Grassland restoration in northern China is far from complete: evidence from carbon variation in the last three decades

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Citation: Ma, A., N. He, L. Xu, Q. Wang, M. Li, and G. Yu. 2017. Grassland restoration in northern China is far from complete: evidence from carbon variation in the last three decades. Ecosphere 8(4):e01750. 10.1002/ecs2.1750

Abstract. Ecosystem restoration requires considering both above-ground biomass (AGB) and soils, and the latter is even more essential due to the importance and restoration difficulty of soil organic matter (SOM). Remote sensing studies have shown that AGB has recovered in the grasslands of northern China, but the recovery of soil organic carbon (SOC) or SOM is still unclear. Here, based on the published data between the 1980s and 2014, we used the variation in carbon (C) density observed in the vegetation and soils of four regions across northern China as integrative indicator to explore grassland restoration. Overall, northern Chinese grasslands were a weak carbon source (−14 Tg C), although C density in AGB and below-ground biomass increased on average by 0.019 and 0.224 kg C/m², respectively, during the period considered in the present study. Unexpectedly, SOC density in the 0–20 cm soil layer decreased by 0.193 kg C/m² on average, and all regions registered a decrease in SOC, although values differed among them. Our findings were consistent with previous evaluations using remote sensing and with the idea that vegetation in northern China has been restored. However, SOC has not been restored, and given its importance for sustaining nutrient supply and water conservation, as well as the high difficulty of SOC restoration, grassland restoration in northern China is still far from being achieved.

Key words: carbon; China; grassland; restoration; sequestration; soil organic matter; storage.

INTRODUCTION

Evaluation of the restoration of grassland ecosystems at a large scale using only field data is very difficult; therefore, remote sensing-based approaches have been widely used. Unfortunately, although remote sensing offers the possibility of spatial and temporal estimates of above-ground biomass (AGB), it is not a mature technology to estimate soil properties such as soil organic matter (SOM), and reports on SOM direct quantification using remote sensing are limited (Gehl and Rice 2007). Ideally, grasslands’ restoration should consider the good conditions of vegetation and soil (Fig. 1), but practical limitations on data acquisition and/or on the methods used restrict the evaluation of vegetation and soil restoration at large scale, and assessments are always based on one or two parameters (biomass, plant species, or soil; Andrade et al. 2015).

Most studies focusing on vegetation restoration considered vegetation biomass as the only indicator and used remote sensing at regional scales (Fang et al. 2007, Piao et al. 2007, Ma et al. 2010). For example, remote sensing showed that degraded grasslands in northern China were well restored based on their AGB (Piao et al. 2007). Is this restoration real? First, the evaluations presented in
Piao et al. (2007) did not consider species composition and soil properties, which is the disadvantage of using remote sensing. Yu et al. (2010), based on decreases in forage quality (legumes), reported that Chinese grasslands became worse since 1980s. Furthermore, it is difficult to assess the restoration of northern grasslands by AGB which is highly limited by variations in precipitation (Knapp et al. 2002). Compared with AGB, SOM would be a better indicator, because of its stability and persistence in sustaining primary productivity (Wolf and Snyder 2009). Soil organic carbon (SOC) could also be used as an indicator, instead of SOM, as it is highly available at a large scale. Unfortunately, SOC storage levels in northern China have been reported as controversial in the past decades, ranging from relatively constant (Yang et al. 2010) to decreasing (Xie et al. 2007), although SOC storage is expected to increase after implementing serious management or restoration practices (He et al. 2012). Theoretically, it will be possible to develop a new evaluating scheme for grassland restoration by combining vegetation and SOC assessments.

