CLEAN
Soil Air Water

Lei Deng[1]
Sandra Sweeney[2]
Zhouping Shangguan[1]

[1]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, Shaanxi, P. R. China
[2]Institute of Environmental Sciences, University of the Bosphorus, Istanbul, Turkey

Research Article

Long-Term Effects of Natural Enclosure: Carbon Stocks, Sequestration Rates and Potential for Grassland Ecosystems in the Loess Plateau

The aim of this study was to better understand the effects of grassland restoration on carbon sequestration at the total carbon stock (plant and soil) scale. The objective of the study was to investigate the temporal carbon sink and sequestration dynamics of grassland ecosystems with five different succession communities, namely, *Stipa grandis*, *Stipa bungeana*, *Artemisia sacrorum*, *Thymus mongolicus*, and cropland succession in the hilly-gully region of the Loess Plateau, China. Twenty-four research papers were analyzed to form the basis of the subsequent field survey conducted at the Yunwu Observatory for Vegetation Protection and Eco-environment in Ningxia. Following the conversion of cropland to grassland, carbon sequestration values all increased at deeper soil depths of 40–100 cm; carbon stocks within the 0–40 cm profile were largely unchanged. Five time intervals, 0 (cropland) 23, 35, 58, and 78 years yielded carbon stocks of 7.69, 14.58, 16.25, 19.22, and 19.95 kg/m^2 at the total carbon stock scale. The main finding indicates that the conversion of cropland to grassland results in significant changes to ecosystem carbon pool properties. This finding has broad implications for the anthropogenic management of terrestrial carbon sequestration at the regional scale.

Keywords: Carbon sequestration; Land-use conversion; Soil organic carbon; Vegetation restoration

Received: March 7, 2013; *revised:* May 16, 2013; *accepted:* June 5, 2013

DOI: 10.1002/clen.201300176

1 Introduction

That concentrations of global atmospheric carbon dioxide (CO$_2$) have increased during the last several decades and continue to do so [1, 2], mainly due to the combustion of fossil fuels [3, 4]. The extent to which this rise in atmospheric carbon dioxide contributes to global climate change will likely be debated for some time to come. The same will probably be true with respect to both the anticipated and realized positive and negative effects of said change on human activities and terrestrial vegetation [5, 6].

The largest terrestrial pool of organic carbon is stored in the world's soils [7]. Land-cover change can alter the amount of organic carbon stored in the soil [8]. Carbon stocks in soils and vegetation respond to changes in land use – and by implication, its management, and to be able to fully realize the potential for terrestrial sequestration is an attractive means of CO$_2$ offset and greenhouse gas (GHG) reduction in the near term [9]. Brown et al. [10] assert that carbon sequestration through land use modification and management has been consistently identified as an essential component of a comprehensive GHG management strategy. Within such a framework, one option was to restore degraded drylands and desert fringes to their original carbon content, or where economically feasible, by increasing their carbon storage capacity [10]. Terrestrial sequestration has the advantage of providing multiple environmental and economic benefits [11] beginning with linking the cost of carbon storage with that of ecosystem restoration. The majority of these restoration efforts have been on non-agricultural or newly abandoned cropland [12]. The restoration of abandoned cropland achieves the goal of reducing to a fraction the amount of carbon otherwise emitted and thus shares in the overall cost of both restoring drylands and reducing atmospheric carbon. However, the potential for carbon sequestration is restricted or limited by land use change, especially the conversion from arable land to semi-natural vegetation. Given that a sufficient surface of arable land is needed to ensure food security; in short, because China needs enough cropland to feed its population, the present limitation is unlikely to change.

In China, the Loess Plateau has suffered from chronic erosion [13] as a consequence of the fact that the plateau soils are now barren [14]. To simultaneously reduce land degradation and control soil and water losses, the central government has carried out extensive vegetation restoration throughout the past three decades [15]. Several studies have addressed the effects of restoration on, for example, water storage [16], aggregate formation and stability [17], vegetation effects on C and N stocks [15], influences of vegetation restoration on soil properties [14] and changes in above- and belowground vegetation characteristics [18]. Within this context, previous research on soil organic carbon stocks has mainly focused on the upper soil layer [14, 19]. Little research effort has been reported regarding the influence of ecosystem restoration on the production of soil organic carbon at lower depths. Yet, understanding the carbon sequestration dynamics of ecosystems is important for vegetation restoration,

---

Correspondence: Professor Z. P. Shangguan, Institute of Soil and Water Conservation, Northwest A&F University, No. 26 Xinong Road, Yangling, Shaanxi 712100, P. R. China
E-mail: shangguan@ms.iswc.ac.cn

Abbreviations: **BD**, bulk density; **GHG**, greenhouse gas; **SOC**, soil organic carbon; **SOM**, soil organic matter especially when converting cropland to grassland or reforested plantation. More specifically, on the Loess Plateau, because of the area's very sparse natural vegetation, it is necessary to understand the process of natural vegetation recovery and its importance to ecological rehabilitation. A fuller appreciation of this process will help guide ongoing vegetation restoration in western China [14].

In semi-arid hilly-gully loess regions, in which a hilly region characterized by loess (slit-loam Aeolian deposits) has many gullies due to water erosion, natural grasslands on degraded land were rehabilitated to hold soil and water [20]. Over time the restoration efforts developed different patterns of secondary succession. Therefore, the objective of the field work was to investigate the carbon sequestration dynamics of grassland ecosystems in five different succession communities, namely, *Stipa grandis*, *Stipa bungeana*, *Artemisia sacrorum*, *Thymus mongolicus* and cropland. The study hypothesized that the carbon sequestration characteristics of local grassland ecosystems, both plant and soil, were largely the result of plant succession along a vegetation restoration chronosequence which made differences between grazed and enclosed natural grassland an important component of the research.

2 Materials and methods

2.1 Study method

A common method for studying vegetation restoration is to monitor plants and soils under similar climatic and soil type conditions following the sequence of vegetation development [21]. This chronological method is widely adopted in applied ecosystem research [22] and considered a "retrospective" research method because it compares existing conditions with original conditions and treatments [23]. The substitution of "space" for "time" is an effective way of studying changes over time [23, 24]. Sites stabilized through re-vegetation for different periods of time offer an ideal opportunity to understand vegetation succession processes in extreme environments, because before re-vegetation, soil conditions are largely driven by soil erosion.

