustine et al. 2001), especially on the QTP.

The purpose of this study was to quantify soil carbon and nitrogen storage and loss due to severe degradation and carbon and nitrogen accumulation in artificially re-vegetated grasslands in the HWATR of the QTP. Our objectives were as the follows: 1) to estimate the total amount of carbon loss and nitrogen loss caused by BSB in the HWATR; 2) to assess effects of the re-vegetated grasslands in restoring soil carbon pools and nitrogen pools; and, 3) to examine how carbon and nitrogen pools vary with time after the establishment of re-vegetated grasslands.

1 Materials and Methods

1.1 Study area

The HWATR is situated at the southwestern part of the Qinghai Province (31°39'N–36°12'N, 89°45'E–102°23'E). The headwaters of the Yangtze, Yellow and Mekong Rivers are located in the centre of the QTP and contained within the HWATR of China (Wang et al. 2002). One of the most important protection targets is alpine grasslands and biodiversity. These extensive alpine grasslands have an average elevation of 4500 m above sea level and cover an area of 36.3×10^5 km^2, accounting for 50.3% of the total territory of Qinghai Province. The alpine grassland of the HWATR contains of alpine meadows, alpine steppes and swamps. The alpine meadow vegetation is dominated by *Kobresia spp.*, *Polygonum spp.* and *Poa spp.* The alpine steppe is dominated by an assemblage of forbs (*Potentilla nivea*, *Gentiana straminea*, and *Leontopodium nanum*) and graminoids (*Festuca ovina*, *Elymusutans*, and *Poa crymophila*, *Kobresia humilis*, *Kobresia pygmaea*), and approximately 87% of all plant species at the sites are perennial. The swamp is dominated by *Carex muliensis*, *Eleocharis uniglumis*, *Carex enervis*, *Kobresia tibetica*, and *Potentilla leuconota*. Seasonally rotating herds of Tibetan sheep and yak are kept on these grasslands by Tibetan pastoralists as a tradition, i.e, grazing on high-altitude pastures in summer and low-altitude pastures in winter. Without strict control of grazing density, most of these alpine grasslands are overgrazed, leading to land degradation. These grasslands were grouped into non-degraded/fenced (non-degraded), moderately degraded, heavily degraded, and severely degraded grassland, according to the criteria of alpine grassland degradation advanced by Ma et al. (2002). Some patches of the severely degraded alpine grassland, namely the BSB, have been experimentally re-vegetated with native perennial grasses, mostly *Elymus nutans* with seeding rate of 110 kg/ha since the year of 2000.

1.2 Landscape-scale land use patterns

We used Landsat Thematic Mapper (Landsat TM) images with a spatial resolution of 30 m to identify land use patterns across the HWATR of the QTP. The images were collected on July 15th, 2009 (a clear day) from the Remote Sensing Centre of the Chinese Academy of Sciences. Before interpretation, a number of preliminary treatments were performed. Based on different spectrum section information features, correlation coefficients and stand variance, we selected false colour composition images of TM5, TM4, and TM3 as basic interpretation images. We then executed the geometric correction followed by processing the image mosaic and cutting with the existing topographic and administrative county maps. In the process of interpretation, we marked key points to identify specific locations on the images. To identify the BSB on the Landsat TM images, we revised Liu and Wei's (2007) definition and categories to perform the interpretation (Table 1). By definition, the BSB is a large area of sparsely covered ground derived from the severe degradation of alpine meadows, presenting a mosaic of patches in the landscape. This mosaic produced differences in colour, hue, vein and spatial relationships when presented in images for changes of spectrum characteristics. We also conducted ground surveys by using a Global Position System (GPS) to verify or correct the image interpretations. Then spatial analysis tool of Geographic Information System (GIS) software named ESRI ArcGIS was applied to calculate the area of the BSB to figure out the total SOC and TN in all BSB of the HWATR on the QTP, combined with the site-scale data. According to ArcGIS data, the BSB in the HWATR was predominantly distributed in the eastern and central parts of the HWATR (Figure 1). The total area of BSB was

Table 1 Definition and categories of "Black Soil Beach" degraded grasslands (Liu 2007)

Definition	Categories	Features
"Black soil beach" degraded grasslands: large area of sparsely covered ground derived from severe degradation of alpine meadow	Small patch (<100 km^2)	Vegetation cover varies between 40% and 60%, the image colour is mostly hoar with little red and a fleck texture.
	Medium sized patch (100-800 km^2)	Vegetation cover varies between 20% and 40%, the image colour is mostly hoar with little red and a broken plaque texture.
	Large patch (>800 km^2)	Vegetation cover is below 20%, the image colour is shallow hoar with a patchy texture.

