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Management and land use change effects on soil carbon in northern China's grasslands: a synthesis

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ABSTRACT

Grasslands cover about 40% of China's land area. This paper synthesizes 133 papers from China on the impacts of land use conversion and improved management practices on soil organic carbon (SOC) in China's grasslands. The synthesis finds that overgrazing and conversion of freely grazed grassland to cropland lead to an annual average decline of 2.3–2.8% in SOC, and have caused a loss of 30–35% of total grassland SOC in China. Improved management practices may reverse the loss of SOC. Exclosure of degraded grassland from grazing and conversion of cropland to abandoned fields (i.e. natural restoration) increased carbon content by 34% and 62% on average. Carbon sequestration rates were greatest during the first 30 yr after treatments began and tended to be greatest in the top 10 cm of soil. Carbon sequestration potential was negatively related to initial carbon and nitrogen concentrations in soils. Exclosure from grazing and the conversion of cropland to abandoned fields resulted in average carbon sequestration rates of 130.4 g C m^{-2} yr^{-1} for 0–40 cm soil and 128.0 g C m^{-2} yr^{-1} for 0–30 cm soil, representing annual average increases of 5.4–6.3%. Based on our results, achievement of the national objective to exclude grazing livestock from 150 million ha of China's grasslands and to establish 30 million ha of cultivated pasture by 2020 would sequester over 0.24 Pg C yr^{-1}, which is equivalent to about 16% of fossil fuel CO_2 emissions in China in 2006.

1. Introduction

Land-use change is identified as a cause of soil carbon (C) losses and has been a significant source of atmospheric carbon dioxide (CO_2) over the last two centuries (Esser, 1987, 1995; Houghton et al., 1999; Smith et al., 2000; Wu et al., 2003; Xie et al., 2007). Atmospheric CO_2 concentrations have increased by 31% since 1750, and the current increase of approximately 1.5 mL L^{-1} yr^{-1} is predominantly due to fossil fuel combustion and land use changes (IPCC, 2007). Soil is the largest organic C reservoir in the terrestrial biosphere, about two times larger than that of vegetation or the atmosphere (Schlesinger, 1997). Even a minor change in SOC storage could result in a significant alteration in atmospheric CO_2 concentration (Callesen et al., 2003; Wynn et al., 2006). Therefore, enhancing carbon sequestration in terrestrial ecosystems is an important strategy for controlling the rise in atmospheric CO_2 concentration.

Grasslands are one of the world's most widespread vegetation types, covering nearly 20% of the world's land surface (Scurlock and Hall, 1998). Soil organic matter (SOM) in temperate grasslands averages 331 Mg ha^{-1}, and grasslands contain 12% of the earth's SOM (Schlesinger, 1997). China's grasslands cover about 40% of China's total land area (Chen and Fischer, 1998), which accounts for approximately 6–8% of the total world grassland area and contain 9–16% of the world's total grassland carbon stocks (Ni, 2002). Given their large surface area and carbon stocks, changes in Chinese grasslands may have significant effects on regional climate and regional to continental carbon cycles.

Grassland SOC can be strongly influenced by management (Conant et al., 2001). SOC losses due to conversion of 'native' or freely grazed grassland (FGG) to cropland or poor pasture management have been observed (Davidson and Ackerman, 1993; Milchunas and Lauenroth, 1993; Guo and Gifford, 2002). However, historical SOC losses can potentially be reversed, and atmospheric C sequestrated, through improvements in agricultural management

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(Smith et al., 2008). Since the techniques for accomplishing this are well-known, restoring soil carbon pools through changes in management is a rapidly deployable strategy for partially offsetting atmospheric CO_2 increases. Smith et al. (2008) estimated the global technical mitigation potential from agriculture by 2030 at approximately 5500–6000 Mt CO_2 equiv. yr^{-1}, of which more than 20% is due to improved grazing land management. However, effects of management on SOC are variable across different conditions, and more systematic analysis is required (Christopher et al., 2009; Luo et al., 2010).

Conant et al. (2001) synthesized the effects of improved management on SOC changes through analysis of data from 115 international publications. Of these publications, only two reported on measurements in the Euro-Asian steppe, and only 24 reported measurements in developing countries, where the driving forces of land use change may differ from those in developed countries. This paper contributes to filling that gap by reporting results of an analysis of reports from 133 papers published in the last 10 years on the effects on soil carbon of grassland management and related land use conversions in China. On the basis of the evidence synthesized, three issues are addressed: (1) how grazing and cultivation affects SOC, (2) how land use change affects SOC, and (3) the potential for C sequestration through improved management of grasslands in China.

2. Methods

2.1. Background information and logical structure of the synthesis

Only paired design experiments were surveyed in the paper. These experiments began with different background conditions (e.g. FGG or cropland), which are called "initial condition" or "initial management" below. New land use or management practices (e.g. exclosure, abandoning cropping) were brought in at some time in one plot, while the initial management or land use remained unchanged in another plot. After several years or decades, soil carbon was compared between the initial and subsequent land management practices or land uses. This was the most common method for deriving data in the experiments synthesized. The effects of grazing on soil carbon were most commonly evaluated by comparing FGG with exclosures, and occasionally by comparing between different grazing intensity levels through controlled experiments.

Grazing is the main land use practice of grasslands in China, and most grasslands have been grazed for between several decades to hundreds of years, hence our use of the term FGG rather than 'native' or 'natural' grassland. About 9% of the studies related to grazing (Table 1). Grazing levels in most studies were narratively described, and only a few authors explained the criteria used to judge whether a pasture was heavily or lightly grazed, such as percentage intake of above ground biomass. Driven by the perception that overgrazing is the main cause of rangeland degradation in China, several recent policies have been implemented that promote exclusion of grazing animals from grasslands by fencing degraded plots for natural restoration (Yeh, 2005). Such exclosures (Aerts et al., 2009) rarely have any other management practice applied. Studies of exclosures provided the largest number of data points of any single management practice analyzed (ca. 28% of studies). Conversion of FGG to croplands has been common in many of north China's grassland areas since at least the 17th century (Ho, 2000), and large areas were converted in the 1960s. Conversion of FGG to cultivated pasture or cropland (22.8% of studies) was generally halted about 10 years ago when legal restrictions became well enforced. Due to concerns with soil erosion, conversions from cropland to abandoned field (i.e. natural restoration to grassland) or to cultivated pasture or to shrubland in arid and semi-arid areas have been common since the implementation in 2000 of the 'Grain for Green Program' (Liu et al., 2008), and studies of these conversions accounted for 26.5% of the total number of studies. A final type of land conversion synthesized involves cultivating high quality perennial forages on FGG using intensive agronomic procedures such as plowing, sowing, and in some cases irrigation and fertilization. In the last 10 years some FGG has been converted to this type of land use, which we term 'cultivated pasture' in this synthesis. There were 15 reports of the effects on SOC of conversion of FGG to cultivated pasture (Table 1).

Grassland fires are relatively rare events in China. Some researchers have suggested that fire on grasslands need not be suppressed if animals are kept in safety, and that fire even benefits soil fertility by promoting nutrient cycling (Li and Jiang, 1994). Two papers were synthesized on the effects of burning on soil carbon. Mowing is a common land use in temperate grassland (e.g. in Inner Mongolia) where hay provides a main source of fodder for livestock in winter. Studies on the effects of mowing on soil carbon were few and accounted for only 1.9% of the studies. Fertilization is also a common management practice for cultivated pasture, but just 4.3% of the studies reported fertilization effects (Table 1).