2.2 Study site

The study was carried out in a grassland region of the Loess Plateau (Fig. 1) where the Yunwu Observatory for Vegetation Protection and Eco-environment, Ningxia, China is situated (1800–2148 m a.s.l.). The altitude of most of the land ranges between 1800 and 2040 m and is crisscrossed with steep gulleys. Hilly land makes up 90%, rivers and villages 4%, and land suitable for intensive farming 6%. The region is characterized by a semi-arid climate with heavy seasonally distributed rainfall resulting in seasonal local floods and droughts. The soil type in the study area is Aeolian soil (silt loam), and soil pH ranged from 7.99 to 8.20 [19]. The study area's Aeolian soil(s) receive an annual mean precipitation of approximately 410.7 mm (1960–2010), which, for the most part, is distributed between July and September. The area's semi-arid temperate continental monsoon climate produces an annual mean temperature of 6.7°C (1960–2010), an annual mean total of 2518.2 sunshine hours, an annual mean evaporation of 1600 mm, and 137 frost-free days per year on average. The main herbaceous plants are *S. bungeana*, *T. mongolicus*, *A. sacrorum*, *Potentilla acaulis*, *S. grandis*, *Androsace erecta*, *Heteropappus altaicus*, *Artemisia capillaries*, and *A. frigid*, of which, *S. bungeana* is the most widely distributed.

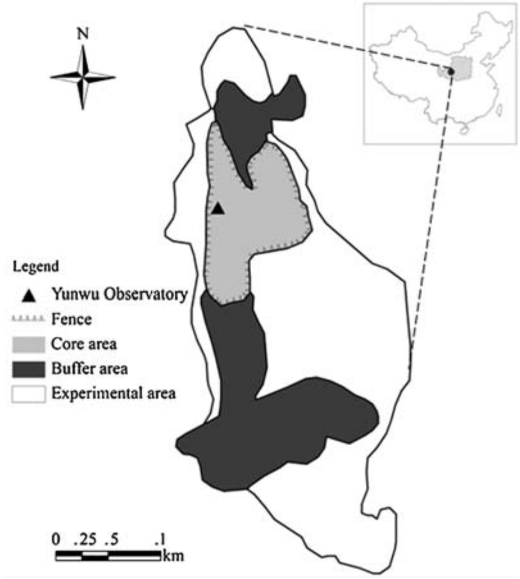

Figure 1. Location of the Yunwu Observatory on the Loess Plateau.

The only remaining grassland on the Loess Plateau is found in this region. It is protected by fencing and is more than 100 years old. In the region, five sites on which vegetation has been allowed to naturally rehabilitate for different periods of time according to the process of plant succession [19] (Tab. 1) were chosen for investigation. Fenced in 1980, the region covers approximately 1000 ha. Before the region was fenced its lands were cropland. In terms of their natural succession times, the plant communities under study were: *S. grandis* (78 years), *S. bungeana* (58 years), *A. sacrorum* (35 years), *T. mongolicus* communities (23 years), and cropland (0 year). Grazed grasslands are those grasslands outside the fenced area. These are mostly degraded *S. bungeana* community grasslands. In the grazed grasslands, *A. capillaries* and *A. frigid* were the dominant species.

2.3 Data source

The study has collected data on the grassland vegetation and soils of Yunwu Observatory, including soil organic carbon content (SOC), soil organic matter (SOM), soil bulk densities (BD), above- and below-ground biomass, root/shoot ratios, vegetation type, and restoration period. For the purpose of the study, 24 different papers, all coming from the Yunwu Observatory, accounting for 135 samples, published between 2004 and 2012, were analyzed. Internationally, SOC usually refers to the organic carbon stock at a medium depth (0–100 cm). According to Powers et al. [25] field observations are sampled at inconsistent depths that are typically only above 30 cm making it difficult to draw reliable conclusions on land-use effects deeper in the soil profile. Thus, somewhat typically, the published papers used in this study had obtained values for the SOC or SOM at various depths (0–200 cm). Consequently, for ease of comparison, the reported SOC or SOM values were transformed into the SOC or SOM of one soil layer. In the study, the SOC and SOM data all came from the collected literature and the vegetation biomass came from both the collected literature and our field survey.

In addition, in August 2011, four typical plots (*T. mongolicus*, *A. sacrorum*, *S. bungeana*, and *S. grandis*) representing four restoration

Table 1. Grassland biomass and soil properties at four different vegetation restoration stages (biomass as dry organic matter by g/m^2 next to SOC contents C g/kg soil)

	Biomass				Soil property	
Restoration stage	Aboveground (mean ± SE) (g/m^2)	Belowground (mean ± SE) (g/m^2)	Total (mean ± SE) (g/m^2)	Root/shoot ratio (mean ± SE)	SOC content in 0–100 cm soil (weighted mean value) (g/kg)	BD in 0–100 cm soil (weighted mean value) (g/cm^3)
Grazed grassland	201.35 ± 17.21 ($n = 10$)	892.88 ± 147.24 ($n = 10$)	1094.23 ± 149.01 ($n = 10$)	4.60 ± 0.71 ($n = 10$)	9.15	1.21
Sloping farmland	–	–	–	–	6.30	1.22
T. mongolicus	187.11 ± 16.33 ($n = 15$)	925.40 ± 75.24 ($n = 15$)	1112.51 ± 90.34 ($n = 15$)	4.99 ± 0.14 ($n = 15$)	11.92	1.18
A. sacrorum	399.90 ± 82.35 ($n = 8$)	936.65 ± 207.67 ($n = 8$)	1336.55 ± 280.84 ($n = 8$)	2.39 ± 0.21 ($n = 8$)	13.74	1.14
S. bungeana	150.17 ± 10.34 ($n = 23$)	1511.48 ± 100.89 ($n = 23$)	1661.6547 ± 109.10 ($n = 23$)	10.06 ± 0.30 ($n = 23$)	16.94	1.09
S. grandis	736.48 ± 17.82 ($n = 6$)	1368.76 ± 101.42 ($n = 6$)	2105.24 ± 110.66 ($n = 6$)	1.86 ± 0.12 ($n = 6$)	17.55	1.08

The restoration stages were those periods of time during which the cropland was converted into *T. mongolicus*, *A. sacrorum*, *S. bungeana*, and *S. grandis* communities, which were aged 23, 35, 58, and 78 years, respectively. Among them, the number of the samples from our field survey was five. The other samples were taken from the literature.

periods (23, 35, 58, and 78 years), were delineated. Each plot surveyed five 1 m × 1 m quadrats. In each quadrat, the above- and belowground biomass (0–100 cm) and soil BD at a depth of 0–100 cm soil (0, 5, 10, 20, 30, 50, 70, 100 cm) were observed.

2.4 Data processing

2.4.1 Data transformation

Of the literature-collected data, the biomass units of "kg/ha" and "mg/ha" were transformed into "g/m^2". When the reported samples only had SOM, their SOC was calculated using Guo and Gifford's [26] equation:

$$\mathrm{SOC} = 0.58\,\mathrm{SOM} \tag{1}$$

When the literature reported only above- or belowground biomass, their above- or belowground biomass was estimated as follows: first, according to the reported samples and our field survey data with both above- and belowground biomass, to calculate the root/shoot ratios; and then according to the mean values of the root/shoot ratios, to estimate the above- or belowground biomass. Thus, in the end, every sample had complete data for both above- and belowground biomass. In addition, the study supposed that the carbon stock for cropland vegetation was held to be zero because the crops had been harvested.