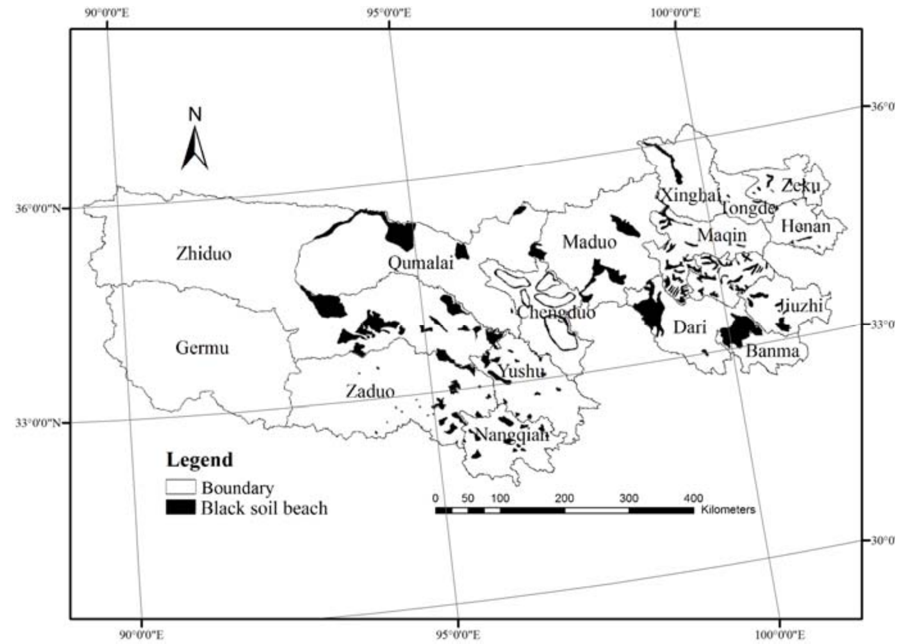

Figure 1 Distribution of black-soil-type land in the Headwater Area Nature Reserve, Qinghai Province, China on the Qinghai-Tibetan Plateau.

2.29×10^4 km^2, accounting for 6.47% of the HWATR. There were hundreds of patches of BSB varying from 3.08 km^2 to 2.24×10^3 km^2 in size. The large, medium and small patches of BSB amounted to 0.98×10^4 km^2, 1.03×10^4 km^2 and 0.28×10^4 km^2, accounting for 42.75%, 45.05% and 12.20% of the BSB in the whole HWATR, respectively.