The restoration level achieved in northern China’s grasslands under several practices (e.g., fencing, controlling grazing intensity) is important for public opinion, but results have been controversial. In the present study, we compiled field data on carbon (C) density in vegetation and soil in northern grasslands across China, collected from 4967 sites during the 1980s and from 5044 sites between 2004 and 2014 (hereafter, 2010s; Fig. 2), to assess the status of grasslands’ restoration using C storage as the standard parameter. Specifically, this study aimed to (1) evaluate changes in the C storage of vegetation and soil in northern China’s grasslands from over approximately three decades and (2) develop a new frame to evaluate grassland restoration based on SOC. Our results may provide new insights into large-scale evaluations of C sequestration and ecosystem restoration.

**METHODS**

**Data sources**

Data on C density in AGB, in the roots, that is, below-ground biomass (BGB), and in the soil of northern China’s grasslands from 1980 to 1990 were obtained from (1) the forage yield estimated for national grassland resources for approximately 10 yr, surveyed in 1991 (DAHV and CISNR 1994); (2) public field-measured data; and (3) SOM (or SOC transformed) content, published in China’s National Soil Inventories during the 1980s (Appendix S1).

Data on C density between 2004 and 2014 were obtained from (1) field-measured data published in scientific papers available from the Web of Science (www.webofknowledge.com) and China National Knowledge Infrastructure (http://epub.cnki.net) websites (Ma et al. 2016) and (2) unpublished field-measured data (personal communication; Appendix S2).

To estimate SOC storage changes, SOC values referred for the topsoil (0–20 cm soil layer) in both study periods were used, because the topsoil is sensitive to anthropogenic activities and changes in SOC storage occur mainly in this layer (Conant et al. 2001).

Northern China’s grassland area was obtained from land-use maps published in 1990 and 2008 in the National Data Sharing Infrastructure of Earth System Science website.

**Data processing**

The C densities in AGB (AGBC, kg C/m²) and in BGB (BGBC, kg C/m²) were calculated using a C content coefficient of 0.45 (Ni 2004).

Carbon data on AGB were treated differently according to the original data types. The fresh weight of forage yield was converted to dry...
weight using the grassland type-based dry/fresh weight ratio (DAHV and CISNR 1994), where AGB was calculated as the dry weight of forage yield minus 15% water content (AGB = 85% carbon dry weight; Fang et al. 1996). Field-measured AGB was used directly, and in cases where AGB was measured monthly, we chose the values obtained in August, which is commonly considered the peak C storage period in Chinese grasslands (He et al. 2008). Similarly, BGB values obtained for the 2010s period were directly used, as they were mainly derived from field measurements, whereas BGB values in the 1980s dataset were calculated from root to shoot (R/S) carbon content ratios (Piao et al. 2004).

Soil organic carbon density (kg C/m²) in the 1980s was calculated using Eq. 1, where SOC content was inferred from SOM content in the topsoil (0–20 cm) using the Bemmelen index (0.58) (Yan et al. 2010), unless SOC was reported directly.

\[
SOC = \sum_{j=1}^{n} (H_j \times c_j \times b_j \times 0.1)
\]

where SOC is SOC density (kg C/m²), \(H_j\) is soil thickness (cm), \(c_j\) is the soil C content (%), and \(b_j\) is the bulk density (g/cm³).

Field-measured bulk density was used directly; when bulk density was not referred, the empirical relationship between bulk density and SOC concentration was used to estimate it (Yang et al. 2007, Xu et al. 2015). In the present study, ecosystem C density (kg C/m²) was calculated as the sum of AGBC, BGC, and SOC values.

Overall, the total number of sampling sites for AGBC, BGC, and SOC was 1984, 1962, and
1021, respectively, for the 1980s period and 2432, 1291, and 1321, respectively, for the 2010s period, respectively (Fig. 2).

