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ORIGINAL PAPER

Soil carbon and nitrogen stores and storage potential as affected by land-use in an agro-pastoral ecotone of northern China

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Abstract Equilibrium carbon stock is the result of a balance between inputs and outflows to the pool. Changes in land-use are likely to alter such balance, resulting in different carbon stores under different land-use types in addition to the impacts of global climate change. In an agro-pastoral ecotone of Inner Mongolia, northern China, we investigated productivity and belowground carbon and nitrogen stores under six different types of land-uses, namely free grazing (FG), grazing exclusion (GE), mowing (MW), corn plantation (CP), fallow (FL), and alfalfa pasture (AP), and their impacts on litter and fine roots in semiarid grassland ecosystems. We found that there were great variations in aboveground net primary production (ANPP) across the six land-use types, with CP having markedly high ANPP; the FG had significantly reduced soil organic carbon (SOC) and nitrogen stores (SON) to 100 cm depth compared with all other types of land uses, while very little litter accumulation was found on sites of the FG and CP. The top 20 cm of soils accounted for about 80% of the root carbon and nitrogen, with very little roots being found below 50 cm. About 60% of SOC and SON were stored in the top 30 cm layer. Land-use change altered the inputs of organic matters, thus affecting SOC and SON stores accordingly; the MW and GE sites had 59 and 56% more SOC and 61% more SON than the FG. Our estimation suggested that restoring severely degraded and overgrazed grasslands could potentially increase SOC and SON stores by more than 55%; conversion from the native grasses to alfalfa could potentially double the aboveground biomass production, and further increase SOC and SON stores by more than 20%. Our study demonstrated significant carbon and nitrogen storage potential of the agro-pastoral ecotone of northern China through land-use changes and improved management in the context of mitigating global climate change.

Keywords Agro-pastoral ecotone · Grassland · Land-use · Productivity · SOC · SON

Introduction

The anthropogenic CO_2 emission into the atmosphere plays a vital role in driving the global climate change (Petti et al. 1999; Falkowski et al.

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2000), which in turn affects the productivity of terrestrial ecosystems (Cramer et al. 1999; Nemani 2003). Apart from the burning of fossil fuel, land-use conversion is considered to be having a significant impact on global carbon balance by profoundly altering land cover, biota, and biogeochemical cycles (Houghton et al. 1999). Many studies have demonstrated that changes in land-use are inevitably followed by changes in carbon stores (Houghton et al. 1999; Canadell 2002; Guo and Gifford 2002; Grünzweig et al. 2004). Assessment of the carbon sequestration potential in terrestrial ecosystems to mitigating the global climate change requires development of comprehensive database that contains spatially explicit information on carbon stores under various types of land-use, vegetation, and climatic conditions, as well as quantification of changes in carbon stores associated with land-use conversion.

The historical conversion of land-use from native vegetation to agriculture resulted in sharp declines in soil organic matter (Wilson 1978), such that in the last two centuries, this land-use conversion has been suggested as a significant source of atmospheric CO_2 (Degryze et al. 2004). An estimation by Houghton et al. (1999) indicated that over the period 1700–1990, changes in land-use released about 25 Pg C to the atmosphere, resulting mostly from conversion of forests to agricultural lands and from cultivation of grasslands. However, unlike the burning of fossil fuel, the anthropogenic carbon emission due to land-use change could be reversible through management of lands in favor of sustainable long-term carbon stores.

There exist many land management options, such as afforestation and reforestation, no tillage, reduced grazing intensity and fertilization, and reversed land-use changes. These practices could play an important role in managing the distribution and magnitude of terrestrial carbon sinks with the goal of increasing net uptake (Watson et al. 2000). For example, Conant et al. (2001), in a review of carbon sequestration studies, suggested that improved management could increase soil organic carbon by 51%; moderate grazing could increase soil carbon by an average of 0.19 Mg C ha^{-1} yr^{-1} compared to overgrazing (Derner et al. 1997; Schuman et al. 1999; Conant et al. 2001). Selection and implementation of specific land management options for mitigating atmospheric carbon will ultimately depend on knowledge of carbon sequestration potential under various types of land-use in different ecosystems and biomes, with consideration of the compromised land-use for food and fiber production to support global socio-economic activities.

In the biosphere, terrestrial ecosystems contain almost three times more carbon than the atmosphere (Schimel 1995), and the amount of carbon stored in soil organic matter is twice or three times higher than in living vegetation (Post and Kwon 2000). In grassland ecosystems, less than 10% of organic carbon is stored in the above-ground biomass, while the remainder is in roots and soils (Burke et al. 1997; Parton et al. 1993). Because of the significant capacity for carbon storage, soil has been the focus of increasing efforts in assessing the carbon sequestration associated with land-use change and ecosystem succession (Post et al. 1982; Degryze et al. 2004; Sun et al. 2004). Land-use changes can affect soil carbon stores by altering the input rates of organic matter, changing the decomposability of organic matter inputs that increase the light fraction organic carbon (Cambardella and Elliott 1992), transporting organic matter deeper in the soil either directly by increasing belowground inputs or indirectly by enhancing surface mixing by soil organisms, and enhancing physical protection through either intra-aggregate or organo-mineral complexes (Post and Kwon 2000; Degryze et al. 2004; Richter et al. 1999). The soil carbon and nitrogen stores may increase or decrease depending whether the changed land-use is favorable or prohibitive to the above processes.

Grasslands account for 40% of the national land area in China (Sun 2005). As a dominant form of landscape and an integral component of the Eurasian continent, the grasslands of northern China play important roles in servicing the ecological environment and socio-economics of the region, and in supporting diverse species of plants and animals. However, the expanding human population and changing lifestyle have contributed to widespread grassland conversion into croplands, and to ecosystem degradation in the region due to intensive land-use (Chuluun and Ojima 2002). The economic reform of China beginning in late 1970s has led to rapid expansion of livestock and large-scale grassland conversion to other types of land-use, resulting in various degrees of vegetation degradation and productivity declines on much of the grasslands on the Inner Mongolia Plateau in northern China. Increased carbon stock with improvement in management of grasslands could be anticipated in light of the awareness by the Chinese government and the general public on the significance of grassland ecosystems to serve as carbon sink for mitigating global climate change.