2.4.1.1 SOC

$$\mathrm{SOC} = \frac{\mathrm{SOC}_1 D_1 + \mathrm{SOC}_2 D_2 + \cdots + \mathrm{SOC}_\mathrm{i} D_\mathrm{i}}{D_1 + D_2 + \cdots + D_\mathrm{i}} \tag{2}$$

where SOC is the weighted mean soil organic carbon content in i soil layer (g/kg); SOC$_1$, SOC$_2$, ..., SOC$_\mathrm{i}$ is soil organic carbon contents in soil layers 1, 2, 3, and ... (g/kg); D_1, D_2, ..., D_i is soil thickness of soil layers 1, 2, 3, etc., in cm.

2.4.1.2 Soil bulk density

$$\mathrm{BD} = \frac{\mathrm{BD}_1 D_1 + \mathrm{BD}_2 D_2 + \cdots + \mathrm{BD}_\mathrm{i} D_\mathrm{i}}{D_1 + D_2 + \cdots + D_\mathrm{i}} \tag{3}$$

where BD is the weighted mean bulk density in i soil layer (g/cm^3); BD$_1$, BD$_2$, ..., BD$_\mathrm{i}$ is soil bulk density in soil layers 1, 2, 3, and ... (g/cm^3); D_1, D_2, ..., D_i is soil thickness of soil layers 1, 2, 3, etc., in cm. The study collected the BD at a depth of 0–100 cm for the different restoration periods from both the literature and fieldwork, and averaged them in an arithmetic manner.

2.4.2 Carbon stock estimation

2.4.2.1 Vegetation carbon stock

The study used the following equation to calculate the vegetation carbon stock [27]:

$$C_\mathrm{v} = BC_\mathrm{f} \tag{4}$$

where C_v is the vegetation carbon stock (g/m^2), B is the vegetation biomass (g/m^2), and C_f is the plant biomass carbon coefficient. The study set 0.45 as the plant biomass carbon coefficient for estimating the vegetation carbon stock [27].

2.4.2.2 Soil carbon stock

The study used the following equation to calculate the soil organic carbon stock [26]:

$$C_s = \frac{\mathrm{BD} \times \mathrm{SOC} \times D}{100} \tag{5}$$

where C_s is the soil organic carbon stock (kg/m^2), BD is the soil bulk density (g/cm^3), SOC is the soil organic carbon content (g/kg), and D is soil thickness (cm). In this study, we uniformly transformed the collected SOC into organic carbon stocks at a depth of 0–100 cm. The sum of carbon stocks of every soil layer in 0–100 cm soil were 0–100 cm soil carbon stocks. In the literature-collected data the SOM or SOC was mainly taken from the 0–40 cm soil depth rather than from the 40–100 cm soil layer and thus, the values were transformed into the SOC of the 0–100 cm soil layer, which were weight averaged as the weighted mean SOC at a depth of 0–100 cm. The soil carbon stock at a depth of 0–100 cm was calculated using the weighted SOC and BD for the 0–100 cm soil layer, and the carbon stocks for soil at a depth of 40–100 cm were calculated by subtracting the carbon stock in the 0–40 cm soil layer from the weighted average soil organic carbon stock in the 0–100 cm soil layer.

2.4.2.3 Carbon sequestration rate

The carbon sequestration rate was estimated depending on changes in ecosystem carbon stocks at different time sequences. The study set the carbon stock of cropland as the baseline for calculating the carbon sequestration rate throughout the restoration process following its conversion into grassland. The study used the following equation to calculate the carbon sequestration rate:

$$C_r = \frac{C_{t_2} - C_{t_1}}{t_2 - t_1} \tag{6}$$

where C_r is the carbon sequestration rate (g/(m^{2}year)), C_{t_1} is the carbon stock at time 1 (t_1) (g/m^2), and C_{t_2} is the carbon stock at time 2 (t_2) (g/m^2), and $t_2 > t_1$.

2.4.2.4 Carbon sequestration potential

Grassland communities are the main vegetation types found on barren hills and wasteland in China. Most of them are at different stages of succession because of their different recovery rates. Generally speaking, ecosystem carbon stocks increase with vegetation restoration [19, 28] meaning the higher carbon stock store is to be found in the more advanced plant communities. Occupying the core part of the region under study, the *S. grandis* community achieved the highest vegetation succession stage under restoration. The carbon stock of the *S. grandis* community was the highest realizable, so it was defined as the reference point for estimating the carbon sequestration potential of other natural grasslands, including, by implication, the succession vegetation of the restoration efforts. The formula used to calculate carbon sequestration potential is as follows:

$$C_p = C_{\mathrm{rel-mas}} - C_{\mathrm{rel-n}} \tag{7}$$

where C_p is the carbon sequestration potential possible in vegetation type n (g/m^2) that can be realized; $C_{\text{rel-mas}}$ is the highest achievable carbon stock (g/m^2); $C_{\text{rel-n}}$ is the realistic carbon stock of n vegetation types (g/m^2).

2.4.3 Data analysis

In terms of the length of the restoration period and land-use, the study divided the data collected from the literature and its field investigation into six categories: grazing land, cropland, *T. mongolicus*, *A. sacrorum*, *S. bungeana*, and *S. grandis*. The study calculated carbon sequestration stocks, rates, and potential for the grassland ecosystems for the different restoration periods.

In the study, we did not collect an ideal soil dataset, in which every sample has the full 0–100 cm SOC or SOM. Data from the deeper soil layer (40–100 cm) was less available. There were only one or two ideal data from the collected literature for some restoration stages. For example, some samples have data for 0–20 and 20–40 cm, but they do not have any data for the deeper soil layer (40–100 cm); however, some samples only have data for 0–100 cm and the number of the samples was less than three, so we could not calculate the variability of the data. Therefore, we used the mean value of each soil layer in each restoration stage to represent the soil organic carbon content of each soil layer.

3 Results

3.1 Carbon stocks

3.1.1 Plant

The total dry organic matter (including aboveground and belowground biomass) carbon stocks showed a linear increase throughout vegetation restoration (Fig. 2). Belowground biomass carbon stocks were all higher than aboveground biomass carbon stocks. The total biomass carbon stocks were separately 500.63, 601.45, 747.74, and 947.36 g/m^2 for the different vegetation restoration stages. The above- and belowground biomass carbon stocks appeared different (Fig. 2). At the vegetation restoration stage typical of the *S. bungeana* community, the aboveground biomass carbon stock was the lowest, lower than those of the vegetation restoration stages typical of the *T. mongolicus* and *A. sacrorum* communities; the belowground biomass carbon stock was highest at the vegetation restoration stage typical of