**Scaling-up methods**

As site-level comparisons across different decades are hard to perform at a large scale, pairwise regional comparisons and the spatial interpolation method were used to evaluate the differences in C density between the two study periods in northern China grasslands. Ma et al. (2016) demonstrated that the empirical Bayesian kriging interpolation was the most suitable method to estimate grassland C storage at large scale. According to the Rangeland Resources of China (DAHV and GSAHV 1996), northern grasslands were classified into four major regions (Fig. 2): temperate semi-humid meadow steppe (Northeast), temperate semi-arid steppe and desert steppe (Inner Mongolia), temperate and warm temperate arid desert and mountain steppe (Northwest), and Qinghai–Tibet alpine (or Qing–Tibet). According to this classification, data from sampling sites were pooled into larger regional samples.

**Statistical analysis**

Spatial interpolation and statistical analysis were performed in ArcGIS 8.2 (ESRI, Redlands, California, USA) and SPSS 18 (SPSS, Chicago, Illinois, USA). Abnormalities in primary data were removed using the Pauta criterion (3σ). Grassland C storage was summarized from the AGB, BGB, and SOC values registered in the 0–20 cm soil layer across the different periods, and differences were defined as significant for \( P < 0.05 \).

**RESULTS**

The AGBC, BGBC, and SOC estimated in the four regions of northern China in the two periods are presented in Fig. 3. On average, AGBC and BGBC increased and SOC decreased over time (0.019, 0.243, and −0.193 kg C/m², respectively; Table 1). Furthermore, C density variation in AGBC, BGBC, and SOC differed among the four regions (Table 1). The largest increase in AGBC was observed in Inner Mongolia (0.028 kg C/m²), whereas the smallest occurred in Northeast (0.014 kg C/m²); for BGBC, the largest increase was recorded in Northeast (0.416 kg C/m²) and...
the smallest, in Northwest (0.147 kg C/m²). C density in SOC presented the opposite trend, as it was lower in the 2010s than in the 1980s, especially in Inner Mongolia (0.576 kg C/m²) and in Northeast (0.402 kg C/m²). Considering C density variation at the ecosystem level, it decreased in Inner Mongolia (0.367 kg C/m²) and increased in the remaining regions, although at lower rates (0.191, 0.084, and 0.028 kg C/m² in Qing–Tibet, Northwest, and Northeast, respectively). On average, ecosystem C consistently increased by 0.050 kg C/m² over the study period.

The total grassland area in northern China decreased from 262.99 × 10⁴ km² in the 1980s to 259.66 × 10⁴ km² in the 2010s (Table 2). Considering these total areas, C sequestration in northern China grasslands increased 0.048 and 0.575 Pg C in AGBC and BGBC, respectively, and decreased −0.638 and −0.014 Pg C in SOC and at the ecosystem level, from the 1980s to 2010s (Table 2, Fig. 4). Carbon sequestration rates differed among different ecosystem components and regions (Fig. 4). Whereas the largest increase in AGBC storage was found in Qing–Tibet (0.024 Pg C), no variation was observed in Northeast (0.000 Pg C). The largest increase in BGBC storage was also registered in Qing–Tibet (0.380 Pg C), whereas the smallest was found in Northeast (0.034 Pg C). Although SOC decreased in all regions, the largest value (−0.338 Pg C) was detected in Inner Mongolia; the other regions presented almost identical values (Table 2).

**DISCUSSION**

Our study provided a systematic evaluation of C storage in the northern grasslands of China, estimating it varied 0.048, 0.575, −0.638, and −0.014 Pg C in AGBC and BGBC, respectively, and decreased −0.338 Pg C in SOC and at the ecosystem level, from the 1980s to 2010s (Table 2, Fig. 4). Carbon sequestration rates differed among different ecosystem components and regions (Fig. 4). Whereas the largest increase in AGBC storage was found in Qing–Tibet (0.024 Pg C), no variation was observed in Northeast (0.000 Pg C). The largest increase in BGBC storage was also registered in Qing–Tibet (0.380 Pg C), whereas the smallest was found in Northeast (0.034 Pg C). Although SOC decreased in all regions, the largest value (−0.338 Pg C) was detected in Inner Mongolia; the other regions presented almost identical values (Table 2).