2.2. Survey data

Following the model presented by Conant et al. (2001), we compiled data from the published English and Chinese language literatures on the influence on soil carbon of grassland management practices, and of land use conversions from FGG to other uses and from other uses to grassland or cultivated pasture. As with Conant et al. (2001), we analyzed only studies that had been designed so that management was the primary factor influencing soil carbon. Literature searches were performed using the Chinese

Table 1
Number of studies and data points summarized by type of management change implemented.

Treatment[a]	Studies	Data points	Percentage of total
Exclosure from grazing	45	205	27.8 (30.6)
Grazing	15	69	9.2 (10.3)
Conversion: FGG to cultivated pasture	15	53	9.2 (7.9)
Conversion: FGG to cropland	19	103	11.7 (15.4)
Conversion: FGG to shrubland	3	6	1.9 (0.9)
Conversion: cropland to abandoned field	18	63	11.1 (9.4)
Conversion: cropland to cultivated pasture	21	67	13.0 (10.0)
Conversion: cropland to shrubland	4	13	2.5 (1.9)
Conversion: bare sand to vegetation	10	54	6.2 (8.0)
Fertilization	7	22	4.3 (3.3)
Burning	2	9	1.2 (1.3)
Mowing	3	5	1.9 (1.0)
Total	162	669	100.0 (100.0)

[a] FGG denotes freely grazing grassland.

Journal paper database with keywords relating to grasslands, pasture, or grassland management, restoration of degraded grassland or sand dunes, burning, mowing, soil organic matter (SOM) or soil carbon. More than 200 articles in Chinese and English were evaluated, and 133 articles (of which less than half were in English) were selected as containing suitable data comparing soil carbon for different management practices.

The management practices and land uses identified and analyzed included grazing management (mostly grazing intensity, but a small number of studies of rotational and seasonally controlled grazing), exclosure of grassland from grazing, mowing, burning, and conversions from FGG to cultivated pasture, shrubland or cropland, and from cropland to FGG, cultivated pasture or shrubland, and establishment of vegetation on bare sand dunes (Supporting Information and Table 1). If more than one management practice was evaluated within an article, each was compared with an explicitly specified control plot by author/s of source paper. In most cases the control plot was one or several fenced exclosures of different durations (years). For example, intensity of grazing management (64.3% of grazing studies) was compared with an ungrazed or lightly grazed site if there was no ungrazed site reported. Exclosure from grazing (i.e. inside a fenced plot from which livestock have been excluded) was compared with 'freely grazed' sites (i.e. outside a fence). Mowing management was compared with free or no grazing. From the 133 articles, 407 experimental treatments were identified.

Many of the papers reported data for multiple depths, permitting a soil carbon by depth comparison with 251 points from 56 of the articles. In addition to soil carbon, information on latitude, longitude, soil texture (i.e. clay, silt and sand content), nitrogen concentration, duration of treatment, mean annual temperature (MAT), mean annual precipitation (MAP), measurement techniques, experimental design, and primary production were recorded when reported in the original paper. Summary information about each data point is available in Supporting Information (Supporting Information and Table 1).

For comparability with the previous reports, when only data on SOM was presented, we also assumed that SOM was 58% C (Nelson and Sommers, 1982; Conant et al., 2001). Other data shortcomings described in Conant et al. (2001) were also encountered when examining the data for China (e.g. reports as percent C by weight with no indication of bulk density) and we followed the same procedure of standardizing both data with and without bulk density measurements by calculating the annual percent change following management change or conversion and the ratio of soil carbon under initial and final management scenarios. This requires the assumption that bulk densities were uniform between comparative sites (Conant et al., 2001).

2.3. Statistical analysis

Simple correlation and regression analyses were performed using SPSS Version 12.0 to evaluate the influence of initial carbon concentration and soil carbon stocks, initial nitrogen concentration and nitrogen content, initial soil texture (percent clay, silt and sand), and MAT, MAP, latitude, longitude, and altitude on soil carbon response variables.

Meta-analysis was conducted on those studies that reported sample size and standard error or standard deviation. Standardized mean difference (SMD) was taken as the measure of the effect size of land use change on soil carbon content. Random-effect and mixed-effect models were adopted for those cases without or with moderators included, respectively. Meta-analysis was conducted using the R (version 2.11.0) package in METAFOR (version 1.1-0), a software that has been widely used in published scientific papers (Viechtbauer, 2010).

Table 2
Summary of environmental variables from the 133 articles used in the analysis.

Variable	Mean	Minimum	Maximum	SE
Latitude	39.2	24.4	49.0	4.1
Longitude	110.3	83.2	126.4	8.0
Altitude (m)	1756.8	150.0	4100.0	1111.7
Mean annual temperature (°C)	3.8	−4.8	18.7	4.1
Mean annual precipitation (mm)	423.5	79.0	1664.0	166.1
Soil depth (cm)	28.7	1.0	200.0	27.3
Duration (yr)	14.2	1.0	100.0	13.8

2.4. Quantities of the studies surveyed

The synthesis covers studies from 15 out of China's 31 provincial-level administrative units (Fig. 1). About 95% of the studies were from temperate steppe (i.e. Inner Mongolia, Xijiang, Gansu, Ningxia, Shaanxi, Shanxi, Hebei, Jilin, Liaoning) and alpine and subalpine meadow (i.e. Qinghai, Gansu and Sichuan) (Table 2). Often many treatments or studies with different soil depths were compared in the same article, resulting in 162 studies with 669 data points from 133 separate articles (Table 1). Many studies (53%) used experimental treatments to control conditions, but a large proportion (40.3%) evaluated using substitution of space for time approaches.

The depths of soil samples ranged from 1 to 200 cm. Soil samples were collected from only one depth in 62.4% of the studies. The treatment duration ranged from 1 to 100 yr, and treatment duration was ≤20 yr for 74.5% of the studies (Table 2). Most of the treatment durations >20 yr were conversions from cropland to cultivated pasture or grassland, or from grazing to exclosure.

3. Results

3.1. Changes in soil carbon in response to land use and management practices

Grazing decreased soil carbon concentration, especially when initial soil carbon concentration was higher than 2% (Fig. 2A). Compared with no or light grazing, average soil carbon concentration decreased in response to heavy grazing by 30.0%, and moderate grazing by 17.0% Fig. 2A). For the 6 studies reporting C content (24 data points), it decreased on average by 16.2% in response to heavy grazing and by 8.2% in response to moderate grazing (Fig. 3A). Bulk density tended to increase by 6.2% in response to heavy grazing compared with no or light grazing.

For conversion of freely graze grassland (FGG) to cultivated pasture, cropland or shrubland, the soil carbon concentration results were mixed. Of 50 data points on conversion from FGG to cultivated pasture, 37 data points showed an increase in carbon concentration (Fig. 2B). The average increase was small at 4.9%. By contrast, among the 104 data points on conversion from FGG to cropland, 89 showed decrease, with average carbon concentration decreasing by 35.7% after FGG was converted to cropland (Fig. 2B). Six out of seven data points on conversion from FGG to shrubland resulted in a decrease in average soil carbon concentration, decreasing on average by 59.0% (Fig. 2B).

Similar to the results of carbon concentrations, soil carbon content increased when FGG was converted to cultivated pasture and decreased when FGG was converted to cropland or shrubland. 27 out of 37 data points on conversion of FGG to cultivated pasture showed increased soil carbon content (Fig. 3B), with an average increase of 11.0%. 35 out of 43 data points on conversion of FGG to cropland showed a decrease (Fig. 3B), with an average decrease in soil carbon content of 36.0%. There were only 3 data points on conversion from FGG to shrubland, all of which showed a decrease, by 58.4% on average.