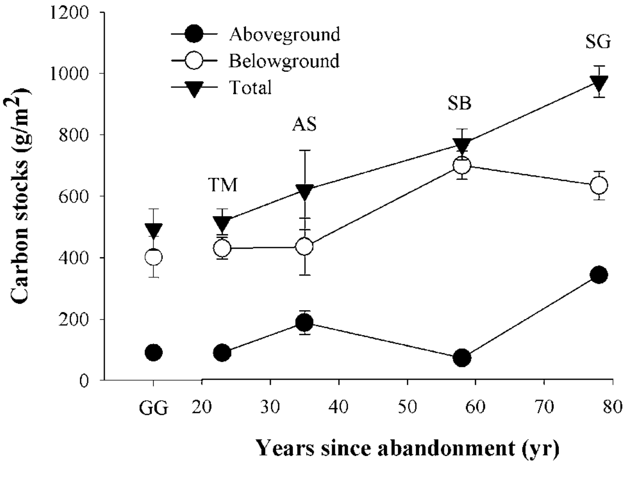

Figure 2. Dry organic matter carbon stocks of grassland vegetation at four different vegetation restoration stages. Restoration stages: GG, grazed grassland; TM, *T. mongolicus*; AS, *A. sacrorum*; SB, *S. bungeana*; and SG, *S. grandis*. The error bars indicate standard error. The number of the samples are given in Tab. 1.

the *S. bungeana* community (Fig. 2). The aboveground carbon stock increased at the vegetation restoration stage typical of the *S. grandis* community, but the belowground had decreased at this stage, compared with the vegetation restoration stage typical for the *S. bungeana* community. All four restored grasslands had higher carbon stocks than did grazed grassland, and for the *T. mongolicus* and *A. sacrorum* communities, it did not always differ from grazed grassland.

3.1.2 Soil

Following the conversion of cropland to grassland, carbon stocks increased in the different soil layers (Fig. 3a). The organic carbon stocks in the 0–100 cm soil depth gradually increased as the vegetation restoration was underway. In the 0–20 and 20–40 cm soil layers, the organic carbon stocks were almost unchanged with vegetation restoration (Fig. 3a). In the 0–20 cm soil layer, the organic carbon stock of the grazed grasslands (4.38 kg/m^2) was higher than that of the *T. mongolicus* community, but lower than that of the other three grassland communities (*A. sacrorum*, *S. bungeana*, *S. grandis*) under natural enclosure. However, the organic carbon stocks in soil below a depth of 20 cm and in the 0–100 cm soil layer were both lower than that of either the fenced or fully restored grasslands.

After the conversion of cropland to grassland, the relative contribution of SOC stocks in the 0–20 and 20–40 cm soil layers to soil organic carbon stock in the 0–100 cm soil layer decreased with vegetation restoration. At the early vegetation restoration stage (<35 years), the organic carbon stock was higher in the 0–40 cm soil layer than in the 40–100 cm layer, but the opposite situation appeared in later stages of succession (>35 years). The proportion of the SOC stock in the 40–100 cm layer to soil organic carbon stock in the 0–100 cm layer increased (Fig. 3b). In the grazed grassland, the SOC stock was also distributed mainly in the 0–40 cm depth (Fig. 3b).

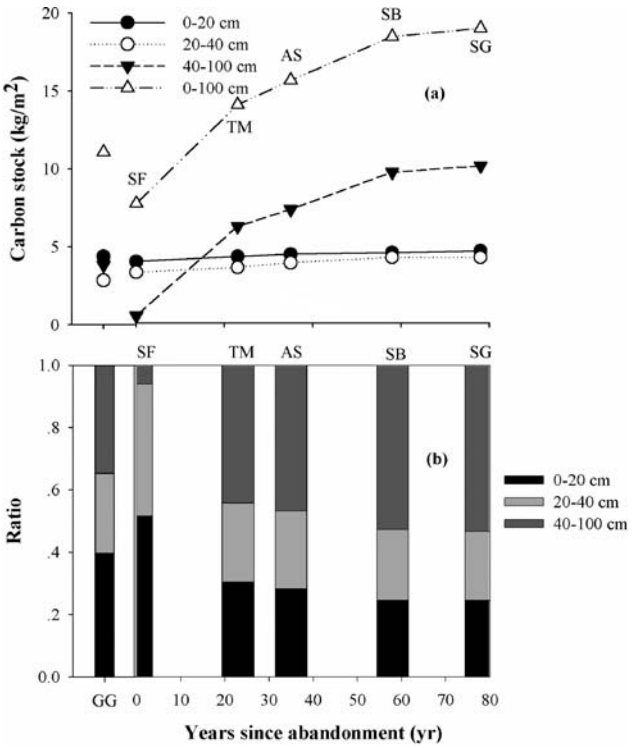

Figure 3. Distribution of soil carbon stocks at four different vegetation restoration stages. Restoration stages: SF, sloping farmland; GG, grazed grassland; TM, *T. mongolicus*; AS, *A. sacrorum*; SB, *S. bungeana*; and SG, *S. grandis*.

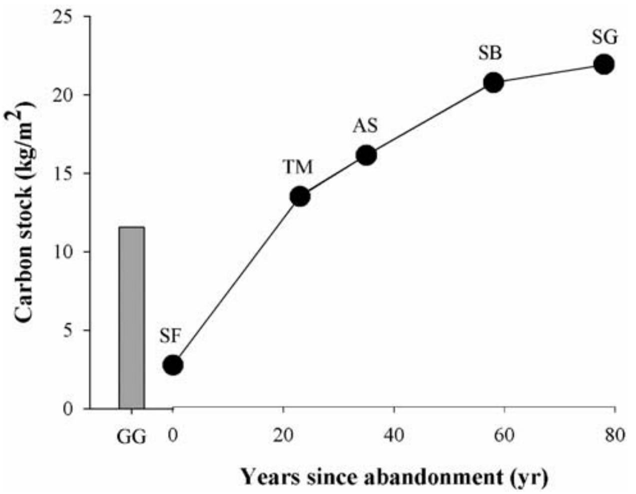

Figure 4. Total carbon stocks (plant total biomass and 0–100 cm soil carbon stocks) at four different vegetation restoration stages. Restoration stages: SF, sloping farmland; GG, grazed grassland; TM, *T. mongolicus*; AS, *A. sacrorum*; SB, *S. bungeana*; and SG, *S. grandis*.

3.2 Total carbon stock

Following the conversion of cropland to grassland total carbon stocks (plant carbon stock and 0–100 cm soil carbon stock) increased with vegetation restoration (Fig. 4). The carbon stocks at the different restoration stages were 7.69, 14.58, 16.25, 19.22, and 19.95 kg/m^2. The ecosystem carbon stock of the grazed grassland was lower than that of the fenced grassland (Fig. 4) and the carbon stock was 11.56 kg/m^2.

3.3 Carbon sequestration rate

3.3.1 Plant

At the different restoration stages, the carbon sequestration rates of the vegetation fluctuated with vegetation restoration (Fig. 5). The carbon sequestration rate of vegetation was highest in the early successional stage (0–23 years), reaching 21.77 g/(m^2 year) (Fig. 5). The changes in the vegetation biomass (Tab. 1) resulted in the carbon sequestration rate of the vegetation first decreasing and then increasing as the length of time over which the restoration of vegetation increased. The carbon sequestration rate of the *A. sacrorum* (23–35 years), *S. bungeana* (35–58 years), and *S. grandis* (58–78 years) community stages were 8.40, 6.36, and 9.98 g/(m^2 year), respectively (Fig. 5).