**Table 1. Changes in carbon density (kg C/m²) of grasslands from the 1980s to the 2010s in northern China.**

| Region         | AGBC† | BGBC | SOC† | Ecosystem C |
|----------------|-------|------|------|-------------|
|                | 1980s | 2010s | Change | 1980s | 2010s | Change | 1980s | 2010s | Change | 1980s | 2010s | Change |
| Northeast‡     | 0.072 (0.020) | 0.086 (0.023) | 0.014 (0.023) | 0.419 (0.170) | 0.836 (0.330) | 0.416 (0.218) | 4.453 (2.103) | 4.050 (1.735) | −0.402 (1.315) | 4.944 (0.330) | 4.972 (0.147) | 0.028 |
| Inner Mongolia | 0.030 (0.021) | 0.058 (0.031) | 0.028 (0.031) | 0.201 (0.101) | 0.381 (0.218) | 0.181 (0.218) | 3.222 (1.923) | 2.647 (1.135) | −0.576 (1.135) | 3.453 (0.218) | 3.086 (0.014) | −0.367 |
| Northwest      | 0.026 (0.011) | 0.046 (0.032) | 0.020 (0.032) | 0.185 (0.108) | 0.332 (0.173) | 0.147 (0.173) | 3.722 (2.024) | 3.638 (3.015) | −0.084 (3.015) | 3.933 (0.218) | 4.017 (0.084) | 0.084 |
| Qing–Tibet     | 0.026 (0.020) | 0.042 (0.034) | 0.016 (0.034) | 0.184 (0.146) | 0.437 (0.306) | 0.253 (0.306) | 4.478 (2.306) | 4.400 (2.654) | −0.078 (2.654) | 4.687 (0.218) | 4.879 (0.191) | 0.191 |
| Average        | 0.029 | 0.048 | 0.019 | 0.197 | 0.421 | 0.224 | 4.076 | 3.883 | −0.193 | 4.302 | 4.352 | 0.050 |

**Note:** Data are presented as means and standard deviation.
† AGBC, carbon density of above-ground biomass; BGBC, carbon density of below-ground biomass; SOC, soil C density (0–20 cm soil layer); ecosystem C, ecosystem C density.
‡ Northeast, temperate semi-humid meadow steppe regions; Inner Mongolia, temperate semi-arid steppe and desert steppe regions; Northwest, temperate and warm temperate arid desert and mountain steppe regions; Qing–Tibet, Qinghai–Tibet alpine regions.

**Table 2. Changes in grassland area and the estimation of C storage from the 1980s to the 2010s in the northern grasslands of China.**

| Region         | Area (10⁴ km²) | Change in C storage (Pg C) |
|----------------|--------------|-----------------------------|
|                | 1980s | 2010s | Change | AGBC‡ | BGBC | SOC | Ecosystem C |
| Northeast‡     | 10.921 | 9.524 | −1.397 | 0.000 | 0.034 | −0.101 | −0.066 |
| Inner Mongolia | 55.679 | 55.029 | −0.650 | 0.015 | 0.098 | −0.338 | −0.224 |
| Northwest      | 46.867 | 45.198 | −1.668 | 0.009 | 0.064 | −0.100 | −0.028 |
| Qing–Tibet     | 149.524 | 149.906 | 0.382 | 0.024 | 0.380 | −0.100 | 0.305 |
| Total          | 262.991 | 259.657 | −3.333 | 0.048 | 0.575 | −0.638 | −0.014 |