Agro-pastoral ecotone is a transitional land-use from livestock-grazing to farming in between grasslands and cultivated land-use practices, where climatic and soil conditions are categorically marginal for crop production. In such area, land-use types are often diverse and experience more frequent changes. For example, in a typical agro-pastoral ecotone of northern China, the Duolun County of Inner Mongolia, the land-use has subjected to marked changes since the mid-20th century. The Duolun County, which currently administers 3773 km^2 in total land area, is situated to the southeast of the Inner Mongolian grasslands (Fig. 1). Traditional land-uses have been mixture of livestock-grazing and farming. From the late 1950's to the late 1970's, the land-uses of the region were managed under communal systems subject to strict government regulations. During the period 1970–1977, Duolun County experienced rapid expansion of farmlands at the expense of grasslands (Baoyin and Liu 2001). The economic reforms and open policy since 1978 have resulted in private ownership of lands and free practices of land-uses by the locals. Consequently, the area was subjected to intensive farming, grazing, and land-use changes that reduced the areas of forests and grasslands (Liu and Tong 2003; Zhan et al. 2004). The extremely intensified land-uses placed tremendous pressure on the regional grasslands and caused severe land degradation, and to an extreme level, desertification (You et al. 2003; Liu and Tong 2003; Zhan et al. 2004). In recognition of the environmental problems caused by over-exploitation of the lands in this agro-pastoral ecotone, the local government imposed a policy banning livestock-grazing from 2000 onwards, and started working with scientists to explore alternative land-uses that help to sustain both the regional land productivity and economy.

In this study, we investigated the carbon and nitrogen stores under six different land-use types, namely uncontrolled grazing, grazing exclusion, mowing, corn plantation, fallow, and alfalfa pasture, and their impacts on litter and fine roots in the agro-pastoral ecotone of Duolun. The objectives of our study were to: (1) quantify the influence of different land-uses on soil carbon and nitrogen stores; (2) identify the suitable land-use and management options for carbon sequestration and socio-economic activities; and (3) examine the inter-relationship between carbon and nitrogen stores and productivity as influenced by land-uses for the semi-arid

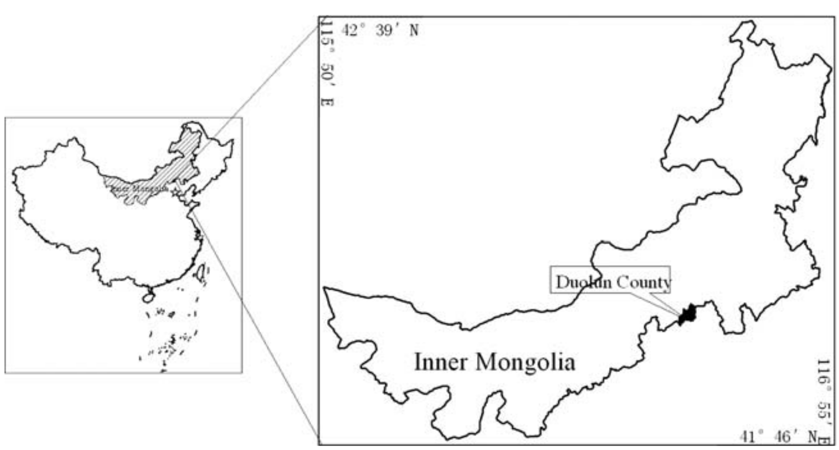

Fig. 1 Location of study area in northern China

grassland ecosystems of northern China. The aims of our study was to provide regionally based, policy-relevant information on the impact of land-use change on carbon stock as called for by the international carbon cycle research communities (GCP 2003), and to identify carbon sequestration potential of the region through improved land management.

Materials and methods

Study site

Our study was conducted in Duolun County of Inner Mongolia (latitude 41°46′–42°39′ N, longitude 115°50′–116°55′ E, elevation 1150–1800 m a.s.l.; Fig. 1), northern China. The long-term mean annual, minimum and maximum air temperatures for the area are 1.6, –18.3, and 18.7°C. Mean annual precipitation is 385 mm (67% fall between June and August). The soil is of chestnut type (*i.e.* Calcic Kastanozems, which is equivalent to Calcic-orthic Aridisol in the US soil taxonomy classification system) in the top 40 cm layer and mixture of sandy soil and gravels below 40 cm. Vegetation of the region consists predominantly of grassland plants such as *Stipa krylovii* Roshev., *Agropyron cristatum* (L.) Gaertner, *Allium bidentatum* Fisch. ex Prokh. & Ikonn.-Gal., and *Artemisia frigida* Willd.

Six study sites were selected based on major land-use types and pre-existing experimental set-ups in the region, which included uncontrolled or free grazing (FG), grazing exclusion (GE), mowing (MW), corn plantation (CP), fallow (FL), and alfalfa pasture (AP). The GE site was established in 2001 by putting fence around 21 ha of previously grazed grassland. The MW site had been subjected to mechanical mowing in late August each year since 2001, with ~80% of aboveground biomass harvested as forage. The FG site had been heavily grazed since 1979, with an estimated amount of 75% aboveground biomass consumed by livestock each year. The FL site was on abandoned agricultural land previously converted from grassland. The CP site was managed without tillage and fertilization, with shoots harvested as green-forage in mid-August. The AP site was established in 2001 on agricultural land; aboveground biomass of alfalfa was harvested as forage in late August each year since 2001.

Measurements

In spring of 2004, we established four 30 × 30 m plots on each representative site of land-uses for measurements of above- and belowground biomass, soil physical properties and chemistry, and carbon and nitrogen concentrations in plant tissues and soils.