3.3.2 Soil

With vegetation restoration, SOC stocks increased in the different soil layers when compared to that of the cropland. Moreover, the SOC stocks were all higher at a depth of 40–100 cm than at a depth of 0–40 cm (Fig. 6). The SOC stocks for each of the vegetation restoration stages were 6.38, 7.96, 10.78, 11.31 kg/m^2. When compared to

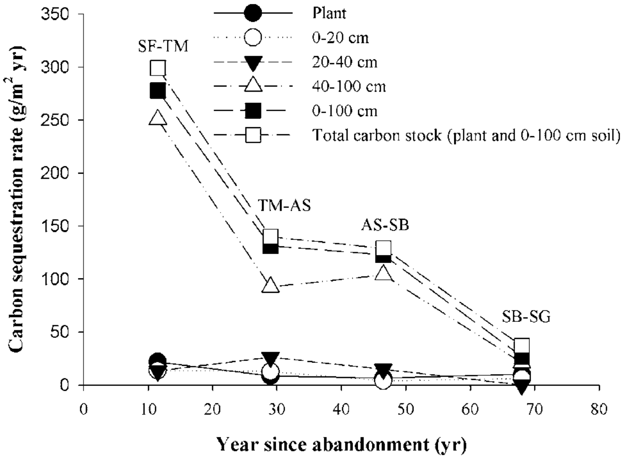

Figure 5. Vegetation, soil and total (plant and 0–100 cm soil) carbon sequestration rates at four different vegetation restoration stages. Restoration periods of time: SF to TM, sloping farmland to *T. mongolicus*, TM to AS, *T. mongolicus* to *A. sacrorum*, AS to SB, *A. sacrorum* to *S. bungeana*, SB to SG, *S. bungeana* to *S. grandis*.

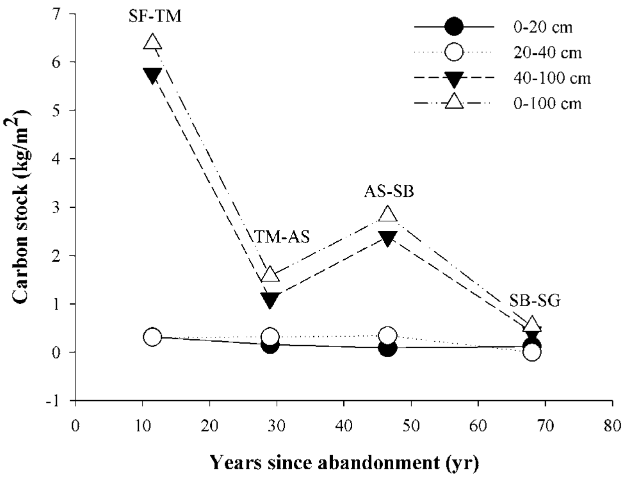

Figure 7. Soil carbon sequestration at the different vegetation restoration stages. Restoration periods: SF to TM, sloping farmland to *T. mongolicus*, TM to AS, *T. mongolicus* to *A. sacrorum*, AS to SB, *A. sacrorum* to *S. bungeana*, SB to SG, *S. bungeana* to *S. grandis*.

cropland, the percentage of increase was 82.96, 103.51, 140.18, and 147.07%, respectively.

On the whole, SOC stocks decreased at different soil depths at different stages of vegetation restoration (Fig. 7). SOC stock was largest in the early vegetation restoration stage (0–23 years), reaching 6.38 kg/m^2. As the vegetation restoration progressed, the sequestering of carbon decreased. The SOC stocks of the *A. sacrorum* (23–35 years), *S. bungeana* (35–58 years), and *S. grandis* (58–78 years) community stages were 1.57, 2.82, and 0.54 kg/m^2, respectively. At the different vegetation restoration stages, sequestration was higher at the 40–100 cm depth than that of the 0–40 cm layer.

Following the conversion of cropland to grassland, the soil carbon sequestration rates decreased with vegetation restoration (Fig. 5). However, the soil carbon sequestration rates differed in the different soil layers (Fig. 5). At the early vegetation restoration stage (0–23 years), the soil carbon sequestration rate was the highest, reaching 277.7 g/(m^2 year). At other stages, the carbon sequestration rates decreased. The carbon sequestration rates for the *A. sacrorum* (23–35 years), *S. bungeana* (35–58 years), and *S. grandis* (58–78 years) communities were 131.2, 122.7, and 26.8 g/(m^2 year), respectively. The soil carbon sequestration rates in the different soil layers differed (Fig. 5). Overall, the carbon sequestration rates were higher at a depth of 40–100 cm than in the 0–20 and 20–40 cm soil layers.

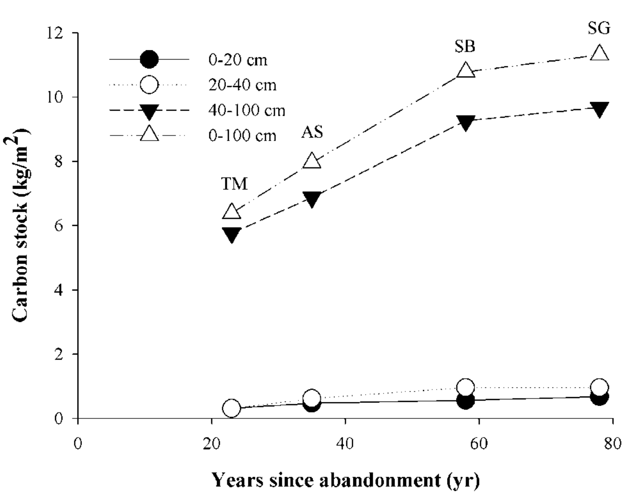

Figure 6. Carbon sequestration compared to sloping farmland in the different soil layers at the different vegetation restoration stages. Restoration stage: TM, *T. mongolicus*, AS, *A. sacrorum*, SB, *S. bungeana*, SG, *S. grandis*.

3.4 Total carbon stock

Following the conversion of cropland to grassland, the total stocks' (plant and 0–100 cm soil) carbon sequestration rates decreased with vegetation restoration (Fig. 5). The carbon sequestration rates of *T. mongolicus* (0–23 years), *A. sacrorum* (23–35 years), *S. bungeana* (35–58 years), and *S. grandis* (58–78 years) were 299.1, 139.6, 129.0, and 36.8 g/(m^2 year), respectively.

3.5 Carbon sequestration potential

With vegetation restoration, the potential for vegetation and soil carbon sequestration decreased. Both the vegetation and soil carbon sequestration potential of the grazed grassland was the highest (Tab. 2). At the various stages of restoration, the soil carbon sequestration potential in the different soil layers also differed. The carbon sequestration potential was higher at a depth of 40–100 cm than at a depth of 0–40 cm at the different stages of vegetation restoration. With vegetation restoration, the potentials for total carbon sequestration were shown in Tab. 2. The total carbon sequestration potential of the grazed grassland was the highest (Tab. 2).