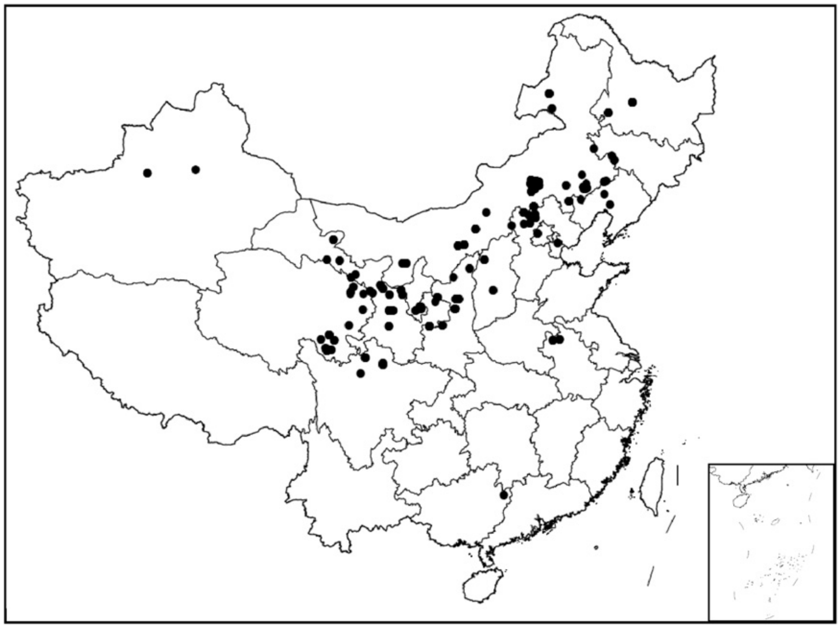

Fig. 1. National distribution of study sites.

For burning, 7 out of 9 data points from 2 articles showed that burning decreased soil carbon concentration by 24% (Fig. 2C). Mowing increased soil carbon concentration by 103% compared to free grazing, but decreased soil carbon concentration by 8% compared to no-grazing (Fig. 2C).

Among the 133 articles synthesized, 27 studies with 190 data points were suitable for the conduct of meta-analysis because they reported both sample size and either standard error or standard deviation. Of the 190 values of effect size (ES) measured by standard mean difference, 63.2%, 34.7% and 2.1% were positive, negative and zero, respectively. In the test of ES with a random-effects model without moderators, the p-value was 0.0032. In the test of ES with a mixed-effects model with duration (years) and soil depth (cm) as moderators, the p-value of ES was 0.1171. Duration had a far from significant effect on ES ($p = 0.5839$) while soil depth had an apparently significant but negative effect on ES ($p = 0.0744$).

3.2. Changes in soil carbon with improved management

The management changes synthesized here covered the most common grassland management practices in northern China. Several management practices are oriented to restoration of degraded grasslands. Exclosures are widely implemented for long periods to increase plant coverage. Some croplands have been reverted back into grassland or shrubland to protect soil from wind erosion. This is commonly done either by simply abandoning cropland to allow vegetation grow, or by planting abandoned cropland with legumes or grasses. In practice, fertilization is restricted to cultivated pasture, but 3 papers were synthesized reporting the results of fertilization on FGG as a viable procedure for restoring degraded grasslands. Establishing vegetation on bare sand dunes has been widely adopted to protect infrastructure such as railways or highways from being buried by sand flows. This is mostly done by planting grasses or shrubs in gridded patterns on bare sand dunes. Together these management practices are referred to as 'improved management practices' and 'restoration-oriented land use conversions'.

Soil carbon increased following adoption of improved management and restoration oriented land use conversions for 86.2% of those data points that reported changes in C concentration, and for 84.8% of data points reporting C content (Figs. 4 and 5). Increased soil carbon concentration was reported in response to exclosure for 169 out of 205 data points, while 32 out of 205 data points showed a decrease (Fig. 4A). Converting cropland to grassland, cultivated pasture or shrubland increased soil carbon concentration in 115 out of 143 data points, but decreased C concentration in 22 data points (Fig. 4B). Fertilization (Fig. 4C) and establishing vegetation on bare sand dune (Fig. 4D) increased soil carbon concentration. For those studies that documented soil carbon content, exclosure, conversion of cropland to grassland, cultivated pasture or shrubland, and fertilization increased C content in 87.5%, 80.4% and 88.9% of data points, respectively (Fig. 5).

The average change for concentration data was an increase of 116.0% and the average for C content data was a 68.0% increase. For studies that showed an increase in soil carbon, soil carbon concentration increased on average by 144.3% (20–582%) and soil carbon content increased by an average of 138.2% (8–356%). The 6% of the data points with the smallest increase averaged 20% for soil carbon concentration, and these were responses to fertilization. The average increase for the 16% of data points with the largest increase was 582%, which were due to establishing vegetation on bare sand dunes. Although this rate of increase is extremely high, it must be noted that the initial C concentrations on bare sand dunes were very low. For C concentration data, exclosure from grazing (46% of data points) and conversions of cropland to grassland, cultivated pasture or shrubland (32% of data points) increased on average 55% and 52%, respectively. Among land use conversions, conversion from cropland to cultivated pasture gave the smallest increase (26%), and conversion of cropland to shrubland gave the largest increase (111%). Natural restoration of formerly cultivated croplands showed a 62% increase in soil carbon concentration. For those studies with a net loss of carbon after adoption of improved management, soil carbon concentration decreased on average by 14% (range of 5–23%). For studies reporting soil carbon content data, exclosure from grazing (52% of the data points reporting carbon content) caused the smallest increase (on average 34%), while establishing vegetation on bare sand dunes (4% of the data points) resulted in the largest increase (on average 356%).

Restoration-oriented land use conversions (44% of data points) increased soil carbon content by an average of 104%. Soil car-

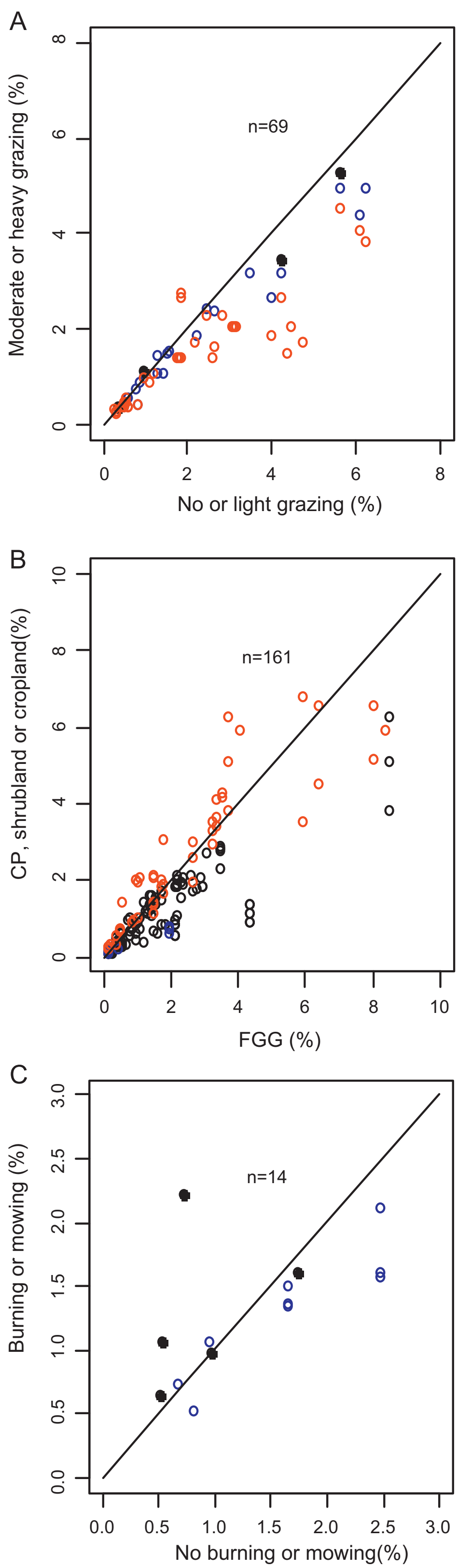

Fig. 2. (A) Soil carbon concentration for no-grazing or light grazing vs. moderate or heavy grazing; black filled points denote no-grazing vs. light grazing; blue unfilled points denote no or light grazing vs. moderate grazing; red unfilled points denote no or light grazing vs. heavy grazing. (B) FGG vs. conversion of FGG to cultivated pasture (red) or shrubland (blue) or cropland (black). (C) Free grazing or no-grazing vs. mowing (black filled) and burning (blue unfilled). Soil carbon concentration increased for points above the line and decreased for points below the line. All data are in percent carbon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