In predominantly herbaceous ecosystems such as grasslands and annual crops, the aboveground net primary production (ANPP) may be estimated by equating peak biomass with annual productivity, assuming that aboveground plant tissues would dieback completely each growing season and that aboveground biomass would increase up to a point after which senescence occurs (Sala and Austin 2000). The plants on all our study sites are predominantly herbaceous and meet the above assumptions. Therefore we determined the ANPP by measuring the peak biomass on each plot. As for the shrubs and semi-shrubs, such as *Artemisia frigida* and *Thymus serphyllum*, their ANPP was determined by clip-harvesting subsamples at beginning (late April) and peak growth seasons (mid-August) and taken as the differences between the two harvests. We measured the aboveground biomass by clipping all living tissues in three replicated 1 × 1 m quadrates on each plot between 15th and 25th of August 2004. Biomass sampling on MW plots was made prior to mowing. Our timing of sampling corresponded with the approximate time of peak aboveground biomass in our study area. The clipped plant tissues were oven-dried at 70°C to constant weight (approx. 48 h). The ANPP on the FG site was estimated based on the remaining aboveground biomass and the coefficients of Wang et al. (2003) and McNaughton (1985) for corrections of biomass removal by grazing, which was further calibrated based on measurements of open and enclosed mini-plots in 2005. Litter samples were also collected from within each 1 × 1 m quadrate and oven-dried at 70°C to constant weight.

Root biomass was determined by soil coring method sampling to 100 cm depth in August 2004. We collected soil cores from four random locations within each 1 × 1 m quadrate established for vegetation survey by using an 8-cm diameter soil core sampler and separated into 10 cm layers. The dry mass of roots was determined by over-drying at 70°C to constant weight. Separate soil samples were collected from another three random locations within the same quadrates using a 4-cm diameter soil sampler, and separated into 10 cm layers down to 100 cm depth. All soil samples were air-dried in a ventilation room, and cleared of roots and organic debris before being prepared for chemical analysis. Soil bulk density was also measured within each quadrate for the layers of 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–100 cm.

Chemical analysis was made on plant and soil samples for organic carbon using a modified Mebius method (Nelson and Sommers 1982). Briefly, 0.5 g soil or 0.1 g plant samples were digested with 5 ml of 1 N $K_2Cr_2O_7$ and 10 ml of concentrated H_2SO_4 at 150°C for 30 min, followed by titration of the digests with standardized $FeSO_4$. Total plant and soil nitrogen were measured using the Kjeldahl digestion procedure (Gallaher et al. 1976) with NH_4-N analyzed colorimetrically by the alkali method with a Tector Kjeltec System 1026 Distilling unit. The residue NH_4–N was titrated with standardized H_2SO_4. Total nitrogen was calculated as the difference between the Kjeldahl-N and the residual NH_4–N.

We calculated the soil organic carbon density (SOCD) and total nitrogen density (STND) on a ground area basis as follows:

$$\text{SOCD} = \sum D_i \times P_i \times \text{OM}_i \times S$$
$$\text{STND} = \sum D_i \times P_i \times \text{TN}_i \times S$$

where D_i, P_i, OM_i, TN_i, and S represent the soil thickness, bulk density, organic carbon concentration, total nitrogen concentration, and cross section area of soil core of the ith layer; and $i = 1$, 2, 3, ..., and 10.

Data analysis

Analysis of variance (ANOVA) was used to determine treatment effects (i.e. different land-use types) of resulting data. Means of the main effects were compared by Duncan's multi-range test at $p \leq 0.05$. The relationships of soil carbon and nitrogen stores with root and litter carbon and nitrogen stores were examined with Pearson correlation analysis. All statistical analyses were performed using SPSS 11.0 program.

Results

Among the six land-use types, ANPP varied markedly and highly significantly ($p < 0.0001$); the values ranged on average from 40 g C m^{-2} year^{-1} for the FG to 738 g C m^{-2} year^{-1} for the CP, and ranked in the order of CP > AP > FL > GE > MW > FG (Fig. 2); the ANPP for the CP was between nearly five- to more than 18-folds greater than other five land use types. Differences among land-use types were all significant ($p < 0.05$) except between the MW and the GE. For the three grassland types, the ANPP for the FG was only 55 and 42%, respectively, of that for the GE and MW.

Total belowground carbon stores, inclusive of surface litter and roots, were much less variable than ANPP across the six land-use types, and ranged from 5.6 kg C m^{-2} for the FG to 11.2 kg C m^{-2} for the AP, predominantly in soil organic matter (>94%). Total belowground soil nitrogen

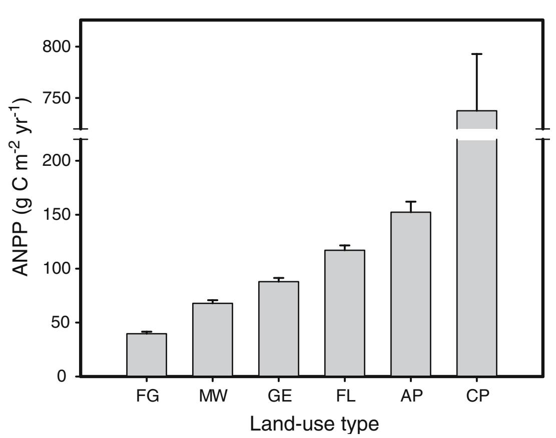

Fig. 2 Changes of aboveground NPP with land-use types in an agro-pastoral ecotone of northern China. Vertical bars indicate standard errors of means ($n = 4$). ANPP – Aboveground net primary production; FG – Free-grazing; MW – Mowing; GE – Grazing exclusion; FL – Fallow; AP – Alfalfa pasture; CP – Corn plantation

stores ranged from 0.4 kg N m^{-2} for the FG to 0.8 kg N m^{-2} for the AP. Despite the markedly high ANPP, the CP only ranked the third in the total belowground carbon stores and the fifth in the total belowground nitrogen stores (Table 1).

Among the carbon pools belowground, litter was most variable across the land-use types (Fig. 3A). Although the patterns of variation in carbon stores were inconsistent among litter, roots, and soil organic matter (SOM) with land-use type, the AP was ranked the highest in carbon store for all the three pools; the lowest carbon store was displayed by the CP in litter and roots (Fig. 3A and B), and by the FG in SOM (Fig. 3C). The carbon store in SOM for the FG was significantly ($p < 0.05$) less than all other land-use types.

