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Changes in soil carbon stocks and related soil properties along a 50-year grassland-to-cropland conversion chronosequence in an agro-pastoral ecotone of Inner Mongolia, China

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Abstract: Land use change significantly influences soil properties. There is little information available on the long-term effects of post-reclamation from grassland to cropland on soil properties. We compared soil carbon (C) and nitrogen (N) storage and related soil properties in a 50-year cultivation chronosequence of grassland in the agro-pastoral ecotone of Inner Mongolia. Field surveys on land use changes during the period of 1955–2002 were conducted to build a chronosequence of cropland of different ages since the conversion from grassland. The results showed that soil C and N storage, soil texture, and soil nutrient contents varied with land use types and cropland ages ($P < 0.01$). In the 0–30 cm soil layer, the soil organic carbon (SOC) density was significantly lower in the croplands (3.28 kg C/m² for C50 soil) than in the grasslands (6.32 kg C/m²). After 5, 10, 15, 20, 35, and 50 years of crop planting (years since the onset of cultivation), the SOC losses were 17%, 12%, 19%, 47%, 46%, and 48%, respectively, compared with the grasslands. The soil total nitrogen (TN) density of the grasslands was 65 g N/m², and TN density of the cropland soil was 35 g N/m² after 50 years of crop planting. Both the SOC and TN densities could be quantitatively determined by a negative exponential function of cropland age ($P < 0.0001$, $R^2 = 0.8528$; $P < 0.0001$, $R^2 = 0.9637$). The dissolved organic carbon (DOC) content, soil available potassium (AK) content, clay content, and pH value were decreased; and the soil bulk density and sand content were increased since the conversion of grassland into cropland during the 50-year period. Our results show soil nutrients were higher in grassland than in cropland. The conversion of grasslands to croplands induced a loss of soil C storage and changes of related soil properties. The reclamation time of cultivated soil (cropland age) had significant effects on soil properties in the study area.

Keywords: land use type; cropland age; grassland; soil physical-chemical properties; agro-pastoral ecotone

In recent years, numerous studies have focused on soil organic carbon (SOC) changes in various ecosystems (Powlson, 2005). Land use change obviously affects soil C (Houghton, 1999; Zhang, 2010) and N (Potter *et al.*, 1996) cycles. Many studies have reported the effects of land use change from cropland or grassland to forest and vice versa (Post and Kwon, 2000; Guo and Gifford, 2002). There is generally more SOC in grassland soil than in cropland soil (Cole *et al.*, 1993). In China, 8, 16, and 41 years after alpine grassland soils

were converted to arable land, the organic matter contents in the soils decreased by 25%, 39%, and 55%, respectively (Wu and Tiessen, 2002). Celik (2005) reported that the soil organic matter of cropland soils decreased by 48% for the 0–10 cm soil depth and 50% for the 10–20 cm soil depth compared with pasture soils over 12 years. Previous investigations seldom quantified the effects of reclamation age (years since

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the onset of cultivation) on soil carbon and nitrogen storage. Because it takes decades to centuries before the total C in soils equilibrates, it has been suggested that more sensitive soil C fractions should be investigated, such as dissolved organic carbon (DOC; Cambardella and Elliot, 1992). These C components have turnover time from years to decades. Therefore, DOC is easier to detect after land use change. In general, DOC concentrations vary in the following order: forest soils > grassland soils > arable soils. This order is mostly due to different types of plant cover (Delprat *et al.*, 1997; Haynes, 2000).

Nitrogen and phosphorus are key factors that influence the primary production of ecosystems (Mooney *et al.*, 1987; Han *et al.*, 1999). Land use and related management practices affect soil properties, such as SOC content, and are therefore likely to influence soil available potassium (AK) content and soil available phosphorus (AP) content.

In contrast to the vast literature on agricultural soils, few studies have compared the effects of the long-term conversion from grassland to arable land on soil physical properties (Pedersen *et al.*, 1980; Skousen *et al.*, 1998; Shukla *et al.*, 2004a). Soil physical properties change significantly with land degradation in the form of bulk density (Tisdall and Oades, 1982; Elliott, 1986). Bulk density is the most discriminating factor in soil properties in relation to land use and management (Shukla *et al.*, 2004b). Celik (2005) showed that cultivated soils have higher bulk density than adjacent soils under forests and pastures in the southern Mediterranean highlands of Turkey. Soil clay content is also a significant soil property (Mapa and Kumaragamage, 1996). He *et al.* (2005) and Li *et al.* (2006) proved that the sand (1–0.05 mm) content of cropland soils is higher than that of grassland soils. The return of plant residue to grassland soil results in soil organic humus enrichment and soil organic matter turnover (Angers and Caron, 1998).