1.3 Soil carbon and nitrogen investigation

We collected the soil organic carbon and nitrogen data of different soils at different grassland degradation gradients across the HWATR from different sources such as publications, the official census, and reports. Meanwhile, we conducted a site-scale investigation to crosscheck the data in the degraded grasslands at landscape scale of the HWATR and to evaluate the effects of vegetation on the soil carbon and nitrogen stocks. We conducted site-scale investigation at Dawu Village of Maqin County, Qinghai Province (34°28'11"N, 100°12'39"E, and 4200 m a.s.l.) in July-August of 2011. Five types of grassland were sampled, 5-year old artificial grassland (5yAG), which was re-vegetated with *Elymus nutans* at the seeding rate of 110kg/ha in 2006; 7-year old artificial grassland (7yAG), which was re-vegetated with *Elymus nutans* at the seeding rate of 110 kg/ha in 2004; 9-year old artificial grassland (9yAG), which was re-vegetated with *Elymus nutans* at the seeding rate of 110 kg/ha in 2002; non-degraded grassland (NDG), which was fenced due to a grazing ban for a long time, and BSB, which was severely degraded. Three plots in each type of grassland type were sampled. In each plot, 18 soil cores (3.5 cm diameter) were randomly taken to 20 cm depth for analysis. We only sampled the topsoil 0-20 cm on the basis of findings from many studies that SOC and TN were concentrated mainly in surface layer (Wang et al. 2005; Feng et al. 2010; Wu et al. 2010; Dong et al. 2012; Wen et al. 2012). Moreover, SOC and TN in the top (0-20cm) soil of alpine grassland are more prone to anthropogenic factors or land utilization patterns (Wen et al. 2012). After air-drying, the soil samples were split into two subsamples, one was sieved to <2 mm for the analysis of physical properties and the other was sieved to <0.15 mm for the analysis of soil organic carbon and nitrogen. Bulk density was measured using a 100 cm^3 metal cylinder. Soil water content was measured by drying the soil samples at 105°C for 5 days. Total carbon was determined using an OI Analytical TOC analyzer and total nitrogen (TN) measured using a semi-micro Kjeldahl digestion procedure (ISSCAS 1978).

1.4 Data processing and analysis

We used the following formula recommended by Xu (2005) to estimate the carbon and nitrogen stocks in the soil profile:

$$SOC_{density}=C\times\theta\times D\times(1-\delta)\times100 \quad (1)$$

$$SOC_{storage}=S\times SOC_{density}/10^9 \quad (2)$$

where $SOC_{density}$ is the density of soil organic carbon (kg/m^2) and $SOC_{storage}$ (Tg) is the content of soil organic carbon in all BSB of the HWATR on the QTP. C is the average soil organic C content (g/kg), D is soil thickness (cm), θ is soil bulk density (g/cm^3), δ is volume percentage of gravel with a diameter greater than 2 mm, and S is the size of the sampling area. We removed all gravel when collecting the soil samples so that we regard the value of δ as zero. S (m^2) represents the area of BSB in the HWATR on the QTP, which can be calculated via ArcGIS software. The calculation of $TN_{density}$ and $TN_{storage}$ is the same as that of SOC.

All the data were presented as the means ± standard deviations. One-way ANOVAs followed by Fisher's Least Significant Difference post-hoc tests were used to compare differences in the means of soil carbon and nitrogen among different grasslands at a significance level of 0.05. Based on the image interpretations and the data sampled, we utilised ArcGIS 9.3 software's georeferencing tool and digital processing to produce new figures of carbon storage and density in the HWATR of the QTP and carbon loss in the patches of BSB.

2 Results

2.1 Soil physical and chemical properties at site scale

The non-degraded grassland (NDG) had the lowest soil bulk density but the highest values in soil moisture, soil carbon and nitrogen. There were no significant differences in the soil bulk density, soil moisture and pH among the artificial grasslands at various artificial establishment ages. The BSB had the lowest soil water content among all the grasslands. Soil organic matter, organic carbon content and soil total nitrogen were significantly higher in the NDG than those in all the artificial grasslands and the BSB. Among the artificial grasslands, the 7yAG had relatively lower values in soil organic matter, organic carbon and total nitrogen compared with either the 5yAG or 9yAG (Table 2).

2.2 Soil carbon and nitrogen loss associated with grassland degradation

In the BSB, the SOC and TN density were 5.36 and 0.48 kg/m^2, respectively, whereas those in non-degraded grasslands were 9.17 and 0.74 kg/m^2. The TN density was significantly lower than that of SOC in both grassland types. The SOC density and TN density decreased by 71.08% and by 54.17% in the degraded soil as compared to the non-degraded grassland. The total loss of carbon and nitrogen was estimated based on the area of the different sized patches of degraded grassland (Figure 2).