Patterns of nitrogen store with land-use were slightly different from the carbon store such that nitrogen stores showed less variation in roots and SOM across most of the land-use types (Fig. 4). The ground-floor litter nitrogen store varied greatly among the land-use types, and was greatest in the AP and least in the CP (Fig. 4A). The AP also had the greatest nitrogen store in both roots and SOM; the least nitrogen store was displayed by the AP in roots, and the FG in SOM (Fig. 4B and C). The root nitrogen store was similar among the FG, MW, GE, and FL (Fig. 4B); whereas in SOM, nitrogen store was similar among the MW, GE, FL, and CP. Overall, the sites under mowing and grazing exclusion had

Table 1 Total belowground carbon and nitrogen stores[1] under different land-use types in an agro-pastoral ecotone of northern China

Land-use type	Carbon store (g C m^{-2})	Nitrogen store (g N m^{-2})
Free grazing (FG)	5569 ± 452 a	416.29 ± 15.70 a
Mowing (MW)	8872 ± 339 b	663.44 ± 13.15 c
Grazing exclusion (GE)	8682 ± 194 b	664.21 ± 11.07 c
Fallow (FL)	9532 ± 291 c	671.88 ± 3.74 c
Alfalfa pasture (AP)	10645 ± 126 d	808.48 ± 14.97 d
Corn-plantation (CP)	8710 ± 346 b	609.96 ± 14.74 b

Values shown are means ± standard errors ($n = 4$)

Note: [1]Sum of carbon store in litter, roots, and soil organic matter to 100 cm depth; values designated by the same letters are not significantly different at $p \leq 0.05$

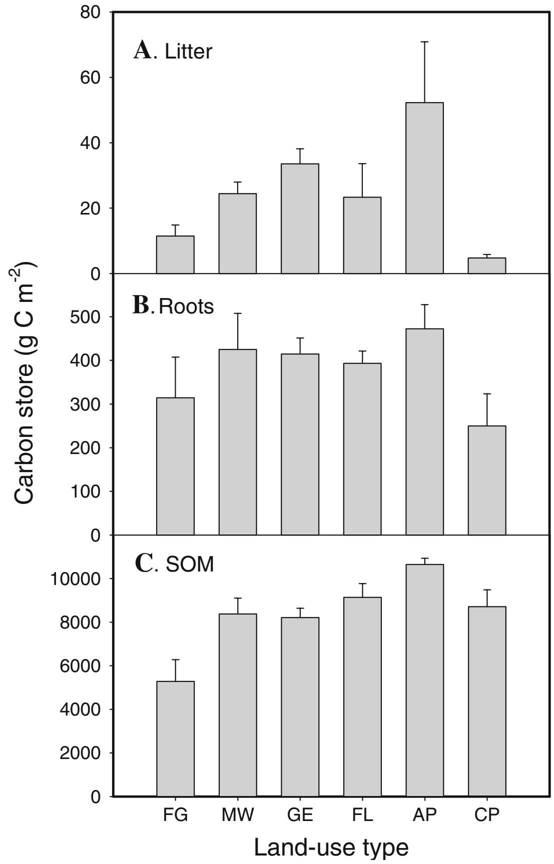

Fig. 3 Changes of carbon stores in ground floor litter, roots, and soil organic matter (SOM) in an agro-pastoral ecotone of northern China. Vertical bars indicate standard errors of means ($n = 4$). ANPP – Aboveground net primary production; FG – Free-grazing; MW – Mowing; GE – Grazing exclusion; FL – Fallow; AP – Alfalfa pasture; CP – Corn plantation

59 and 56% more SOC, and 61% more SON than the sites subjected to uncontrolled grazing.

Pearson correlation analysis indicated closer relationship of SOM with litter in both carbon and nitrogen stores than with roots; the correlations were stronger for nitrogen stores than for carbon (Table 2).

With exception of the CP, SOC and SON stores apparently increased with ANPP across the land-use types (Fig. 5 and 6). Within the same land-use types such trend did not seem to exist.

The root and SOM carbon all declined with depth across the six land-use types, with the relative distribution greatly skewed towards the top layers (Fig. 7). The carbon store in roots

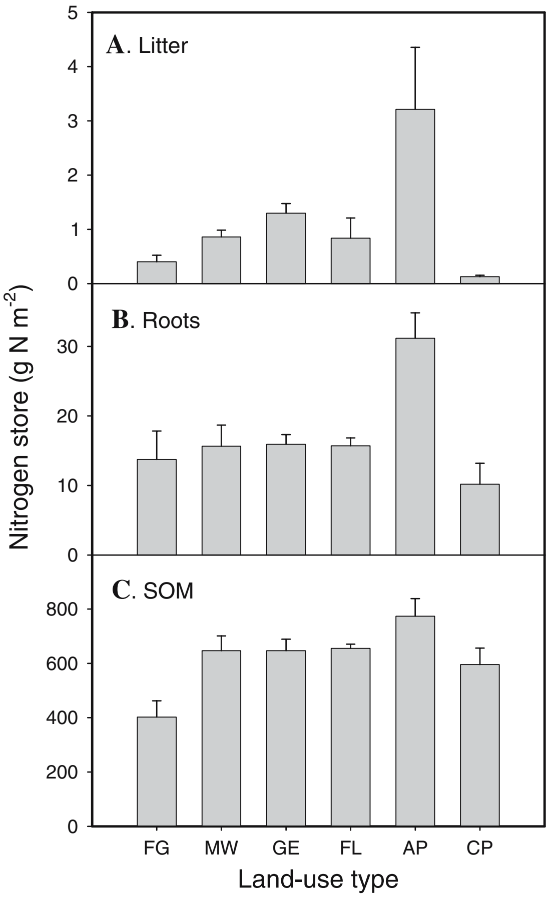

Fig. 4 Changes of nitrogen stores in ground floor litter, roots, and soil organic matter (SOM) in an agro-pastoral ecotone of northern China. Vertical bars indicate standard errors of means (n = 4). FG – Free-grazing; MW – Mowing; GE – Grazing exclusion; FL – Fallow; AP – Alfalfa pasture; CP – Corn plantation

showed similar profile for all land-use types except the AP, with the top 10 cm accounting for more than 60% of total root carbon. SOM carbon was predominantly distributed in the top 30 cm layers, with much less variation being observed at depth below 40 cm (Fig. 7). Among the six land-use types, the FG had the least variation, while the MW and GE showed gradual decline in the relative SOM carbon distribution with depth. Irregular patterns of SOM carbon distribution in top layers were exhibited in the FL, AP, and CP. The vertical profiles of the root and SOM nitrogen were similar to those of the root and SOM carbon (Fig. 8). For the AP, nearly 20% of carbon and nitrogen in the 100 cm profile were distributed in the 20–30 cm layer, which was a much greater proportion compared with other land-use types.