4 Discussion

Vegetation biomass is closely related to vegetation carbon storage [29]. Thus, vegetation carbon stock is dominated by vegetation biomass. The study showed a significantly recovered vegetation

Table 2. Carbon sequestration potential of two grassland types compared to a climax community (*S. grandis* community) at four different vegetation restoration stages

Restoration stage	Vegetation (g/m²)	Soil depth (kg/m²)				Ecological system (kg/m²)
		0–20 cm	20–40 cm	40–100 cm	0–100 cm	
Grazed grassland	454.95	0.26	1.37	6.30	7.94	8.39
Sloping farmland	947.36	0.68	0.96	9.67	11.31	12.26
T. mongolicus	446.73	0.37	0.65	3.92	4.93	5.38
A. sacrorum	345.91	0.21	0.34	2.81	3.36	3.7
S. bungeana	199.62	0.12	−0.00	0.42	0.54	0.73

Note: The other grasslands include grazed grassland, sloping cropland, *T. mongolicus*, *A. sacrorum*, *S. bungeana*; the *S. grandis* community is the climax community.

carbon stock over 78 years, particularly so in the first 23 years (Fig. 2). That plant biomass increased with vegetation restoration is consistent with the results of several long-term studies, which have shown that vegetation restoration leads to plant biomass recovery [30, 31]. The study also found the trends of above-and belowground biomass carbon stocks to be consistent with the above-and belowground biomass (Tab. 1, Fig. 2), and that the aboveground carbon stock was highest at the *S. grandis* community stage, but the carbon stock of the belowground biomass was the highest at the *S. bungeana* community stage (Fig. 2). This may indicate that grassland biomass changes at the different restoration stages were the main reason behind changes in vegetation biomass carbon stocks, which agrees with Mitra et al.'s [29] study. The above- and belowground biomass carbon stocks increased inconsistently although total biomass carbon stocks increased (Fig. 2). This is probably related to the root-shoot biomass allocations of different plant communities [32]. Species compositions have a significant effect on carbon allocation patterns due to above- and belowground niche complementarily [32]. Gao et al. [32] reported that species composition had a significant effect on the carbon allocation pattern due to above- and belowground niche complementarily. The *S. bungeana* community allocated more biomass to its belowground growth, and the *S. grandis* community allocated more biomass to its aboveground growth because it had a higher aboveground height (Tab. 1); a finding in keeping with the root-shoot biomass allocations of different plant communities (Tab. 1). In addition, the study also found that the carbon sequestration rate of the vegetation carbon pool fluctuated with vegetation restoration, peaking at the early vegetation restoration stage (0–23 years) (Fig. 5). After the conversion of cropland to grassland, plants would quickly invade as they competed for unlimited resources. Limited resources are the main factors that determine plant community composition, plant diversity and successional dynamics [33]. As plant succession advances, plant resources become limited and plants reach a relatively stable balance through competition. Therefore, the amount of resources available for plants is a key factor determining the quantity of their biomass. Biomass carbon stocks of the grazed grassland were lower than those of the fenced natural grassland, which is consistent with the results of several studies that reduced herbivore densities lead to the recovery of plant community structure and composition [34, 35].

A plant community has an effect on soil processes, which are correlated with successional plant dynamics [36]. It is generally accepted that soil organic carbon increases over the period of succession [37], although a few studies show limited organic carbon change [38]. In our study, we found that soil carbon stocks were increased in every soil layer in keeping with the restoration of vegetation (Fig. 3). This is consistent with plant carbon stock dynamics because soil changes are associated with increases in belowground plant biomass [30]. Following the conversion of cropland to grassland, plant biomass accumulation was mainly attributed to belowground plant biomass rather than aboveground biomass (Fig. 2), which led to a higher belowground carbon input. The study found that the soil organic carbon stock was lower for the grazed grassland than for the enclosed grassland (Fig. 3). This was probably because overgrazing significantly reduced SOC concentration as it hampers/degrades vegetation cover and hence reduces plant derived C input and makes the soil more vulnerable to soil degradation (e.g. soil erosion) triggering higher levels of C mineralization [39, 40].

Nutrients and soil organic matter accumulation on surface soil result from complex interactions between plant-regulated biotic processes and soil biota, and abiotic processes driven by atmospheric and biochemical processes [41]. With the exception of climatic factors, soil resource changes are important determinants of vegetation characteristics at small spatial scales. Li et al. [23] reported that rehabilitation and re-vegetation could improve soil environments for plant colonization and establishment. Measurements in the desertified area of the Loess Plateau showed that soil properties (including soil nutrients and texture) and vegetative characters changed more rapidly at the early dune stabilization stage than at later dune stabilization stages over a 50-year period [19], which indicates that soil and vegetation recoveries following desertification are slow processes [23]. The study showed a similar trend in that the ecosystem (plant and soil) carbon sequestration rate was highest during the early vegetation restoration stage (0–23 years) and decreased later on (Fig. 5). As Izaurralde et al. [42] have suggested that the carbon sequestration rate is greatest in the earlier stages of restoration. An et al. [19], who also conducted research in the same area, found that soil nutrients and microbial properties all increased very quickly in the earlier vegetation restoration stage lasting as long as 23 years, and were stable without significant fluctuation in later years. Soil microorganisms increase following the availability of increased organic inputs from re-vegetation [19, 43]. Soil nutrients and organic matter probably increase following increases in soil microbial. These are probably the reasons behind the changes observed in both plant and soil carbon sequestration rates.

It is well documented that cropland to grassland conversion will significantly increase soil carbon sequestration [44, 45]. We found a logarithmic increase since cropland abandonment (Figs. 3 and 6), which was similar to the study by De Baets et al. [46]. We also found a significant decline in carbon sequestration rates with vegetation recovery (Fig. 5), which was consistent with observations made by

Zhou et al. [47], who found that after 20 years of recovery and as a result of controlled grazing in a semi-arid ecosystem, soil C stocks remained constant. The reason for the higher sequestration rate at the early stage after cropland abandonment may have been that the mineral soils were not (yet) saturated with carbon. Increased above- and belowground carbon inputs and decreased erosion resulting from permanent grass vegetation are likely to be the main factors contributing to an increase in SOC [45]. Moreover, the study showed that the rate of carbon sequestration was higher in the deeper soil layer (40–100 cm) than that found in the upper layer (0–40 cm) following the conversion of cropland to grassland (Fig. 5). Usually, under conventional farming practices, higher amounts of carbon are stored in the upper levels of cultivated soil due to increased organic fertilizer input to the topsoil, and deeper soil does not usually have many roots because of seasonal or annual crop removal. After cropland converted to grassland, plant roots input significant amounts of organic matter (roots, root exudates) into deeper soil. Thus, deeper soils have a higher potential to increase their SOC following the conversion of cropland to grassland.