Carbon and nitrogen loss was concentrated in the central and eastern regions of the HWATR. In the central region, which included Yushu and part of Golmud, carbon and nitrogen losses were significantly higher in the medium-sized patches followed by the large patches. In the eastern part of the HWATR, which included Guoluo, part of Huangnan, Hainan and Henan (county), the large patches accounted for the greatest loss of carbon and nitrogen. Overall, the large and medium sized patches had an equal contribution to total carbon and nitrogen losses in the HWATR. Although the number of small patches was relatively high, they contributed much less than the other patches (Table 3). For the entire HWATR region, the total amount of C lost from the soil was 92.43 Tg, and total N losses were 7.08 Tg. The central region of the HWATR lost 55.22 Tg of C and 4.64 Tg of N, accounting for 59.74% and 65.53% of the total loss, respectively. The eastern region of the HWATR lost 37.22 Tg of carbon and 2.43 Tg of nitrogen

Table 2 Soil properties (0-20 cm depth) of different grasslands in the Headwater Area Nature Reserve, Qinghai Province, China on the Qinghai-Tibetan Plateau. All values are the mean±s.d.; different letters indicate values are significantly different.

Grassland type	Soil bulk density (g/cm^3)	Soil moisture (%)	pH	Soil organic matter (g/kg)	Soil organic carbon (g/kg)	Total nitrogen (g/kg)
NDG	0.87±0.06a	41.68±8.95b	6.1±0.17a	688.67±15.52c	399.46±9.01c	34.03±1.21c
SDG	0.97±0.03b	29.54±0.50a	6.5±0.20a	174.63±3.85b	101.29±2.24b	8.85±0.46b
5y AG	1.17±0.07c	31.51±1.73a	7.0±0.45a	156.63±4.07b	90.85±2.36b	9.09±1.02b
7y AG	1.18±0.04c	30.19±2.18a	6.0±0.25a	124.40±5.99a	72.16±3.47a	7.12±0.06a
9y AG	1.14±0.06c	31.25±1.88a	6.9±0.15a	171.07±19.56b	99.23±11.34b	9.19±0.40b

Notes: NDG, non-degraded grassland; SDG, severely degraded grassland; 5yAG, 5-year artificial grassland; 7yAG, 7-year artificial grassland; 9yAG, 9-year artificial grassland.

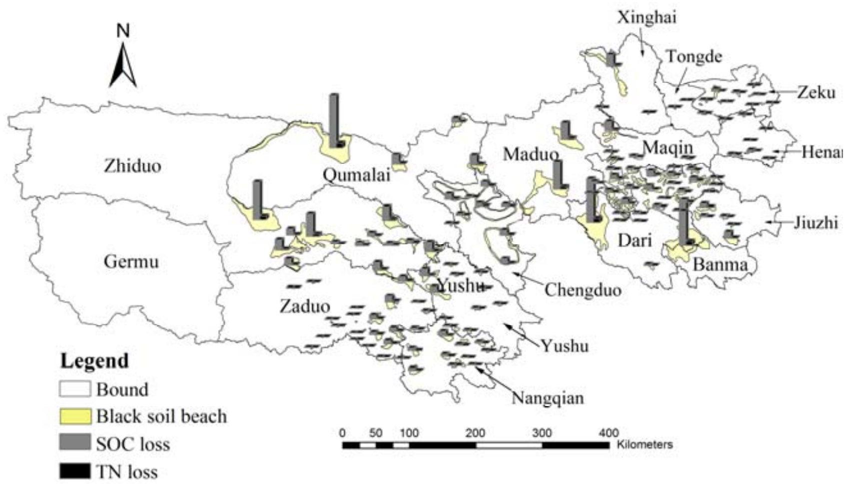

Figure 2 Soil organic carbon and total nitrogen loss of different grasslands in the Headwater Area Nature Reserve, Qinghai Province, China on the Qinghai-Tibetan Plateau.

Table 3 Carbon loss (CL) and nitrogen loss (NL) in different sized patches of severely degraded alpine grasslands in different regions within the Headwater Area Nature Reserve, Qinghai Province, China on the Qinghai-Tibetan Plateau.