Table 2 Pearson correlation coefficients (r) and associated levels of significance (p) between soil and roots and between soil and litter

		Carbon store		Nitrogen store	
		Roots	Litter	Roots	Litter
Soil	r	0.383	0.560	0.576	0.645
	P	<0.001	<0.001	<0.001	<0.001

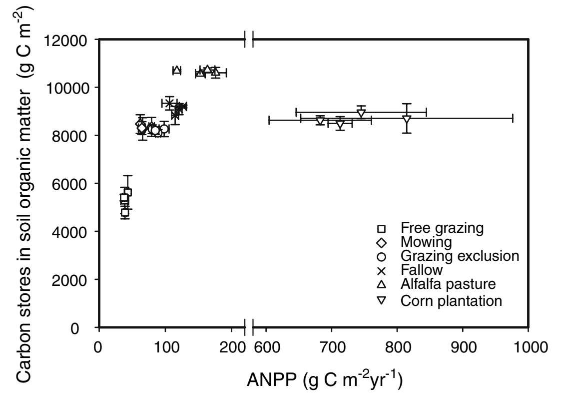

Fig. 5 Relationship between carbon stores in soil organic matter (SOM) and aboveground net primary production (ANPP) as affected by land-uses in an agro-pastoral ecotone of northern China

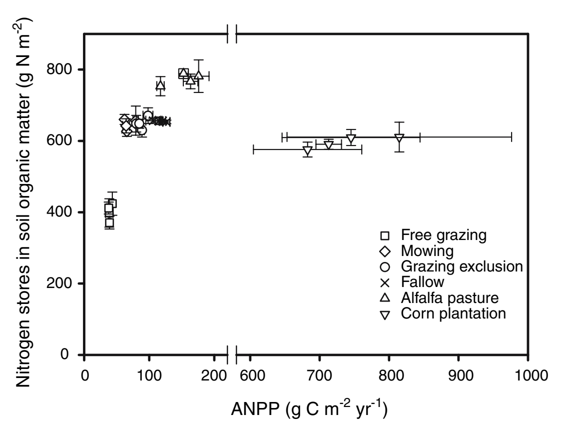

Fig. 6 Relationship between nitrogen stores in soil organic matter (SOM) and aboveground net primary production (ANPP) as affected by land-uses in an agro-pastoral ecotone of northern China. Vertical and horizontal bars indicate standard errors of means (n = 4)

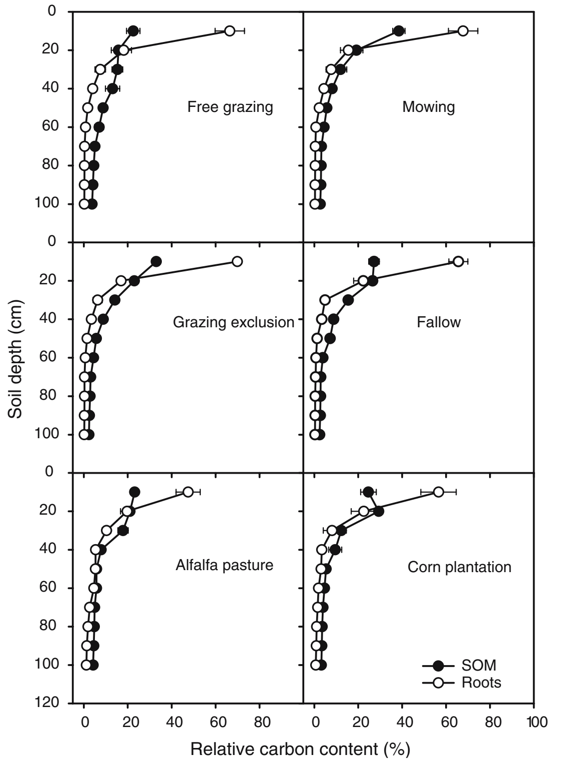

Fig. 7 Relative carbon allocations in roots and soil organic matter (SOM) with depth for six different land-use types in an agro-pastoral ecotone of northern China. Horizontal bars indicate standard errors of means (n = 4)

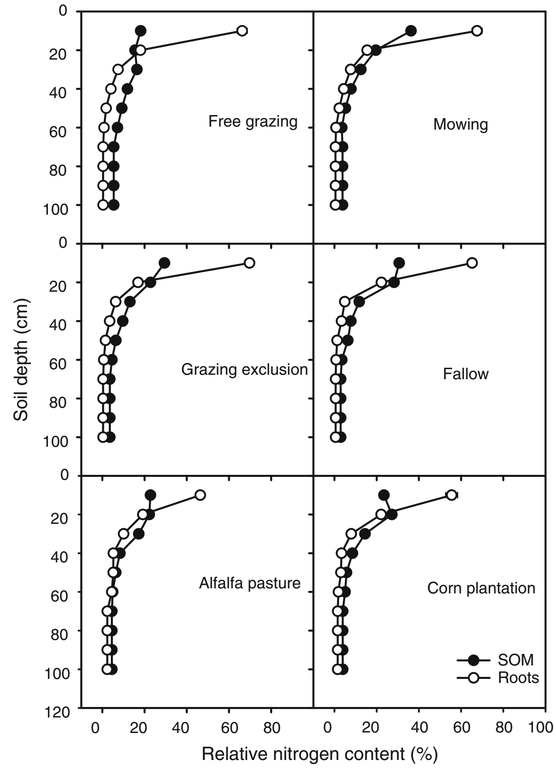

Fig. 8 Relative nitrogen allocations in roots and soil organic matter (SOM) with depth for six different land-use types in an agro-pastoral ecotone of northern China. Horizontal bars indicate standard errors of means (n = 4)

Discussion

It has long been suggested that the terrestrial regions of the Northern Hemisphere represent a large carbon sink in the global carbon budget (Tans et al. 1990), and that below ground allocation of additional carbon to roots and soil organic matter accounts for significant fraction of the carbon sink in non-forest biomes (Hall and Scurlock 1991; Davidson et al. 1995; Scurlock and Hall 1998). As the grasslands of northern China make up a significant portion of the Eurasian continent, land-use practices that enhance or weaken the carbon storage potential of the regional grassland soils could have significant implications to the global carbon budget (Ojima et al. 1993a, b).