Land use conversion from grassland to cropland and vice versa has occurred in the arid and semi-arid lands (ASAL) of Asia during the 20th century. The carbon and nitrogen cycles in this region show high temporal and spatial variability, with some areas acting as carbon sources and others as carbon sinks. Understanding the mechanisms that regulate carbon

fluxes in and out of the ASAL ecosystems would contribute to our knowledge of the complex carbon cycles of terrestrial ecosystems.

The agro-pastoral ecotone of Inner Mongolia lies within the arid and semi-arid regions of Asia. The agro-pastoral ecotone is distributed from northeast to southwest in China, covering 30% of the Chinese land territory. The agro-pastoral ecotone is a transition of land-use practices (livestock-grazing and farming) in places where grassland and cropland are interspersed. The economic reform of China has led to the large-scale conversion of grassland to cropland at the Inner Mongolian Plateau in North China. In the agro-pastoral ecotone, cropland areas were increased by 43,700 hm² due to the reclamation of grassland into cropland (Liu, 2002). In these areas, precipitation is less; land-use types are often diverse and the changes are more frequent. Overgrazing and land use changes that reduce the areas of forests and grasslands (Liu and Tong, 2003; Zhan *et al.*, 2004) along with an increase in agricultural activity have intensified pressures on the regional grasslands, causing severe land degradation (Liu and Tong, 2003; Zhan *et al.*, 2004). The agro-pastoral ecotone is ecologically fragile, and the shift from grassland to cropland is attracting increasing concerns from scholars (Zou, 2003).

In this paper, we investigated and compared soil C, N storage and related physical-chemical properties in a 50-year cultivation chronosequence of cropland in the agro-pastoral ecotone of Inner Mongolia. Grasslands that have never been ploughed were compared with croplands that were converted from grasslands in 1956, 1971, 1986, 1991, 1997, and 2002.

The aims of this research were to explain the variation in soil properties affected by land use changes and provide information for optimizing land use practices and improving soil ecological functions.

1 Materials and methods

1.1 Study area

The study area, with an altitude of approximately 1,400 m, is located in Taipusi county of Inner Mongolia, which lies within the typical agro-pastoral areas of China. It is in the south of the steppe of Xinlin River Basin, which constitutes an important component of

the Eurasian temperate grassland (Zhang *et al.*, 1997; Wang and Wang, 2007). The grassland in this study area is native (Chen and Wang, 2000).

The study area covers 2,667 hm², of which open forest occupies 667 hm², grassland 1,333.33 hm², and cropland 667 hm². This region belongs to the semi-arid temperate climatic zone (Taipusi Government, 1989). The annual mean temperature is approximately 1.6°C. The lowest monthly mean temperature is -17.6°C in January, and the highest is 17.8°C in July. The annual mean precipitation is 400 mm. The wind speed is 6 m/s (Yang *et al.*, 2005). The growing period of plants is from late April to early October.

Grasslands are the most important land use type in the Xilin River Basin. The dominant grass species include *Leymus chinensis*, *Stipa grandis*, *Stipa krylovii*, *Agropyron cristatum* and *Artemisia frigida*. The soil is sandy chestnut (i.e. Calcic Kastanozems, which is equivalent to Calcic-orthic Aridisol in the US soil taxonomy classification system).

1.2 Soil sampling and analysis

Field sampling was done in October 2007. The soils were sampled randomly from 7 sites within adjacent land use types, including flat areas of grassland and cropland (Table 1). All these sites were approximately more than 10 hm² and presented similar slope and soil type. There were 10 sampling sites with 3 replicates for each site. These 7 sites were sampled in the 3 layers of 0–10, 10–20 and 20–30 cm using a stainless steel corer (4 cm in diameter). The mean sampling interval was 50 m for both grassland and cropland, with 210 soil sampling sites and a total of 630 samples. The croplands originated from the reclamation of grasslands from 1955 to 2002.

Croplands reclaimed for 5 (C5), 10 (C10), 15 (C15), 20 (C20), 35 (C35), and 50 (C50) years were used to produce potato, wheat, and barley in 2007. N, P, K compound fertilizers were applied before planting (Table 2). The crop rotation patterns were dominated by potato-wheat-barley for the C5, C10, C15, C20, C35 and C50 soils from 1970 to 2007.

The crops were harvested in September, and the soil was then left bare from September to the following June. The soil was plowed before planting every year. The plowing depth was 30–35 cm.