Locations	Categories	Area (km²)	CL (Tg)	NL (Tg)
Central	Large patches	4.82×10^3	20.86	1.75
	Middle patches	6.71×10^3	29.04	2.44
	Small patches	1.23×10^3	5.32	0.45
	Subtotal	12.76×10^3	55.22	4.64
Eastern	Large patches	4.97×10^3	18.26	1.19
	Middle patches	3.60×10^3	13.23	0.86
	Small patches	1.56×10^3	5.73	0.37
	Subtotal	10.13×10^3	37.22	2.43
Total		22.89×10^3	92.43	7.08

accounting for 44.26% and 34.47% of the total loss, respectively.

2.3 SOC and TN storage of re-vegetated grasslands

Table 4 presents the SOC density in artificially re-vegetated grasslands of different ages (5, 7, and 9 yr) since the re-vegetation of *Elymus natans* to establish a timeline of soil recovery. Compared to the BSB, the 5yAG and 9yAG had higher densities of soil carbon and total nitrogen whereas the 7yAG had lower values. The C: N ratio increased with the age of the re-vegetated grassland but all were lower than the C: N ratio of the BSB.

Figure 3 shows the potential increase of C storage on BSB grasslands of the HWATR when all the BSB were re-vegetated. After 5 years, carbon storage would increase by 27.85% compared with the original severely degraded grasslands and increase to 37.59% after nine years. However, there would be a 4.70% decrease in SOC stocks after 7 years.

Soil total nitrogen pools changed in a similar manner with N storage, increasing by 53.09% and 59.98% after 5 and 9 years, respectively, and decreasing by 4.91% after 7 years (Figure 4).

2.4 Variations of carbon and nitrogen storage with time of grassland re-vegetation

Spatial differences would be remarkable in the potential changes of the C and N stocks in the BSB if all of which were artificially re-vegetated in the HWATR of the QTP (Table 5). The eastern part would gain more SOC and TN stocks than the central part after 5 and 9 years' re-vegetation, while both the central and eastern part would lose SOC and TN stocks after 7 years' re-vegetation.

3 Discussion

3.1 Comparison of soil properties in non-degraded, severely-degraded and re-vegetated grasslands

Since soil properties influence the retention and transfer of soil nutrients (Bengtsson 1998; Swift et al. 2004), we can compare the different grasslands in our study to better understand how C and N storage responds to changes in soil properties. Our results showed that the soil bulk density exhibited a slight change with various grassland types. The non-degraded grassland had a significantly lower bulk density in contrast to the severely degraded grasslands, i.e., BSB, due to trampling of livestock and decrease of soil porosity.

Table 4 Soil carbon density (SCD) and total nitrogen density (TND) in artificially re-vegetated grasslands of different ages since establishment and black soil beach grasslands in the Headwater Area Nature Reserve, Qinghai Province, China.

Cultivation ages	SCD (kg/m²)	TND (kg/m²)	C/N ratio
SDG	5.36±0.04	0.48±0.02	11.28
5yAG	6.56±0.14	0.66±0.07	9.94
7yAG	4.89±0.23	0.41±0.01	9.98
9yAG	7.06±0.60	0.69±0.03	10.23

Among the different aged artificial grasslands, the bulk density exhibited a "V" shape trend over successional time, consistent with the findings by Dong et al. (2012). Soil moisture was closely connected with ground evaporation capacity and showed a strong decrease from non-degraded grasslands to BSB. Soil moisture was slightly elevated in the re-vegetated grasslands as compared to the BSB due to the accrual in vegetation cover and reduced soil evaporation. The non-degraded grassland contained the largest carbon pools, similar to the results of Ni (2001), one of the highest values of all terrestrial ecosystems in China. Compared to the non-degraded grassland, the soil organic matter experienced a sharp decrease on the BSB because of topsoil erosion (Zhu 2011) as well as vegetation composition change. That is, as the number of C3 plants increase the number of C4 plants change inversely, affecting the efficiency of carbon sequestration (Wu et al. 2010). The restored sites did not recover the soil organic carbon and organic matter effectively. There were several primary factors that can explain this result. First, the vegetation structure was relatively simple in the re-vegetated grasslands, limiting transfer of carbon to the soil. Second, the corresponding high respiration rates during the growing period attributed to the large amount of biomass in the re-vegetated grasslands lowered carbon content (Wu et al. 2010). Third, the relatively high soil moisture controlled soil organic matter accumulation via promoting the decomposition of microbial activity (Sarah et al. 2010). Finally, re-vegetation interventions such as ploughing the soils before plantation can cause carbon loss (Bai et al. 2005).