The ecosystem carbon pool is composed of two parts, plant and soil. The plant and soil dynamics of an ecosystem influence its structure and function [48]. The study shows that of the grassland ecosystem, both plant and soil carbon stocks increased with vegetation restoration (Figs. 2 and 3), resulting in an increase in grassland total carbon stocks. Since cropland abandonment, total carbon stocks showed a logarithmic increase (Fig. 4), and the total carbon sequestration rate decreased with vegetation recovery (Fig. 5). To better explain the observed variation in carbon stocks, vegetation density, vegetation composition, soil pH, soil moisture and soil aggregate structure, soil microbes, etc. should be taken into account. Overall, the results demonstrate that the terrestrial carbon sink evolves over time. These findings are unique in two ways. Importantly, they demonstrate that historical land-use change can be used to illustrate the relationship between land-use change and soil carbon stocks at the landscape scale, which can then be extrapolated to regional-level policies and programs. Significantly, the transformation of the soil organic carbon stocks into a uniform soil depth (0–100 cm) allows reliable conclusions to be drawn about land-use effects deep in the soil profile. By demonstrating how the terrestrial carbon sink responds to changes in land use over time not only can management policies and practices be more precisely tailored to specific grassland communities, but estimates in the rate of offset can be revised.

Acknowledgements

The study was funded by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA05060403) and the Scholarship Award for Excellent Doctoral Student granted by Ministry of Education.

The authors have declared no conflict of interest.

References

[1] R. A. Knee, What Happened to Global Warming? Scientists Say Just Wait a Bit, *Science* **2009**, *326*, 28–29.

[2] J. D. Schakun, P. U. Clark, F. He, S. A. Marcott, A. C. Mix, Z. Y. Liu, B. Otto-Biesner, et al., Global Warming Preceded by Increasing Carbon Dioxide Concentrations during the Last Deglaciation, *Nature* **2012**, *484*, 49–54.

[3] R. J. Andres, T. A. Boden, F. M. Breon, P. Ciais, S. Davis, D. Erickson, J. S. Gregg, et al., A Synthesis of Carbon Dioxide Emissions from Fossil-Fuel Combustion, *Biogeosciences* **2012**, *9*, 1845–1871.

[4] D. Topi, B. Seiti, K. Dule, E. Halimi, CO_2 Emissions from Fossil Fuels during the Period 2000–2004 in Albania, *J. Environ. Prot. Ecol.* **2012**, *13*, 442–450.

[5] V. Ramanathan, Y. Feng, Air Pollution, Greenhouse Gases and Climate Change: Global and Regional Perspectives, *Atmos. Environ.* **2009**, *43*, 37–50.

[6] F. M. DaMatta, A. Grandis, B. C. Arenque, M. S. Buckeridge, Impacts of Climate Changes on Crop Physiology and Food Quality, *Food Res. Int.* **2010**, *43*, 1814–1823.

[7] R. Amundson, The Carbon Budget in Soils, *Annu. Rev. Earth Planet. Sci.* **2001**, *29*, 35–562.

[8] A. W. Blair, H. C. McLean, Total Nitrogen and Carbon in Cultivated Land and Land Abandoned to Grass and Weeds, *Soil Sci.* **1917**, *4*, 283–294.

[9] A. M. Thomson, R. C. Izaurralde, S. J. Smith, L. E. Clarke, Integrated Estimates of Global Terrestrial Carbon Sequestration, *Global Environ. Change* **2008**, *18*, 192–203.

[10] J. Brown, J. Angerer, S. W. Salley, R. Blaisdell, J. W. Stuth, Improving Estimates of Rangeland Carbon Sequestration Potential in the US Southwest, *Rangeland Ecol. Manage.* **2010**, *63*, 147–154.

[11] A. A. Keller, R. A. Goldstem, Impact of Carbon Storage through Restoration of Drylands on the Global Carbon Cycle, *Environ. Manage.* **1998**, *22*, 757–766.

[12] J. E. Doll, G. E. Brink, R. L. Cates, J. R. Jackson, R. D. Jackson, Effects of Native Grass Restoration Management on Above- and Belowground Pasture Production and Forage Quality, *J. Sustain. Agric.* **2009**, *33*, 512–527.

[13] S. L. Liu, X. D. Guo, B. J. Fu, G. Lian, J. Wang, The Effect of Environmental Variables on Soil Characteristics at Different Scales in the Transition Zone of the Loess Plateau in China, *Soil Use Manage.* **2007**, *23*, 92–99.

[14] F. Jiao, Z. M. Wen, M. A. Shao, Changes in Soil Properties Across a Chronosequence of Vegetation Restoration on the Loess Plateau of China, *Catena* **2011**, *86*, 110–116.

[15] X. L. Fu, M. A. Shao, X. R. Wei, R. Horton, Soil Organic Carbon and Total Nitrogen as Affected by Vegetation Types in Northern Loess Plateau of China, *Geoderma* **2010**, *155*, 31–35.

[16] L. D. Chen, J. P. Wang, W. Wei, B. J. Fu, D. P. Wu, Effects of Landscape Restoration on Soil Water Storage and Water Use in the Loess Plateau Region, China, *For. Ecol. Manage.* **2010**, *259*, 1291–1298.

[17] Z. B. Guo, G. J. Yan, R. H. Zhang, F. M. Li, Z. X. Zeng, H. Liu, Improvement of Soil Physical Properties and Aggregate-Associated C, N, and P after Cropland was Converted to Grassland in Semi-arid Loess Plateau, *Soil Sci.* **2010**, *175*, 99–104.

[18] G. L. Wang, G. B. Liu, M. X. Xu, Above- and Belowground Dynamics of Plant Community Succession Following Abandonment of Farmland on the Loess Plateau, China, *Plant Soil* **2009**, *316*, 227–239.

[19] S. S. An, Y. M. Huang, F. L. Zheng, Evaluation of Soil Microbial Indices along a Revegetation Chronosequence in Grassland Soils on the Loess Plateau, *Northwest China. Appl. Soil Ecol.* **2009**, *41*, 286–292.

[20] China Ministry of Agriculture, Notice of Department of Agriculture Office on further strengthening implementation and management of "Returning Grazing Land to Grassland" project, *Gazette of the Ministry of Agriculture of the People's Republic of China*, #2008, 58, China Ministry of Agriculture, Beijing **2008**, pp. 31–32.

[21] P. P. Bhojvaid, V. R. Timmer, Soil Dynamics in an Age Sequence of *Prosopis juliflora* Planted for Sodic Soil Restoration in India, *For. Ecol. Manage.* **1998**, *106*, 81–193.

[22] W. Fang, S. L. Peng, Development of Species Diversity in the Restoration Process of Establishing a Tropical Man-Made Forest Ecosystem in China, *For. Ecol. Manage.* **1997**, *99*, 185–196.

[23] X. R. Li, D. S. Kong, H. J. Tan, X. P. Wang, Changes in Soil and Vegetation Following Stabilization of Dunes in the Southeastern Fringe of the Tengger Desert, China, *Plant Soil* **2007**, *300*, 221–231.