The samples were air-dried and sieved through a 2-mm mesh for chemical analysis. Soil samples for soil bulk density analysis were taken using a steel cylinder which is 4 cm in diameter and 5 cm in height. The bulk density, SOC, total nitrogen (TN), soil texture, soil available phosphorous, and soil available potassium were analyzed according to the method of Liu (1996).

Table 1 Site characteristics of agro-pastoral ecotone in the Taipusi county of Inner Mongolia

Site	Latitude	Longitude	Land use history
G	41°49'52"N	115°13'26"E	Natural grassland
C5	41°50'29"N	115°13'19"E	Cropland reclaimed for 5 years
C10	41°50'49"N	115°13'43"E	Cropland reclaimed for 10 years
C15	41°50'54"N	115°14'02"E	Cropland reclaimed for 15 years
C20	41°50'53"N	115°14'05"E	Cropland reclaimed for 20 years
C35	41°48'28"N	115°19'13"E	Cropland reclaimed for 35 years
C50	41°50'53"N	115°13'23"E	Cropland reclaimed for 50 years

Note: G means natural grassland; C5, C10, C15, C20, C35, and C50 mean cropland reclaimed for 5, 10, 15, 20, 35, and 50 years, respectively. The same below.

Table 2 Information for the investigated land and planting history of the sample sites

Treatment ^a	Plant name	Planting history	Mean age ^b
G	<i>Leymus chinensis</i> , <i>Stipa capillata</i>	Undisturbed natural grassland	
C5	Potato	Potato was planted in 2006 and 2007	5
C10	Potato, oat	Two years of rotation of potato and oat. Potato was planted in 2007 and oat in 2006	10
C15	Wheat	Wheat was planted in 2006 and 2007	15±2
C20	Wheat	Wheat was planted in 2006 and 2007	20±2
C35	Wheat	Wheat was planted in 2006 and 2007	35±3
C50	Potato	Potato was planted in 2006 and 2007	50±5

Note: ^asources from field inventory and Taipusi county record (Taipusi County Record Compilation Committee, 2000); ^bErrors denote uncertainty of the mean age of sampled sites. Once cropland was plowed, N, P, K compound fertilizer (450 kg/km²) was incorporated in soil before annual planting.

Samples of 0.5 g soil were digested with 5 ml of 1 N K₂Cr₂O₇ and 10 ml of concentrated H₂SO₄ at 150°C for 30 min, followed by titration of the digests with standardized FeSO₄ to measure SOC. The TN was measured using the Kjeldahl digestion procedure (Horneck and Miller, 1998). Dissolved organic carbon in the soil samples was measured using a Total Organic Carbon Analyzer (MODEL TOC-5000A, SHIMADZU, Kyoto, Japan). Concentrations of total C (TC) and inorganic C (IC) in the prepared soil supernatant liquid were determined by the combustion/nondispersive infrared gas analysis method (de Castro *et al.*, 1999). The DOC was then determined by subtracting the IC from the TC concentration.

1.3 Calculation of SOC density and statistical analysis

The SOC density and TN density were calculated as follows (Zhou *et al.*, 2007):

$$\text{SOC density} = \sum_{i=1}^n D_i \times B_i \times O_i, \quad (1)$$

$$\text{TN density} = \sum_{i=1}^n D_i \times B_i \times N_i. \quad (2)$$

Where, n is the number of soil horizons, D_i the depth interval (cm) of horizon i from the topsoil downward, B_i the bulk density (BD) (g/cm³) in horizon i , O_i the mean SOC content (%) in horizon i , and N_i the mean TN content (%) in horizon i .

A statistical analysis was performed using the SYSTAT 10.0 program. An analysis of variance (ANOVA) was used to determine the significant differences in the mean BD (g/cm³), SOC (%), SOC density (kg C/m²), DOC (mg/L), TN (g/m²), AP, AK and soil clay content among the depth intervals and between the land uses in each site at $P < 0.05$. The analyses of land use were performed using the SYSTAT 10.0 program with land use as a fixed variable. Corre-

lation and regression analyses were performed using the SYSTAT 10.0 program.