3.2 Changes in soil carbon and nitrogen stocks in severely-degraded and re-vegetated grasslands

The dynamics of soil organic carbon and

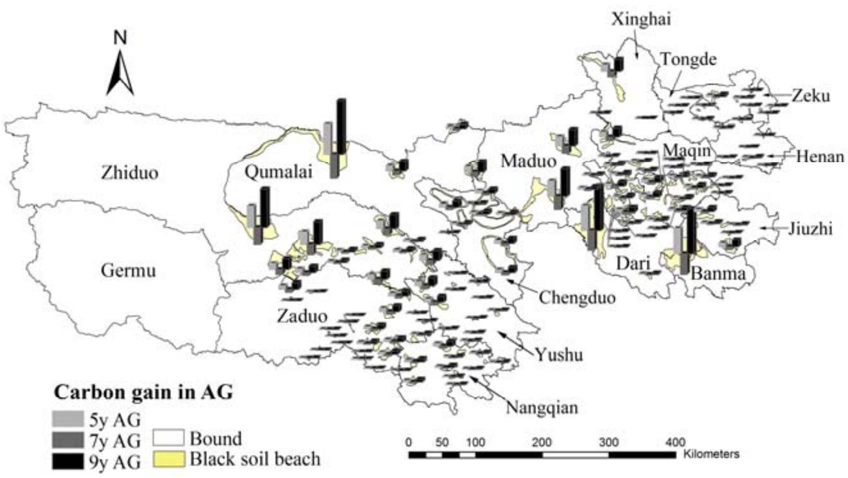

Figure 3 Soil organic carbon gain in artificially re-vegetated grasslands of different ages since establishment on severely degraded grasslands in the Headwater Area Nature Reserve, Qinghai Province, China.

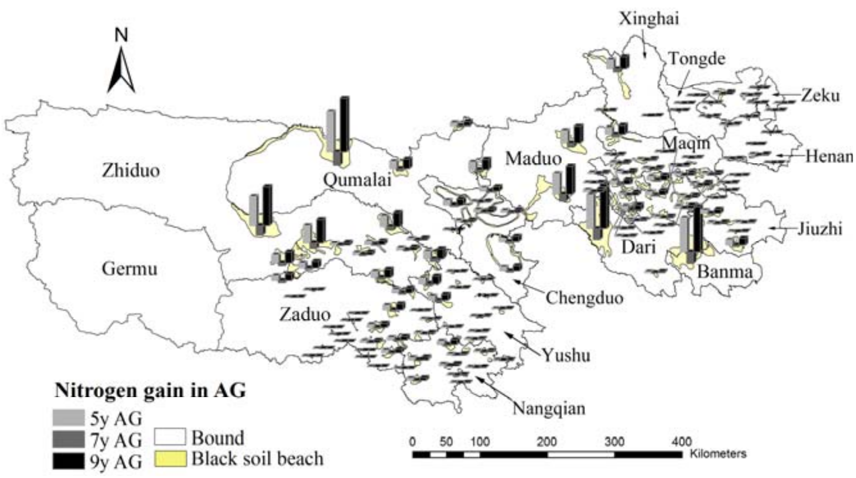

Figure 4 Soil total nitrogen gain in artificially re-vegetated grasslands of different ages since establishment on severely degraded grasslands in the Headwater Area Nature Reserve, Qinghai Province, China

Table 5 Soil carbon and nitrogen gain in artificially re-vegetated grasslands of different ages since establishment on severely degraded grasslands in different regions and on different sized patches in the Headwater Area Nature Reserve, Qinghai Province, China