[24] G. P. Sparling, L. A. Schipper, W. Bettjeman, R. Hill, Soil Quality Monitoring in New Zealand: Practical Lessons from a 6-Year Trial, *Agric. Ecosyst. Environ.* **2003**, *104*, 523–534.

[25] J. S. Powers, M. D. Corre, T. E. Twine, E. Veldkamp, Geographic Bias of Field Observations of Soil Carbon Stocks with Tropical Land-Use Changes Precludes Spatial Extrapolation, *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 6318–6322.

[26] L. B. Guo, R. M. Gifford, Soil Carbon Stocks and Land Use Change: A Meta-Analysis, *Global Change Biol.* **2002**, *8*, 345–360.

[27] J. Y. Fang, Z. D. Guo, S. L. Piao, A. P. Chen, Terrestrial Vegetation Carbon Sinks in China, 1981–2000, *Sci. China Ser. D* **2007**, *50*, 1341–1350.

[28] S. P. Wang, A. Wilkes, Z. C. Zhang, X. F. Chang, R. Lang, Y. F. Wang, H. S. Niu, Management and Land Use Change Effects on Soil Carbon in Northern China's Grasslands: A Synthesis, *Agric. Ecosyst. Environ.* **2011**, *142*, 329–340.

[29] A. Mitra, K. Sengupta, K. Banerjee, Standing Biomass and Carbon Storage of Above-Ground Structures in Dominant Mangrove Trees in the Sundarbans, *For. Ecol. Manage.* **2011**, *261*, 1325–1335.

[30] M. Potthoff, L. E. Jackson, K. L. Steenwerth, I. Ramirez, M. R. Stromberg, Soil Biological and Chemical Properties in Restored Perennial Grassland in California, *Restor. Ecol.* **2005**, *13*, 61–73.

[31] W. J. Li, J. H. Li, J. M. H. Knops, G. Wang, J. J. Jia, Plant Communities, Soil Carbon, and Soil Nitrogen Properties in a Successional Gradient of Sub-Alpine Meadows on the Eastern Tibetan Plateau of China, *Environ. Manage.* **2009**, *44*, 755–765.

[32] Y. Z. Gao, Q. Chen, S. Lin, M. Giese, H. Brueck, Resource Manipulation Effects on Net Primary Production, Biomass Allocation and Rain-Use Efficiency of Two Semiarid Grassland Sites in Inner Mongolia, China, *Oecologia* **2011**, *165*, 855–864.

[33] T. Mclendon, E. F. Teclente, Nitrogen and Phosphorus Effects on Secondary Succession Dynamics on a Semi-Arid Sagebrush Site, *Ecology* **1991**, *72*, 2016–2024.

[34] Q. Guo, Slow Recovery in Desert Perennial Vegetation Following Prolonged Human Disturbance, *J. Veg. Sci.* **2004**, *15*, 757–762.

[35] A. J. Tanentzap, L. E. Burrows, W. G. Lee, G. Nugent, J. M. Maxwell, D. A. Coomes, Landscape-Level Vegetation Recovery from Herbivory: Progress after Four Decades of Invasive Red Deer Control, *J. Appl. Ecol.* **2009**, *46*, 1064–1072.

[36] D. K. Woods, Dynamics in Late-Successional Hemlock-Hardwoods Forests over Three Decades, *Ecology* **2000**, *81*, 110–126.

[37] K. R. Brye, C. J. Kucharik, Carbon and Nitrogen Sequestration in Two Prairie Topochronosequences on Contrasting Soils in Southern Wisconsin, *Am. Midland Nat.* **2003**, *149*, 90–103.

[38] A. Bonet, Secondary Succession of Semi-Arid Mediterranean Old-Fields in South-Eastern Spain: Insights for Conservation and Restoration of Degraded Lands, *J. Arid. Environ.* **2004**, *56*, 213–223.

[39] X. D. Wang, Y. Yan, Y. Z. Cao, Impact of Historic Grazing on Steppe Soils on the Northern Tibetan Plateau, *Plant Soil* **2012**, *354*, 73–183.

[40] M. Wiesmeier, O. Kreyling, M. Steffens, P. Schoenbach, H. W. Wan, M. Gierus, F. Taube, et al., Short-Term Degradation of Semiarid Grasslands – Results from a Controlled-Grazing Experiment in Northern China, *J. Plant Nutr. Soil Sci.* **2012**, *175*, 434–442.

[41] D. U. Hooper, D. E. Bignell, V. K. Brown, Interactions between Aboveground and Belowground Biodiversity in Terrestrial Ecosystems: Patterns, Mechanisms, and Feedbacks, *BioScience* **2000**, *50*, 1049–1061.

[42] R. C. Izaurralde, W. B. McGIll, A. Bryden, S. Graham, Scientific challenges in developing a plan to predict and verify carbon storage in Canadian prairie soils, in *Advances in Soil Science: Management of Carbon Sequestration in Soil* (Eds: R. Lal, J. Kimble, R. Follett, B. A. Stewart), CRC Press, Boca Raton, FL **1998**, pp. 433–446.

[43] K. Jangid, M. A. Williams, A. J. Franzluebbers, T. M. Schmidt, D. C. Coleman, Land-Use History has a Stronger Impact on Soil Microbial Community Composition than Aboveground Vegetation and Soil Properties, *Soil Biol. Biochem.* **2011**, *43*, 2184–2193.

[44] F. Mensah, J. J. Schoenau, S. S. Malhi, Soil Carbon Changes in Cultivated and Excavated Land Converted to Grasses in East-Central Saskatchewan, *Biogeochemistry* **2003**, *63*, 85–92.

[45] J. D. J. Nelson, J. J. Schoenau, S. S. Malhi, Soil Organic Carbon Changes and Distribution in Cultivated and Restored Grassland Soils in Saskatchewan, *Nutr. Cycl. Agroecosyst.* **2008**, *82*, 137–148.

[46] S. De Baets, J. Meersmans, V. Vanacker, T. A. Quine, K. Van Oost, Spatial Variability and Change in Soil Organic Carbon Stocks in Response to Recovery Following Land Abandonment and Erosion in Mountainous Drylands, *Soil Use Manage.* **2013**, *29*, 65–76.

[47] Z. Zhou, F. Li, S. Chen, H. Zhang, G. Li, Dynamics of Vegetation and Soil Carbon and Nitrogen Accumulation over 26 Years under Controlled Grazing in a Desert Shrubland, *Plant Soil* **2011**, *341*, 257–268.

[48] G. K. Phoenix, B. A. Emmett, A. J. Britton, S. J. M. Caporn, N. B. Dise, R. Helliwell, L. Jones, et al., Impacts of Atmospheric Nitrogen Deposition: Responses of Multiple Plant and Soil Parameters across Contrasting Ecosystems in Long-Term Field Experiments, *Global Change Biol.* **2012**, *18*, 1197–1215.