Anthropogenic activities in terms of exploitation for arable land and overgrazing have contributed to accelerated land degradation in the semiarid and temperate grasslands of northern China in recent decades (Chuluun and Ojima 2002). Some of the land-use changes are not readily reversible without clear evidence demonstrating better land-use options addressing the concerns for both short-term economic development and long-term ecosystem stability. In this study, using an agro-pastoral ecotone as a case study, we demonstrated that land-use changes affected soil organic matter inputs by changing productivity in grassland ecosystems, but higher aboveground biomass productivity resulting from land-use changes did not always support higher belowground carbon and nitrogen stores. Our results showed that, despite of having the greatest aboveground NPP, the corn plantation was ranked only the third in the belowground carbon stores and the fifth in the belowground nitrogen stores among six different land-use types. The corn plantation differs from other land-uses we investigated in such a way that it is annual, while the rest are perennial. The complete removal of aboveground biomass as green-fodder from corn plantation was likely attributable to lower carbon and nitrogen inputs to the system; whereas the perennial grasses were able to maintain a continuous cover of vegetation on the soil that facilitated organic matter input (Brown and Lugo 1990). Given the markedly high productivity, corn plantation may be considered for green-fodder production to partially relieve grazing pressure on the native vegetation, but such practice should be implemented with land management strategy targeted at raising or maintaining soil fertility.

The natural vegetation in our study area is mostly *Stipa krylovii* steppe, which resembles the short-grass prairie of North America. The productivity of the regional *Stipa krylovii* steppe, however, is generally low compared with well-protected sites of the region (cf. Li et al. 1998; Piao et al. 2004) and grasslands in other parts of the world (cf. Sala et al. 1988; Brye et al. 2002). The aboveground NPP for the free-grazing sites was lower than the means of the same type of steppe in a different area (Bai 1999; Wang and Zhou 2004); whereas the values for the mowing and grazing exclusion sites were within the range previously reported for this region (Wang and Zhou 2004; Xiao et al. 1995). The relatively low productivity compared with those in North America might be attributable to nitrogen limitation resulted from long-term overgrazing and other types of intensive land-uses such as farming (Chuluun and Ojima 2002). Prolonged overgrazing can suppress plant biomass productivity, and result in destructions of soil aggregation and vegetation (Fales et al. 1996). Grazing is also known to stimulate root respiration and exudation (Schuman et al. 1990) and accelerate the mineralization of organic matter (McNaughton et al. 1997; Frank and Groffman 1998). Hence grasslands that are historically over-utilized or heavily grazed tend to loose soil organic matter (Lal 2002). In our study, free-grazing decreased the soil nitrogen store by 245 g N m^{-2} compared to the grazing exclusion site. We also found that after period of fallow, the productivity and soil carbon and nitrogen stores on abandoned agricultural lands could be fully restored to the level comparable to the non-degraded native vegetation (i.e. mowing and grazing exclusion). The carbon stores in soil organic matter for restored land-uses in this agro-pastoral ecotone ranged from >8 kg C m^{-2} to >10 kg C m^{-2}, in general agreement with the national average of ~ 8.8 kg C m^{-2} for non-cultivated lands (Wu et al. 2003) but below the world's mean of ~10.6 kg C m^{-2} (Post et al. 1982). The levels of soil carbon and nitrogen stores among different land-use types were found to differ after only 3 years of land-use conversion. Spatial heterogeneity may contribute to some of the differences. Nonetheless, our results showed that the local ecosystems are highly susceptible to environmental perturbation.

The carbon and nitrogen stores displayed similar profiles in roots and soil organic matter, which all declined with depth as commonly found (Ross et al. 1999). About 50% of soil organic carbon and nitrogen were allocated in the top 20 cm soil layers, and 80% for root carbon and nitrogen. Changing land-use types are therefore expected to affect predominantly the soil carbon and nitrogen stores in the top layers. Senescence from roots may represent major organic matter inputs to soils in grassland ecosystems as the decomposition of the aboveground litter is generally slow for the dominant *Stipa krylovii* and other bunchgrass species of the region (Liu et al. 2006). Jackson et al. (1997) estimated that fine roots, which turned over once a year, represented 33% of global annual net primary productivity. Moreover, greater carbon sequestration potential could be achieved through deep-rooted grasses that facilitate organic matter transport into the deeper soil profile, thus making the carbon less prone to oxidation (Fisher et al. 1994). In this regard, the alfalfa pasture has shown to be promising for transporting carbon to the deeper soil layers among the six land-use types we studied.

Free-grazing has historically been an extensive land-use practice for the grasslands of northern China. Although Duolun County belongs to the agro-pastoral ecotone, the agricultural yield is very low and many of the local residents were opted for sheep herding for improved income. Since late 1970's, the livestock density had been sharply increased until reaching peak level around 1995 (Baoyin and Liu 2001), leading to exacerbated land degradation and declining productivity (You et al. 2003; Liu and Tong 2003; Zhan et al. 2004). Concern for deteriorating environmental conditions prompted the local government of Duolun County to impose strict land-use policy officially banning livestock grazing from 2000 onwards. Instead, mowing became the encouraged land-use type for the native grasslands, and some degrading agricultural lands were converted to land-uses for green-fodder production. Although mowing is a better land-use option than overgrazing in maintaining soil organic matter, the prolonged practice could bring about changes in plant community structure leading eventually to functional damage to grassland ecosystems (Bao et al. 2004). Alternation of moderate grazing schemes with mowing should be considered as a mean to sustain grassland productivity in the longer term once the region are fully restored, as moderate grazing facilitates ecosystem stability and enhances productivity (McNaughton 1985). Optimal use of management practices also offer the great potential for significantly increasing soil organic carbon and nitrogen storage and preserving the grasslands (Wright et al. 2004; Bernacchi et al. 2005).