Locations	Categories	Carbon gain (Tg)			Nitrogen gain (Tg)		
		5yAG	7yAG	9yAG	5yAG	7yAG	9yAG
Central	Large patches	8.28	0.23	10.69	1.37	0.16	1.51
	Middle patches	11.53	0.32	14.88	1.90	0.23	2.10
	Small patches	2.11	0.06	2.73	0.35	0.04	0.39
	Sub-total	21.92	0.61	28.30	3.62	0.43	4.00
Eastern	Large patches	5.29	-3.01	7.78	0.79	-0.45	0.94
	Middle patches	3.83	-2.18	5.63	0.58	-0.32	0.68
	Small patches	1.66	-0.94	2.44	0.25	-0.14	0.30
	Sub-total	10.78	-6.13	15.85	1.62	-0.91	1.92
Total		32.71	-5.52	44.15	5.24	-0.49	5.92

nitrogen content caused by land degradation have been studied extensively (Sun 2008; Wang 2008). Nael et al. (2004) concluded that soil organic carbon is a reliable indicator of soil quality and the primary cause of decreased soil carbon pools is grassland degradation. Mensah (2003) indicated that the conversion of degraded lands to grass increases carbon pools in the surface soil layer. The degradation of non-degraded grasslands in the HWATR resulted in very large losses of both C and N. The BSB is at a severe level of degradation where there is an almost complete removal of vegetation and surface soil due to overgrazing, soil disturbances caused by the large population of pika and climate change. As a result, the soils are highly vulnerable to erosion and many soil nutrients are lost in this manner. Moreover, new carbon inputs into the system are limited due to the lack of vegetation. Thus the large losses in carbon and nitrogen in these systems are primarily due to erosion and loss of vegetation cover, but changes in soil texture and the vegetation composition also are contributing factors (Dong et al. 2012). As the most important carrier of soil total nitrogen, soil organic matter is highly correlated with soil TN (Azam et al. 1989). Since soil organic nitrogen, which takes up more than 95% of soil TN, is inclined to reach a stable situation between organic matter inputs and decomposition several years after organic matter is put into soil, the C:N ratio is mainly contingent upon soil organic carbon budget, which has been explained by soil organic matter change. In addition, the accrual of the C:N ratio with re-vegetated time increasing is also attributed to the fact that SOC always outpaces TN accumulation in the grassland (Fu et al. 2010). In the present study, we found that the C:N ratio narrowed significantly from the BSB to re-vegetated sites, but the inverse occurred over re-vegetated time, consistent with soil organic matter.

Other studies have found that soil properties improved in artificially restored grasslands (Wang et al. 2009; Feng et al. 2010). Feng et al. (2010) concluded that soil nutrient concentrations, including SOC and TN, were greater in the re-vegetated grasslands as compared to the BSB grasslands. Wu et al. (2010) also reported that the artificial re-vegetation of the BSB degraded grasslands generally had positive effects on soil nutrient properties and soil carbon storage. Nutrient availability in the surface soils significantly increased and soil carbon showed a significant increase in the 6-year artificial grassland. Our results indicated that there were no significant differences in SOC and TN between the BSB, 5yAG and 9yYG. In addition, SOC and TN concentration in 7yAG were lower than the BSB, which was consistent with Wang et al. (2009) who found that the index of grassland quality declined to its lowest levels after 7 years of artificial establishment. Artificial cultivation can restore grassland productivity, but that does not mean the longer the cultivation age, the better. Why is seven years of restoration regarded as a bottleneck in the artificial establishment process? The results may be explained by several reasons. In initial stage of vegetation establishment, particularly the artificial fertilization increases soil nutrition to some degree. The vegetation composition and structure changes through the succession of these artificial grassland ecosystems, such as forbs invade replacing the grasses, which areas the dominant group affecting soil quality. The re-vegetation for 5-8 years would bring about retrogressive succession of soil development, decreasing SOC and TN (Wang et al. 2009). The vegetation recovery and improved quality of community microhabitat may improve the soil fertility after 9 years' re-vegetation.

In conclusion, the re-vegetation of severely degraded grasslands is a long-term (over 9 years) intervention for restoring the soil carbon and nitrogen storage capacity of alpine grassland. During the process of artificial re-vegetation of degraded grasslands, proper management strategies to increase the soil carbon and nitrogen storage potential and to ensure that the ecosystem succession proceeds in positive direction are essential.

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