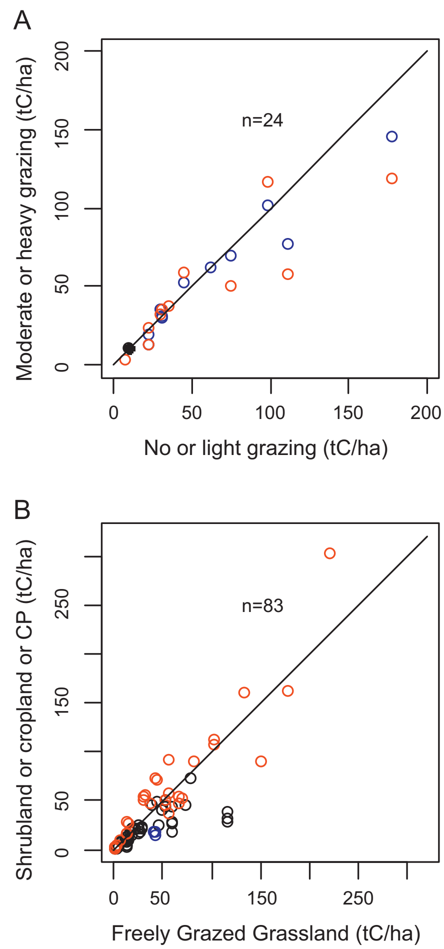

Fig. 3. (A) Soil carbon content for no-grazing or light grazing vs. moderate (blue unfilled) or heavy grazing (red unfilled); black filled point denotes no-grazing vs. light grazing. (B) FGG vs. conversion to shrubland (blue unfilled), cropland (black unfilled) or cultivated pasture (red unfilled); CP denotes cultivated pasture. Soil carbon content increased for points above the line and decreased for points below the line. All data are in t C ha^{-1}. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bon content increased by only 8% for conversion of cropland to cultivated pasture (16% of data points), but by 62% for natural restoration of abandoned cropland (25% of data points), and by up to 130% for conversion of cropland to shrubland (2% of data points). Conversion from cropland to shrubland generally took place in arid areas with sandy soils, where the initial soil carbon was very low (Fig. 4B). The finding that soil carbon was more significantly increased by natural restoration than by conversion to cultivated pasture might be explained by the difference in duration of the two processes. In the studies synthesized, the abandoned croplands have been uncultivated for an average of 16.7 yr, while the duration of cultivated pastures converted from croplands averaged only 4.0 yr.

3.3. Annual change in soil carbon

Generally, grazing resulted in an annual decrease of soil carbon concentration by 4.4% (Table 3), and average annual carbon content decrease of 2.3% (Table 4). However, moderate grazing caused an annual increase of 1.1% in soil C concentration and 1.6% in soil carbon content. Average soil carbon concentration and carbon content decreased by 2.5% and 2.8% per annum for the conversion of FGG to cropland or shrubland, but increased by 6.4% and 7% per annum for conversion to cultivated pasture (Tables 3 and 4).

Table 3
Summary of mean annual change (%) of soil carbon concentration for pooled data from studies with different soil depths and durations under different treatments.

Treatment[a]	Data points	Mean	Maximum	Minimum	SE
Grazing	69	−4.4	16.0	−19.4	0.8
Conversion: FGG to cultivated pasture	53	6.4	41.7	−26.5	1.7
Conversion: FGG to cropland	103	−2.5	10.0	−22.6	1.2
Conversion: FGG to shrubland	6	−2.8	2.6	−9.8	1.6
Burning	9	−13.2	11.5	−35.1	5.4
Mowing	5	0.3	0.1	0.7	0.1
Exclosure from grazing	205	6.3	123.2	−15.7	1.0
Conversion: cropland to abandoned field	63	5.4	57.5	−3.8	1.2
Conversion: cropland to cultivated pasture	67	6.4	42.7	−26.0	1.4
Conversion: cropland to shrubland	13	11.3	96.0	−2.3	7.1
Conversion: bare sand to vegetation	54	42.8	183.3	−3.2	4.8
Fertilization	22	5.0	21.6	−4.6	1.3

[a] FGG denotes freely grazed grassland.

Burning decreased carbon concentration by 13.2% per annum, and compared with free grazing mowing increased carbon concentration and carbon content by 0.3% and 28.6%, respectively, per annum (Tables 3 and 4). Most improved management practices and restoration-oriented land use conversions increased soil carbon concentration and content on average (Tables 3 and 4). The highest average annual percentage increases in soil carbon concentration and soil carbon content were reported for establishing vegetation on bare sand dunes and conversion of cropland to shrubland (Tables 3 and 4).

Decreases in soil carbon concentration mainly happened in the first several years for heavy grazing and for conversion of FGG to cropland, after which annual rates of decrease declined, showing almost no change after 30-yr (Fig. 6A and B). Year explained >50% of the variation in soil carbon concentration and content with logarithmic functions (Fig. 6A and B). Similarly, after adoption of improved management practices, increases in soil carbon concentration and content occurred mostly in the first several years, and almost ceased after 50-yr of implementing improved management (Figs. 7 and 8). The net annual loss or sequestration of soil carbon was mostly within the surface layer (0–30 cm), and especially in the 0–10 cm layer (Figs. 6 and 8C). Sample depth explained about 25–34% of the variation in soil carbon concentration and content with logarithmic functions (Figs. 6 and 8C).

Exclosure resulted in an average carbon sequestration rate of 80.1 g C m^{-2} yr^{-1} for 0–20 cm soil and 130.4 g C m^{-2} yr^{-1} for 0–40 cm soil over a 3–28 yr period (Table 5). Conversion of cropland to grassland by natural restoration on abandoned fields sequestered on average 53.7 g C m^{-2} yr^{-1} for 0–5 cm soil and 128.0 g C m^{-2} yr^{-1} for 0–30 cm soil over 5–60 years. For the conversion of cropland to perennial legume pastures, the average carbon sequestration rate was 56.5 g C m^{-2} yr^{-1} for 0–20 cm soil and 156.3 g C m^{-2} yr^{-1} for 0–200 cm soil over 2–4 years (Table 5). These results indicate that the potential carbon sequestration is greater in the surface soils than in the subsoil, and that improved management can greatly increase soil carbon stocks.

3.4. Factors controlling the annual change of carbon concentration in soils

Initial soil texture and initial chemical components in soils significantly affected the annual change of carbon concentration in soils (Table 6). Negative correlations between initial carbon and/or nitrogen concentrations in soils and the annual change of soil carbon concentration were found for the conversion of cropland to cultivated pasture, fertilization and establishment of vegetation on bare sand dunes (Table 6). This indicates that soil carbon sequestration rates may be greater when the initial soil carbon and/or nitrogen concentrations are lower. Grazing and conversion of cropland to cultivated pasture caused lower annual average change (i.e. lower annual decrease) in soil carbon concentration when initial soil carbon and/or nitrogen concentrations were higher. Initial soil texture (i.e. initial soil clay, silt and sand content) was the main factor controlling the rate of soil carbon decrease for the conversion of FGG to cropland (Table 6). Initial soil nitrogen concentration is a key factor controlling soil carbon sequestration rates. A relationship between annual variations in soil carbon and nitrogen was identified (Fig. 9), and annual variation in soil nitrogen concentration explained 26% of the annual variation in soil carbon concentration.