Among the six land-use types we studied, alfalfa pasture clearly ranks the best from perspectives of feed-stock and soil carbon and nitrogen stores. The state of free-grazing sites suggested apparent overgrazing and severe land degradation. Land-uses such as mowing, grazing exclusion, and fallow were ranked at intermediate levels in both productivity and belowground carbon and nitrogen stores. Based on our measurements, we estimated that restoring severely degraded and overgrazed grasslands could potentially increase soil organic carbon and nitrogen stores by more than 55%, contrary to the findings of Brye et al. (2002) that the restored prairie was not an immediate carbon sink; conversion from the native grasses to alfalfa could potentially double the aboveground biomass production, and further increase soil organic carbon and nitrogen stores by more than 20% (Table 1). The severity and prolonged overgrazing for the grasslands of northern China may explain the discrepancy between our results and those by Brye et al. (2002).

Despite of the promising outlook for the alfalfa pastures, however, large-scale conversion of the native natural vegetation to alfalfa pastures should be treated with caution as alfalfa has not been proven to survive the extreme events of low winter temperatures and drought. Uncertainty with diseases in long-term alfalfa systems may also constrain the wide use of alfalfa hay in the region. Mechanized mowing is not necessarily a long-term solution to carbon sequestration for the purpose of mitigating global climate change due to the costs of fossil fuel consumption. Diversity in land-uses in the agro-pastoral ecotone of northern China should therefore be viewed as necessary for addressing issues concerning both regional productivity and global climate change.

Based on our results, we draw conclusion that through improved management and land-use conversion for better productivity, the agro-pastoral ecotone of northern China could be utilized as a significant carbon sink in the context of mitigating global climate change while maintaining adequate productivity for servicing the regional socio-economic development.

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References

Bai YF (1999) Influence of seasonal distribution of precipitation on primary productivity of *Stipa krylovii* community. Acta Phytoecol Sin 23:155–160

Bao YJ, Li ZH, Zhong YK (2004) Compositional dynamics of plant functional groups and their effects on stability of community ANPPduring 17 yr of mowing succession on *Leymus chinensis* steppe of Inner Mongolia, China. Acta Bot Sin 46:1155–1162

Baoyin T, Liu D (2001) The changing of ploughland and analysis of problem of Duo Lun County on agriculture-animal husbandry ecotone. Acta Sci Nat Uni NeiMongol 32:657–660

Bernacchi CJ, Hollinger SE, Meyers T (2005) The conversion of the corn/soybean ecosystem to no-till agriculture may result in a carbon sink. Global Change Biol 11:1867–1872

Brown S, Lugo AE (1990) Effects of forest clearing and succession on the carbon and nitrogen content of soils in Puerto Rico and US Virgin Islands. Plant Soil 124:53–64

Brye KR, Gower ST, Norman JM et al (2002) Carbon budgets for a prairie and agroecosystems: effects of land use and interannual variability. Ecol Appl 12:962–979

Burke IC, Laurenroth WK, Milchunas DG (1997) Biogeochemistry of managed grasslands in central North America. In: Paul EA, Elliott ET, Paustian K, Cole CV (eds) Soil organic matter in temperature agroecosystems: long-term experiments in North America. CRC Press, Boca Rato, FL, pp 85–102

Cambardella CA, Elliott ET (1992) Particulate soil organicmatter changes across a grassland cultivation sequence. Soil Sci Soc Am J 56:777–783

Canadell JG (2002) Land use effects on terrestrial carbon sources and sinks. Sci China Ser C 45(Supplement):1–9

Chuluun T, Ojima D (2002) Land use change and carbon cycle in arid and semi-arid lands of East and Central Asia. Sci China Ser C 45(Supplement):48–54

Conant RT, Paustian K, Elliott ET (2001) Grassland management and conversion into grassland: effects on soil carbon. Ecol Appl 11:343–355

Cramer W, Kicklighter DW, Bondeau A et al (1999) Comparing global models of terrestrial net primary productivity (NPP): overview and key results. Global Change Biol 5:1–15

Davidson EA, Nepstad DC, Klink C et al (1995) Pasture soils as carbon sink. Nature 376:472–473

Degryze S, Six J, Paustian K et al (2004) Soil organic carbon pool changes following land-use conversions. Global Change Biol 10:1120–1132

Derner JD, Briske DD, Boutton TW (1997) Does grazing mediate soil carbon and nitrogen accumulation beneath C4 perennial grasses along an environmental gradient? Plant Soil 191:47–156

Fales SL, Laidlaw AS, Lamber MG (1996) Cool-season grass ecosystems. In: Moser LE, Buxton DR, Casler MD (eds) Cool-Season Forage Grasses. American Society of Agronomy, Madison, WI, pp 267–296

Falkowski P, Scholes RJ, Boyle E et al (2000) The global carbon cycle: a test of our knowledge of earth as a system. Science 290:291–295

Fisher MJ, Rao IM, Ayarza MA et al (1994) Carbon storage by introduced deep-rooted grasses in the South American savannas. Nature 371:236–238

Frank DA, Groffman PM (1998) Ungulate vs. landscape control of soil C and N processes in grasslands of Yellowstone National Park. Ecology 79:2229–2241

Gallaher RN, Weldon CO, Boswell FC (1976) A semiautomated procedure for total nitrogen in plant and soil samples. Soil Sci Soc Am J 40:887–889

Global Carbon Project (2003) Science Framework and Implementation. Earth System Science Partnership (IGBP, IHDP, WCRP, DIVERSITAS) Report No. 1; Global Carbon Project Report No. 1, 69 pp, Canberra

Grünzweig JM, Sparrow S, Yakir D et al (2004) Impact of agricultural land-use change on carbon storage in Boreal Alaska. Global Change Biol 10:452–472