† Northeast, temperate semi-humid meadow steppe regions; Inner Mongolia, temperate semi-arid steppe and desert steppe regions; Northwest, temperate and warm temperate arid desert and mountain steppe regions; Qing–Tibet, Qinghai–Tibet alpine regions.
‡ AGBC, carbon density of above-ground biomass; BGBC, carbon density of below-ground biomass; SOC, soil C density (0–20 cm soil layer); ecosystem C, ecosystem C density.
0.014 Pg C in AGBC, BGBC, SOC, and at the ecosystem level, respectively (Table 2), indicating that Chinese grasslands are a weak C source. The increases in AGBC reported in the present study agree with those found in the majority of previous studies (Table 3). Piao et al. (2007) reported that AGBC storage increased 0.018 Pg C from the early 1980s to the late 1990s, and Fang et al. (2007) showed that vegetation C storage (AGBC + BGBC) in China’s grasslands increased 0.007 Pg C from 1981 to 2000. Thus, the several grassland restoration projects developed by the Chinese government since 2001 seem to have affected AGBC in northern grasslands, as it began to rebound significantly (Xin et al. 2009, Qian et al. 2010), achieving its highest value in this study.

Estimates of soil C density or C sequestration in Chinese grasslands were inconsistent across studies. Our results showed that SOC in northern Chinese grasslands decreased 0.193 kg C/m² from 1980s to 2010s (or −0.638 Pg C). Yang et al. (2010) reported that in northern Chinese grasslands, and from the 1980s to 2000s, SOC was relatively stable in the 0–30 cm soil layer, increasing only 0.10 kg C/m² during this period. In contrast, Yang et al. (2009) estimated that SOC decreased 0.01 kg C/m² in the Tibetan alpine grasslands between 1980 and 2004. Zhang et al. (2007) reported a fast SOC decrease in the 0–20 cm layer of alpine grasslands from 1990 to 2000. Xie et al. (2007) found a net SOC loss in the Northwest, Northeast, Inner Mongolia, and Tibet from the 1980s to 2000s. The decrease observed in SOC resulted from overgrazing, reclaim, and other human activities (Schipper et al. 2007, He et al. 2008). Overgrazing caused a 25.2% decrease in the SOC content of the 0–20 cm soil layer in Inner Mongolia (Fu et al. 2004), and Li et al. (1998) found that overgrazing and changes in land use were responsible for the 12.4% SOC loss observed in the surface soil of the Xilin River Basin. Thus, northern Chinese grasslands seem
Table 3. Changes in carbon density (kg C/m²) or storage (Pg C) in Chinese grasslands presented in different studies conducted in several recent decades.

| Region           | Data source                        | Periods               | Area (10⁴ km²) | Change in vegetation C density (cm) | Change in SOC C storage (Pg C) | References |
|------------------|------------------------------------|-----------------------|----------------|-----------------------------------|-------------------------------|------------|
| China            | Field-measured, remote sensing     | 1982–1999             | 331.00         | 0.127                             | 0.003                         | Fang et al. (2007)             |
| China            | Field-measured, remote sensing     | 1980s–2000s           | 278.51         | 0.005                             | 0.014                         | Xie et al. (2007)               |
| China            | Field-measured, remote sensing     | 1980s–2000s           | 331.00         | 0.127                             | 0.003                         | Fang et al. (2007)              |
| Northern China   | Field-measured, remote sensing     | 1980s–2000s           | 334.1          | 0.005                             | 0.014                         | Xie et al. (2007)               |
| Northern China   | Field-measured, remote sensing     | 1980s–2000s           | 196.34         | 0.1                               | 0.011                         | Yang et al. (2010)              |
| Northern China   | Field-measured, remote sensing     | 1980s–2000s           | 196.30         | 0.03                              | 0.014                         | Ma et al. (2010)                |
| Temperate grasslands | Model                  | 1951–2007             | 64.96          | 0.410                             |                               | Sui and Zhou (2013)             |
| Tibetan grasslands | Field-measured, remote sensing   | 1980–2004             | 200.00         | 0.03                              |                               | Yang et al. (2009)              |
| Inner Mongolia   | Field-measured, remote sensing     | 1980s–2010s           | 58.55          | 0.21                             | 0.12                          | Dai et al. (2014)               |
| Northern China   | Field-measured, remote sensing     | 1980s–2010s           | 200.00         | 0.03                              |                               | Yang et al. (2009)              |
| Northern China   | Field-measured, remote sensing     | 1980s–2010s           | 259.66–262.99  | 0.019                            | 0.224                         | He et al. (2008)                |

Note: AGBC, carbon density of above-ground biomass; BGBC, carbon density of below-ground biomass; SOC, soil organic carbon.

to be a weak C source, according to the interaction found between the increasing vegetation C storage and the decreasing SOC storage.