4. Discussion

4.1. Effects of management on changes in soil carbon stocks

Grasslands in China are distributed mostly in the northern temperate region and on the Tibetan Plateau, which together account for about 78% of the total grassland area in China (Chen and Wang, 2000). Data points synthesized here in general gave a good geographical coverage of northern China, although western parts of the country remain under-represented (Fig. 1). The main management measures historically and currently common in China's grassland areas were covered in this synthesis, though some common management practices were under-represented (Table 1). Initial carbon

Table 4
Summary of mean annual change (%) of soil carbon stocks for pooled data from studies with different soil depths and durations under different treatments.

Treatment[a]	Number	Mean	Maximum	Minimum	SE
Grazing	24	−2.3	4.0	−16.5	1.1
Conversion: FGG to cultivated pasture	37	7.0	42.1	−19.8	2.0
Conversion: FGG to cropland	43	−2.6	1.7	−22.1	0.8
Conversion: FGG to shrubland	3	−2.8	−2.1	−3.7	0.5
Mowing	4	28.6	56.3	7.9	10.3
Exclosure from grazing	104	4.4	44.8	−4.9	0.8
Conversion: cultivation to abandoned field	57	5.9	39.1	−9.5	1.0
Conversion: cultivation to cultivated pasture	36	2.4	32.3	−14.9	1.4
Conversion: cultivation to shrubland	4	7.4	10.4	5.7	1.1
Conversion: bare sand to vegetation	9	12.5	15.5	−0.8	2.7

[a] FGG denotes freely grazed grassland.

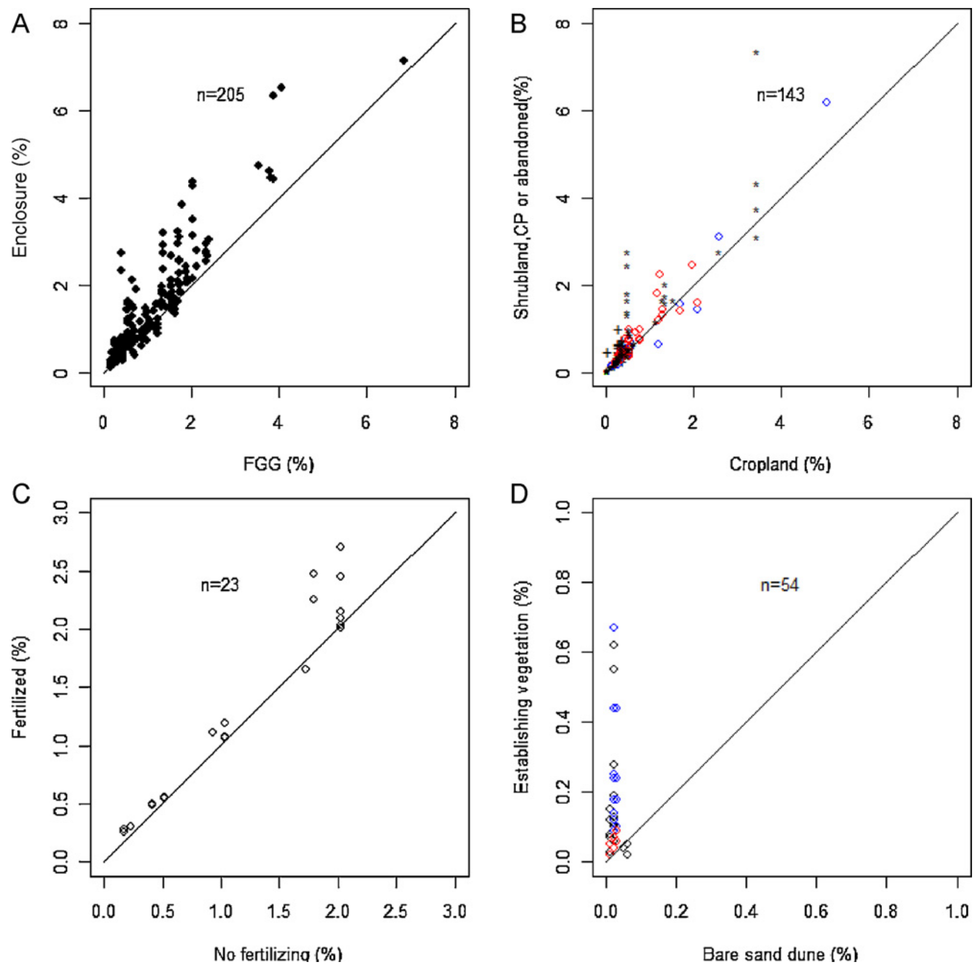

Fig. 4. (A) Soil carbon concentration for grazing vs. exclosure from grazing. (B) Cropland vs. conversion to shrubland (black cross), to cultivated pasture planted grasses (blue unfilled circle) or legumes (red unfilled circle) or abandoned (black star); CP denotes cultivated pasture. (C) No fertilization vs. fertilization. (D) Bare sand dune vs. establishing vegetation with grasses (blue unfilled) or with legumes (red unfilled). Soil carbon concentration increased for points above the line and decreased for points below the line. All data are in percent carbon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

concentration for 20 cm soil depth was greater before grazing, burning and converting FGG to cropland compared to initial carbon concentrations for exclosure of grassland from grazing and conversion of cropland to abandoned fields (i.e. natural regeneration) or cultivated pasture (Table 7). Since initial soil carbon for these latter three treatments can be taken to represent degraded grasslands, this confirms that inappropriate land management causes soil carbon losses.

Grazing may have either positive or negative effects on grassland soil attributes (Milchunas and Lauenroth, 1993; Conant et al., 2001). The effects of hoof action under grazing management have been found to affect near-surface soil physical conditions (Donkor et al., 2002) and grazing intensity and urine and dung deposition may affect potential nutrient storage and cycling (Russelle, 1992; Carran and Theobald, 2000). Conant et al. (2001) found that grazing tended to increase soil carbon most in warm dry regions, especially those with high potential evapotranspiration. The average annual rate of soil carbon content increase was 7.7% for studies with a long history of grazing (Conant et al., 2001). Some studies have reported that long-term heavy grazing increased SOC and total nitrogen content in surface soils compared with less intense grazing management (Frank et al., 1995; Schuman et al., 1999;

Table 5
Mean annual carbon sequestration rates (g C m^{-2} yr^{-1}) of different treatments within 20 and 40 cm soil depths.

Treatment	Soil depth (cm)	Number	Mean (range)	Years	SE	Reference
Exclosure from grazing	0–20	13	80.1 (23–330)	3–28	22.0	Wang et al. (2005), Wei et al. (2005), Wang et al. (2006), Wu et al. (2008), Yan and Tang (2008), Shan et al. (2009)
	0–40	10	130.4 (63–269)	3–28	21.3	
Conversion of cropland to abandoned field	0–5	9	53.7 (34–96)	5–60	7.2	Liu et al. (2006), Wang et al. (2006), Li et al. (2007), Wang and Zhang (2007), Zhao et al. (2008)
	0–30	7	128.0 (60–204)	5–60	18.7	
Conversion of cropland to cultivated pasture	0–20	4	56.5 (40–73)	2	8.7	Zhang et al. (2008)
	0–40	21	156.3 (41–302)	4	18.3	Su (2007)

Table 6
Relationships between mean annual change of soil carbon concentration (%) and initial soil concentrations of carbon and nitrogen and soil texture.