Guo LB, Gifford RM (2002) Soil carbon stocks and land use change: a meta analysis. Global Change Biol 8:345–360

Hall DO, Scurlock JMO (1991) Climate change and productivity of natural grasslands. Ann Bot 67:49–55

Houghton RA, Hackler JL, Lawrence KT (1999) The U.S. carbon budget: contributions from land-use change. Science 285:574–578

Jackson RB, Mooney HA, Schulze ED (1997) A global budget for fine root biomass, surface area, and nutrient contents. PNAS 94:7362–7366

Lal R (2002) Soil carbon dynamics in cropland and rangeland. Environ Pollut 116:353–362

Li LH, Liu XH, Chen ZZ (1998) Study on the carbon cycle of *Leymus chinensis* steppe in the Xilin River Basin. Acta Bot Sin 40:955–961

Liu P, Huang J, Han X et al (2006) Differential responses of litter decomposition to increased soil nutrients and water between two contrasting grassland plant species of Inner Mongolia, China. Appl Soil Ecol 34:266–275

Liu QY, Tong YP (2003) The effects of land use on the eco-environmental evolution of farming-pastoral region in North China: With an emphasis on Duolun County in Inner Mongolia. Acta Ecol Sin 23:1025–1030

McNaughton SJ (1985) Ecology of a grazing ecosystem: the serengeti. Ecol Monogr 55:259–294

McNaughton SJ, Banyikawa FF, McNaughton MM (1997) Promotion of the cycling of diet-enhancing nutrients by African grazers. Science 278:1798–1800

Nelson DW, Sommers LE (1982) Total carbon, organic carbon, and organic matter. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis. American Society of Agronomy and Soil Science Society of American, Madison, WI, pp 101–129

Nemani RR, Keeling CD, Hashimoto H et al (2003) Climate-driven increases in global terrestrial net primary production from 1982 to 1999. Science 300:1560–1563

Ojima DS, Dirks BOM, Glenn EP et al (1993a) Assessment of C budget for grasslands and drylands of the world. Water Air Soil Poll 70:95–109

Ojima DS, Parton WJ, Schimel DS et al (1993b) Modeling the effects of climatic and CO_2 changes on grassland storage of soil C. Water Air Soil Poll 70:643–657

Parton WJ, Scurlock JMO, Ojima DS et al (1993) Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem Cy 7:785–809

Petti JR, Jouzel J, Raynaud D et al (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399:429–436

Piao SL, Fang JY, He JS et al (2004) Spatial distribution of grassland biomass in China. Acta Phytoecol Sin 28:491–498

Post WM, Emanuel WR, Zinke PJ et al (1982) Soil carbon pools and world life zones. Nature 298:156–159
Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. Global Change Biol 6:317–327
Richter DD, Markewitz D, Trumbore SE et al (1999) Rapid accumulation and turnover of soil carbon in a re-establishing forest. Nature 400:56–58
Ross DJ, Tate KR, Scott NA et al (1999) Land-use change: effects on soil carbon, nitrogen and phosphorus pools and fluxes in three adjacent ecosystems. Soil Biol Biochem 31:803–813
Sala OE, Austin AT (2000) Methods of estimating aboveground net primary productivity. In: Sala OE, Jackson RB, Mooney HA et al. (eds) Methods in ecosystem science. Springer-Verlag, New York, pp 31–43
Sala OE, Parton WJ, Joyce LA et al (1988) Primary production of the central grassland region of the United States. Ecology 69:40–45
Schimel DS (1995) Terrestrial ecosystems and the carbon cycles. Global Change Biol 1:77–91
Schuman GE, Booth DT, Waggoner JW (1990) Grazing reclaimed mined lands seeded to native grasses in Wyoming. Journal of Soil and Water Conservation 45:653–657
Schuman GE, Reeder JD, Manley JT et al (1999) Impact of grazing management on the carbon and nitrogen balance of a mixed-grass rangeland. Ecol Appl 9:65–71
Scurlock JMO, Hall DO (1998) The global carbon sink: a grassland perspective. Global Change Biol 4:229–233
Sun OJ, Campbell J, Law BE et al (2004) Dynamics of carbon storage in soils and detritus across chronosequences of different forest types in the Pacific Northwest, USA. Global Change Biol 10:1470–1481
Sun HL (ed) (2005) Ecosystems of China. Science Press, Beijing
Tans PP, Fung IY, Takahashi T (1990) Observational constraints on the global atmospheric CO_2 budget. Science 247:1431–1438
Wang SP, Wang YF, Chen ZZ (2003) The relationship between plant community productivity and forage quality. In: The management of grazing ecosystem. China Science Press, Beijing, pp 45–59
Wang YH, Zhou GS (2004) Responses of temporal dynamics of aboveground net primary productivity of *Leymus chinensis* community to precipitation fluctuation in Inner Mongolia. Acta Ecol Sin 24:1140–1145
Watson RT, Noble IR, Bolin B et al (2000) Land use, land-use change and forestry. In: Special Report of the IPCC, Cambridge, Cambridge University Press, 377 pp
Wilson AT (1978) Pioneer agriculture explosion and CO_2 levels in the atmosphere. Nature 273:40–41
Wright AL, Hons FM, Rouquette Jr FM (2004) Long-term management impacts on soil carbon and nitrogen dynamics of grazed bermudagrass pastures. Soil Biol Biochem 36:1809–1816
Wu HB, Guo ZT, Peng CH (2003) Land use induced changes of organic carbon storage in soils of China. Global Change Biol 9:305–315
Xiao XM, Wang YF, Jiang S et al (1995) Interannual variation in the climate and above-ground biomass of Leymus Chinense steppe and Stipa grandis steppe in the Xilin river basin, Inner Mongolia, China. J Arid Environ 31:283–299
You LY, Lu JF, Chen H et al (2003) Adjustment of land use types for desertification control and prevention: Taking Duolun county of Inner Mongolia as a typical case. Geograph Res 22(6):680–686
Zhan JY, Deng XZ, Yue TX et al (2004) Land use change and its environmental effects in the farming-pasturing interlocked areas of Inner Mongolia. Resources Science 26(5):80–88