According to the increase in C density found in all grassland regions in North China, vegetation has recovered since the 1980s, supporting the results found in the past decades through remote sensing (Piao et al. 2007). However, to assess whether the good condition of other vegetation parameters such as species composition and forage quality has also been restored, further studies are needed.

In contrast, SOC has not recovered to the 1980s condition. From the 1980s to 2014, the average SOC loss was −0.193 kg C/m² in the 0–20 cm soil layer of northern grasslands, and approximately −0.402, −0.576, −0.084, and −0.078 kg C/m² in Northeast, Inner Mongolia, Northwest, and Qing–Tibet, respectively. In grasslands, SOM or SOC restoration is more important indicator than vegetation restoration when considering a long time span, as SOM content is widely considered as an integral index to depict nutrient supply and soil persistence for sustaining primary productivity (Wolf and Snyder 2009). Burke et al. (1995) have demonstrated that a 50-yr period is adequate for the recovery of active SOM and nutrient availability, but the recovery of total SOM pools is a considerably slower process. He et al. (2008) suggested that two-decades grazing exclusion may largely contribute to restore *Leymus chinensis* grasslands from a state of light degradation to a state with similar productivity, SOC storage to undisturbed natural grasslands. However, the time required to restore degraded grasslands to their original steady states could be much longer, if the integrity of biological interactions and SOM quality, rather than quantity, are also considered.

The restoration of C density differed among the four grassland regions considered in the present study. The maximum and minimum increases in vegetation C density occurred in the Northeast and in the Northwest, respectively, which was consistent with Yang et al.’s (2012) results. The lowest and the highest SOC loss occurred in Qing–Tibet and Inner Mongolia, which presented −0.078 and −0.576 kg C/m², respectively, in 2014 than in the 1980s. The restoration of SOC was mainly limited by grassland reclamation in the Northeast, and overgrazing and desertification due to climate change and human activities in Northwest (Liu et al. 2003). Overgrazing in the semi-arid grasslands of Inner Mongolia led to bare or sparse vegetation (Li et al. 2000, Wu et al. 2012), and resulted in additional SOC loss by decomposition and erosion (He et al. 2013). Our results showed that the SOC level in Qing–Tibet in the 2010s was almost equal to the level...
observed in the 1980s. One possible explanation is that Qing–Tibet did not experience a substantial land-use change during the past decades (Liu et al. 2005), although the restoration measures implemented in this region might also be the reason for the similar values obtained.

CONCLUSION

Our findings supported that restoration of vegetation has been achieved in northern Chinese grasslands after the implementation of a series of protection and restoration measures by the government. However, soil C density in the 2010s was even lower than that registered in 1980s, meaning it needs a longer time to be recovered than vegetation C density. Considering the importance of SOM (or SOC) in sustaining nutrient supply and water conservation, and the long time to recover it (especially SOM quality), grassland restoration in northern China is still far from being achieved.

ACKNOWLEDGMENTS

This work was supported by the National Key Research Project of China (2016YFC0500202), the National Natural Science Foundation of China (31290221, 31470506), and the Program for Kezhen Distinguished Talents in Institute of Geographic Sciences and Natural Resources Research (2013RC102). We thank National Data Sharing Infrastructure of Earth System Science to provide data and some researchers to provide the unpublished data (Chen Quansheng, Huang Mei, Hu Zhongmin, Li Jie, Xue Jingyue, and Wang Changhui), and thank our colleagues and graduate students for the help of data collection.

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**SUPPORTING INFORMATION**

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.1750/full