Variable	All	CCP	Fertilizer	Grazing	EVSD	CFGGC	FGGCP
Initial soil carbon concentration	−0.286** (n = 669)	ns	−0.699** (n = 23)	−0.503** (n = 69)	−0.369** (n = 73)	ns	−0.416** (n = 51)
Initial soil nitrogen concentration	−0.301** (n = 319)	−0.456* (n = 26)	ns	−0.526** (n = 32)	−0.457** (n = 32)	ns	ns
Initial clay content	ns	ns	ns	ns	0.570* (n = 18)	0.563** (n = 21)	ns
Initial silt content	−0.337** (n = 59)	ns	ns	ns	ns	0.572** (n = 21)	ns
Initial sandy content	ns	ns	ns	ns	ns	−0.575** (n = 21)	ns

ns: non-significant at $\alpha = 0.05$. CCP: conversion to cultivated pasture from cropland; EVSD: establishing vegetation on bare sand dunes; CFGGC: conversion to cropland from freely grazed grassland; FGGCP: conversion to cultivated pasture from freely grazed grassland.
* Statistically significant at $\alpha = 0.05$.
** Statistically significant at $\alpha = 0.01$

Reeder et al., 2004; Liebig et al., 2006). However, Shi et al. (2009) found that all grazing intensities on average decrease grassland soil carbon content in China. Long-term overgrazing in particular usually causes declines in net primary production (Milchunas and Lauenroth, 1993; Wang et al., 2003) which decreases the carbon input to soils. We also found that grazing mostly decreased SOC, but that under certain conditions moderate grazing increased SOC in the Inner Mongolian steppe (Wang et al., 1998; Wei et al., 2005; Li et al., 2008) and alpine meadow (Gao et al., 2007). In addition, long-term exclusion of grazing livestock may increase the risk of wild fire due to litter accumulation, which may increase carbon emissions from the ecosystem (Bird et al., 2000; Ward et al., 2007).

Land use conversions may also cause significant carbon losses. Large areas of steppe in Inner Mongolia were converted into cropland during the 1960s–1990s. Consistent with Wu et al. (2003) and Xie et al. (2007), the papers synthesized here suggest that the conversion of FGG to cropland causes about 36% SOC loss in surface soils (0–20 cm). Semi-arid regions typically have limited bio-productivity, in addition to which agricultural management practices may further promote carbon losses and limit inputs to soils. In Inner Mongolia, a significant proportion of agricultural residues is removed from soils and used as domestic fuel and animal fodder (Liu and Mu, 1988), so organic matter input to soils is depressed. Furthermore, mineralization of organic matter is intensified by tillage which decreases the amount of physical protection for the decomposition of organic matter (Post and Kwon, 2000) and soil erosion is accelerated by tillage which increases soil exposure to wind and rain thus promoting SOC loss (Lal, 1995; Wang et al., 2006). Long-term cultivation of previously untilled grasslands has been documented to cause more than 50% SOC loss (Post and Kwon, 2000; Guo and Gifford, 2002). Because tillage, in addition to mixing and stirring soil, breaks up aggregates and exposes mineral surfaces otherwise inaccessible to decomposers (Post and Kwon, 2000), this results in a reduction in the amounts of intra-aggregate light fraction of organic carbon and mineralized SOC. By contrast, conversion of FGG to cultivated pasture mostly increases SOC because perennial pasture increases bio-productivity compared with degraded grasslands. This is particularly the case for degraded grasslands with a lower baseline SOC, such as 'black beach' in alpine meadow regions (Wang et al., 2005; Han et al., 2007). No-till management also protects soil from erosion and decreases decomposition of SOM (Post and Kwon, 2000). Additional management, such as perennial legumes like alfalfa which fixes nitrogen from the atmosphere and thus mitigates nitrogen-limitation for bio-production, and fertilization using livestock manure, promote increases in SOC (Conant et al., 2001).

Total soil carbon storage in China's grasslands has been estimated to be 41.03 Pg C, of which ca. 54% is in alpine regions and ca. 31% in temperate regions, together accounting for ca. 85% of total grassland soil carbon in China (Ni, 2002). Li (1997) reported that towards the end of the last century about 50% of northern China's grasslands were degraded to different degrees between the 1960s and 1990s, of which ca. 43% was moderately or heavily degraded. Based on the balance between the decreased soil carbon due to heavy grazing (29.3%) and the increased soil carbon due to moderate grazing (12.8%), and assuming 50% of the total degraded area was heavily degraded, we estimate that the net loss of SOC due to grazing was approximately 1.24 Pg carbon over this period. During the same period, about 6.67×10^6 ha of FGG, equivalent to 1.67% of northern China's FGG, was converted into cropland (Li, 1997). Based on a 36% decrease in soil carbon content due to the conversion of FGG to cropland, this caused a loss of approximately 0.25 Pg C from the 1960s to 1990s. Therefore, we estimate that in total about 1.49 Pg C was lost due to overgrazing and the conversion of FGG to cropland, which compares well with previous estimates of 1.50 Pg C

Table 7
Mean initial soil carbon concentration (%) for pooled data from studies with different treatments within 20 cm soil depth.

Treatment[a]	Number	Mean	Maximum	Minimum	SE
Grazing	43	2.74	9.06	0.30	0.4
Conversion: FGG to cultivated pasture	34	2.74	8.39	0.17	0.4
Conversion: FGG to cropland	64	2.31	8.50	0.19	0.2
Conversion: FGG to shrubland	3	1.94	1.94	1.94	0.0
Burning	6	2.07	2.48	1.66	0.2
Mowing	3	1.00	1.74	0.54	0.4
Exclosure from grazing	107	1.13	4.04	0.13	0.1
Conversion: cropland to abandoned field	9	0.41	1.34	0.03	0.1
Conversion: cropland to cultivated pasture	64	0.69	5.04	0.10	0.1
Conversion: cropland to shrubland	12	0.24	0.35	0.10	0.0
Conversion: bare sand to vegetation	39	0.02	0.05	0.01	0.0
Fertilization	18	1.12	2.02	0.17	0.2

[a] FGG denotes freely grazed grassland.

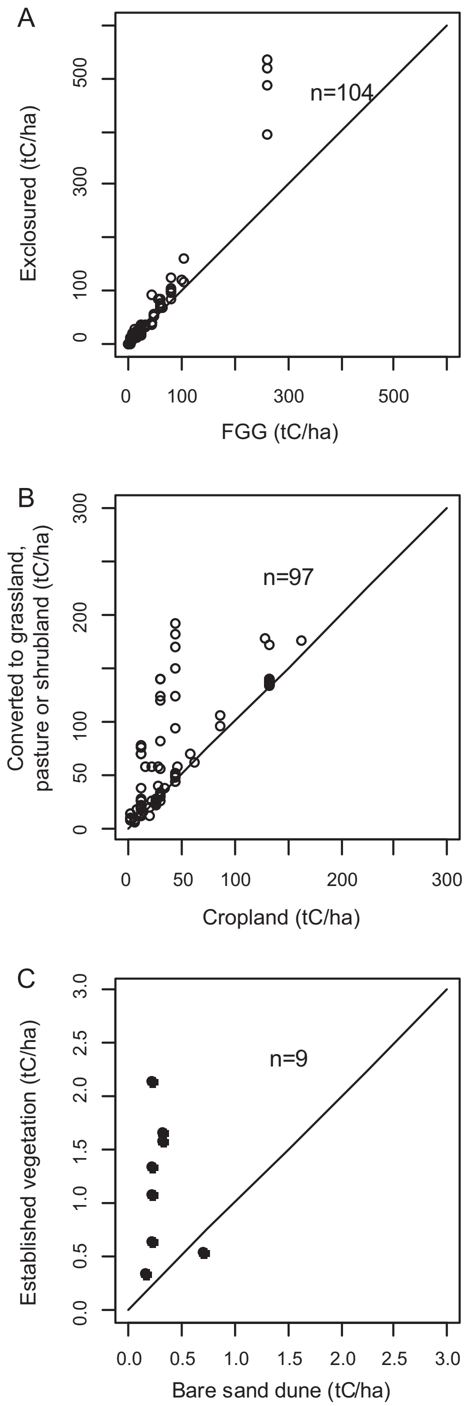

Fig. 5. Soil carbon content for grazing vs. exclosure from grazing (A); cropland vs. conversion to grassland or cultivated pasture or shrubland (B); and bare sand dune vs. establishing vegetation (C). Soil carbon content increased for points above the line and decreased for points below the line. All data are in $t\,C\,ha^{-1}$.

reported by (Xie et al., 2007) using data from the Second State Soil Survey of China completed in the early 1980s.

4.2. Soil carbon sequestration rates and the potential of grasslands to mitigate atmospheric carbon in China

The large and relatively rapid changes in SOC due to inappropriate land management practices indicate that there is considerable potential to enhance soil carbon sequestration through improved management activities that reverse the effects of grazing and

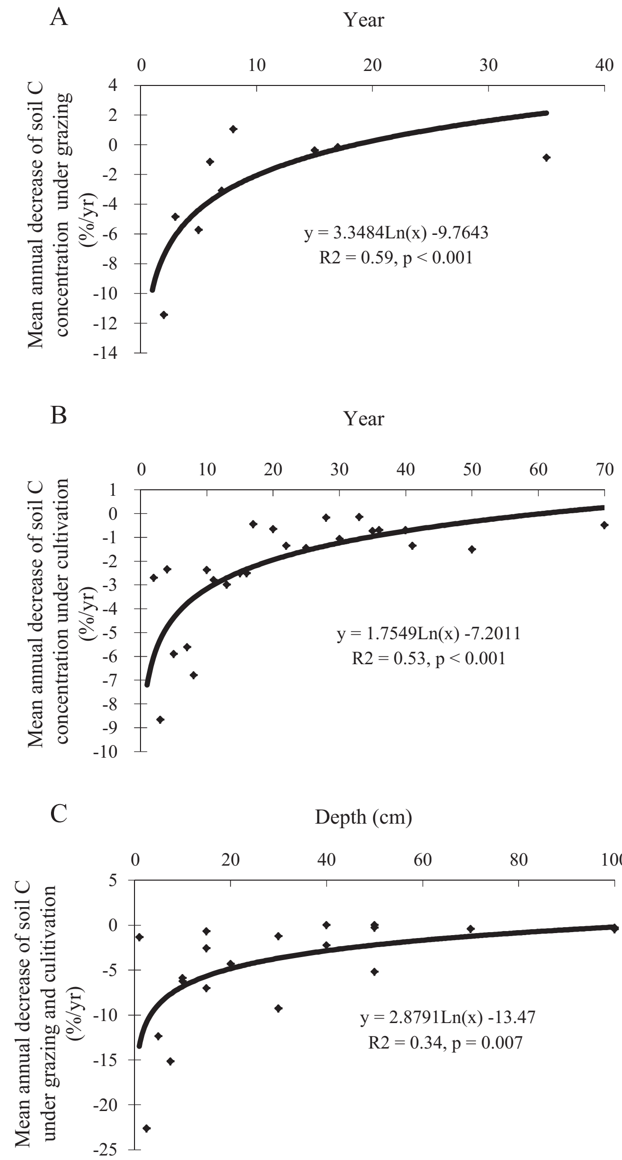

Fig. 6. Mean annual decrease of soil carbon concentration with year under grazing (A) and cultivation (B), and with soil depth under grazing and cultivation (C).

cultivation on SOC pools (Post and Kwon, 2000; Conant et al., 2001). Our results for improved grazing and the conversion of cropland to grassland or cultivated pasture (i.e. sequestration of 60–130 $g\,C\,m^{-2}\,yr^{-1}$) compare well with the reports by Conant et al. (2001) (35–101 $g\,C\,m^{-2}\,yr^{-1}$) and Post and Kwon (2000) (3–110 $g\,C\,m^{-2}\,yr^{-1}$). Conant et al. (2001) found that the conversion of cropland to cultivated pasture has a greater potential carbon sequestration rate (101 $g\,C\,m^{-2}\,yr^{-1}$) than improved grazing (35 $g\,C\,m^{-2}\,yr^{-1}$). However, we found that both grazing exclusion (0–40 cm) and the conversion of cropland to abandoned fields (0–30 cm) had almost the same potential carbon sequestration rate (ca. 130 $g\,C\,m^{-2}\,yr^{-1}$), and that this is similar to the sequestration rate of the conversion of cropland to cultivated pasture. Our result for grazing exclusion (130.4 $g\,C\,m^{-2}\,yr^{-1}$, 0–40 cm) is slightly higher than the average for set-asides under the US Conservation Reserve Program (CRP) (120 $g\,C\,m^{-2}\,yr^{-1}$, 0–30 cm) (Ogle et al., 2003). Since large changes were found to be more likely for soils with low initial carbon and less likely for soils with initial high carbon stocks, this difference is attributed to prior soil carbon depletion following overgrazing and cultivation of grasslands

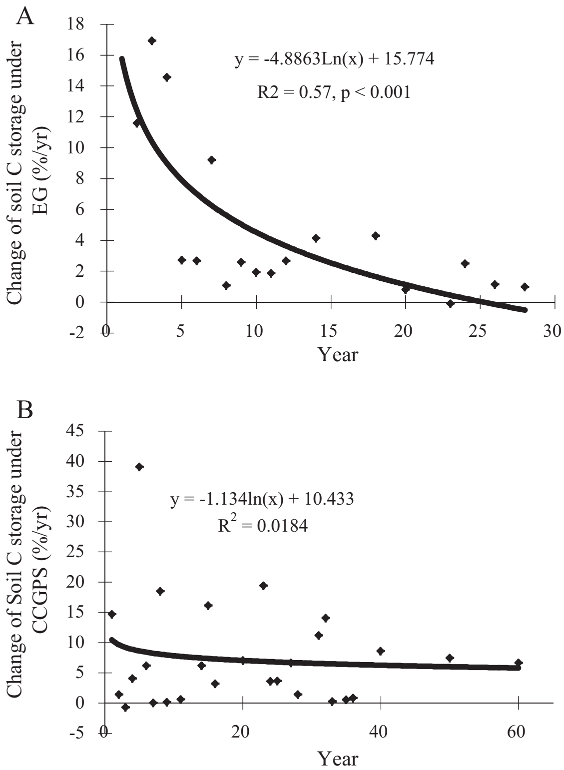

Fig. 7. Mean annual increase of soil carbon concentration with year under exclosure from grazing (EG) (A) and conversion of cropland to grassland, cultivated pasture or shrubland (CCGPS) (B).

in China (Table 7). Shi et al. (2009) reported that carbon sequestration rates in response to exclusion of grazing livestock differed among grassland vegetation types (28, 37, 68 and 223 g C m^{-2} yr^{-1} for temperate desert steppe, typical steppe, temperate meadow and alpine meadow, respectively, averaging 89 g C m^{-2} yr^{-1}). The maximum value (330 g C m^{-2} yr^{-1}) was found in 'black beach' (a type of extremely degraded land in alpine meadow areas) for 0–20 cm soils after 6-yr of grazing exclusion (Wang et al., 2005).

Although some estimates have been made (Lal, 2002; Guo et al., 2008), publicly available data on management activities in grassland areas of China are currently insufficient to enable a precise estimate of the amount of carbon sequestered by adoption of improvement management practices at the national scale, or even for the northern temperate region, in recent years. According to the Ministry of Agriculture's National Grassland Conservation, Establishment and Utilization Master plan (Agricultural Planning Office Document No. 11, 2007), in addition to other improved management measures (e.g. 60% of total national grassland area being put under moderate and rotational grazing), the plan proposes to exclude grazing livestock from 150 million ha of China's grasslands and to establish 30 million ha of cultivated pasture by 2020. Based on our results, i.e. a carbon sequestration rate of 130 g C m^{-2} yr^{-1} in 0–40 cm soil for exclusion of livestock, and 156 g C m^{-2} yr^{-1} in 0–40 cm soil for perennial pasture cultivation, achievement of this planned goal would sequester over 0.24 Pg C yr^{-1}, which is equivalent to about 16% of fossil fuel CO_2 emissions in China in 2006 (i.e. 1.5 Pg C yr^{-1}) (Piao et al., 2009). This is a large contribution compared to estimates of 0.025–0.037 Pg C yr^{-1} for the sequestration potential of no-tillage and agricultural residue management in China (Lal, 2002; Yan et al., 2007), and larger than the 0.165 Pg C yr^{-1} potential identified for the technical sequestration potential of afforestation in China (Zhang and Xu, 2003).

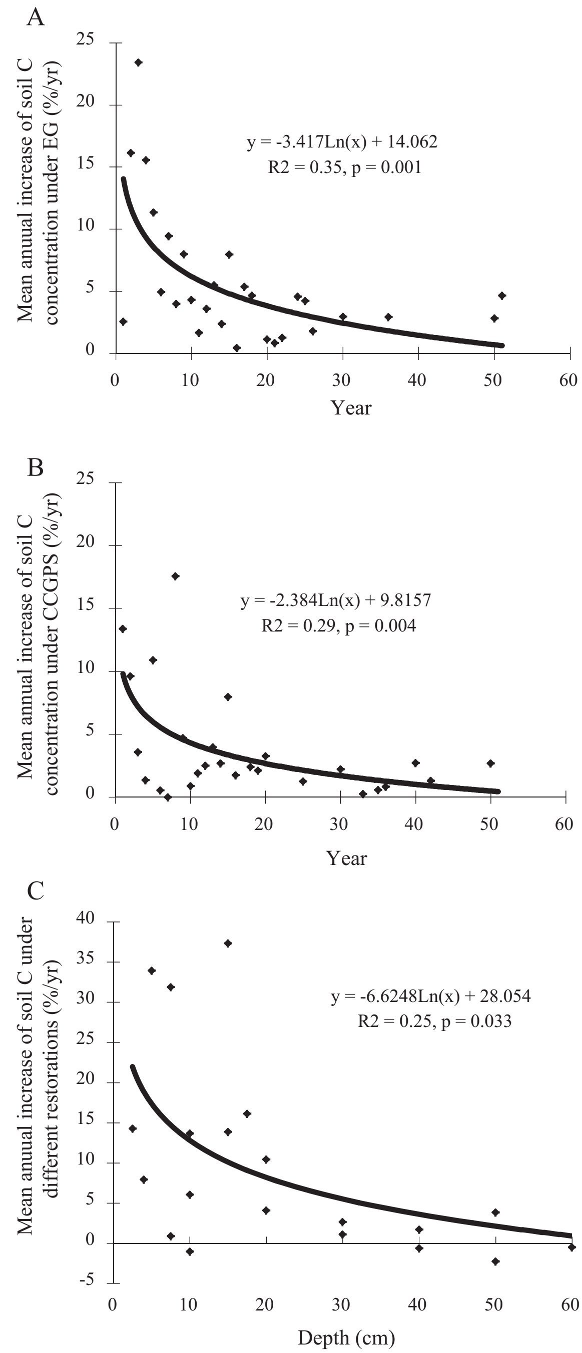

Fig. 8. Mean annual increase of soil carbon content with year under exclosure from grazing (EG) (A), conversion of cropland to grassland, cultivated pasture or shrubland (CCGPS) (B), and with soil depth under the above improved management practices (C).

The estimate of soil sequestration potential from improved grassland management above may underestimate actual carbon sequestration potential since average sample depth of the studies in our synthesis was 28 cm (Table 1). Conant et al. (2001) suggests that 64% of soil C sequestration occurs in the top 50 cm. Furthermore, our estimate has not considered the carbon sequestration potential of other land use conversions and management improvements promoted by current government ecological conservation plans. On the other hand, some measures such as exclusion of grazing livestock may incur high implementation costs (e.g. fencing) and high opportunity costs for herders. Carbon sequestration through cultivating pasture may have a lower trade off with income generation

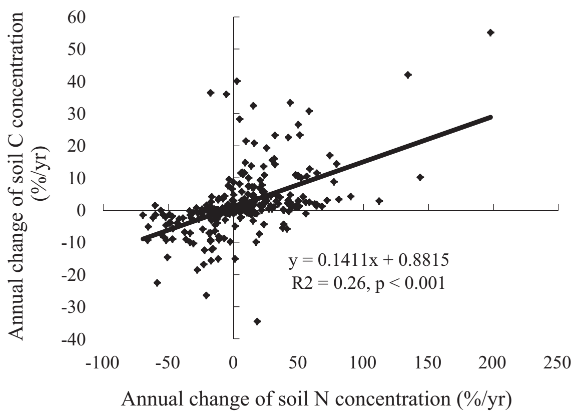

Fig. 9. Relationship between annual change of soil carbon concentration and annual change of soil nitrogen concentration.

for herders, since high quality perennial grasses and legumes may sustain more animals per unit land area than FGG, while cultivation of pasture sequesters more carbon in the soil than either cropland or FGG (Figs. 2B and 5B). Economic studies that might contribute to a better understanding of these tradeoffs in northern China's grasslands are very few.

Terrestrial ecosystems of the Northern Hemisphere have been absorbing atmospheric CO_2 and storing C in both vegetation and soils at a rate of 1–2 Pg C yr^{-1} over the past several decades (Ciais et al., 1995; Fan et al., 1998). The potential for carbon sequestration through ecological conservation and restoration in the grassland regions of China may therefore be conservatively estimated to be at least 5–10% of the carbon accumulation in terrestrial ecosystems of the Northern Hemisphere. Therefore, due to relatively high potential carbon sequestration rates and extensive grassland coverage, improved grassland management may provide a substantial global sink for atmospheric carbon.

5. Conclusions

Grassland SOC can be strongly influenced by changes in land use and management. Great losses of SOC have been observed in China during the last century due to overgrazing, conversion of FGG to cropland, and poor pasture management. Estimates based on national plans for grassland management implemented in China since 2005 indicate that historical SOC losses can potentially be reversed by sequestering atmospheric carbon. However, management activity data is currently insufficient to precisely determine the amount of carbon accumulating at the national scale or even in the northern temperate region of China. Long-term grazing trials have been valuable for understanding soil carbon dynamics in grazing ecosystems. Additional long-term experiments that address SOC dynamics when land is converted from cropland to other land uses under perennial vegetation cover would be valuable in improving our understanding and predictive capacity over short and long time scales (Post and Kwon, 2000). The dearth of data on costs of implementing improved grassland management practices, especially on economic costs to herders in China's pastoral areas, points to a clear need for further interdisciplinary collaboration in research on grassland carbon sequestration.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agee.2011.06.002.

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