2 Results and discussion

2.1 Distribution of bulk density and soil texture

Soil bulk density was largely affected by land use and cropland age (Table 3). The bulk densities were 1.32–1.41, 1.39–1.42, 1.24–1.33, 1.40–1.51, 1.48–1.54, and 1.35–1.40 g/cm³ in the cropland soils C5, C10, C15, C20, C35, and C50 for the 0–30 cm horizons, respectively. The cropland soils did not differ in bulk density among the 0–10 cm, 10–20 cm, and 20–30 cm layers ($F=0.1$, $P>0.1$) (Table 3). The cropland soil had a higher bulk density than the adjacent grassland in the 10–30 cm layers ($F=9.4$, $P<0.0001$). The bulk density had an increasing trend with increased cropland age (the years since the onset of cultivation) ($F=6.8$, $P<0.0001$). Franzluebbers *et al.* (2000) reported that the bulk density of grassland was significantly different from that of the conservation-tillage croplands in the upper 0.125 m of soil. Bauer and Black (1981) reported that the bulk density increased after the conversion of grasslands to croplands for a paired site investigation in North Dakota, USA. Some findings proved that cultivation readily induces soil loosening (Evrendilek *et al.*, 2004; Celik, 2005). The bulk density in agricultural soils was significantly higher than that of grasslands, which could be a result of using heavy agricultural equipment for plowing, planting, harvesting, and applying fertilizers, herbicides, and pesticides. An important factor that influences bulk density is the SOC content. The lower SOC content in agricultural soils leads to a higher soil bulk density. Hajabbasi *et al.* (1997) showed that higher soil organic matter content could improve soil texture, resulting in a decrease of soil bulk density.

Table 3 Effects of land use on soil bulk density and the vertical distribution of soil bulk density

Depth (cm)	Soil bulk density (g/cm ³)						
	G	C5	C10	C15	C20	C35	C50
0–10	1.26±0.09	1.32±0.17	1.42±0.03	1.33±0.05	1.40±0.07	1.54±0.09	1.40±0.10
10–20	1.25±0.02	1.41±0.08	1.39±0.18	1.31±0.08	1.44±0.12	1.53±0.07	1.35±0.06
20–30	1.31±0.08	1.33±0.07	1.39±0.09	1.24±0.09	1.51±0.12	1.48±0.08	1.35±0.03
0–30	1.27±0.05	1.35±0.13	1.40±0.11	1.29±0.07	1.45±0.10	1.51±0.08	1.36±0.08

Note: Mean ± SD.

Statistics show that the highest clay (10.97% as an average for 3 depths) and the lowest sand contents (46.57% as an average for 3 depths) were found in the grassland (Table 4). In the 0–30 cm soil depths, the soil sand content ($F=0.5$, $P>0.1$), clay content, ($F=0.613$, $P>0.5$) and silt content ($F=0.1$, $P=0.933$) did not change with the increase of soil depth. The soil sand content ($F=3.874$, $P<0.0001$) increased with the increase of cropland age. Opposite to the trend for the sand content, the soil clay content ($F=3.9$, $P<0.0001$), and silt content revealed a declining trend. The trend of higher soil sand content and lower clay content observed with increasing cropland age may be due to wind erosion. Cropland soil had a lower plant cover than grassland soil, because the land was bare from September to the following June. Being influenced by wind erosion, the soil fine particles were easily blew away, and the cropland was desertified after the reclamation of grassland. He *et al.* (2005) reported that cropland was more easily influenced by wind erosion than native grassland in agro-pastoral ecotones in Inner Mongolia. Li *et al.* (2006) proved that the sand content is higher in the cropland surface-layer and subsurface-layer soils than in grassland soils.

Table 4 Effects of land use on soil texture and the vertical distributions

Treatment	Depth (cm)	Soil texture (%)		
		Sand	Silt	Clay
G	0–10	40.3	50.5	9.2
	10–20	50.4	38.0	11.3
	20–30	49.0	38.9	12.1
C5	0–10	56.5	27.7	8.9
	10–20	50.3	35.2	8.4
	20–30	53.4	29.0	10.2
C10	0–10	62.8	23.9	8.4
	10–20	62.5	24.5	7.9
	20–30	61.6	24.5	8.4
C15	0–10	61.3	27.6	8.5
	10–20	61.4	25.5	9.6
	20–30	59.9	27.9	6.9
C20	0–10	57.9	25.3	8.1
	10–20	61.2	21.9	9.9
	20–30	62.6	22.0	10.0
C35	0–10	62.6	26.8	7.9
	10–20	65.1	25.2	7.9
	20–30	60.8	28.8	8.3
C50	0–10	61.1	22.4	7.9
	10–20	61.3	20.3	7.9
	20–30	58.6	25.0	8.4

In addition, the return of plant residues in the grassland soil and the lack of plowing caused the enrichment of soil organic humus and accelerated the formation of soil fine particles, which led to relatively higher clay content in grassland soil than in cropland soil. This development implies that the older the cropland age, the higher the soil sand content, which would lead to desertification in the study area.

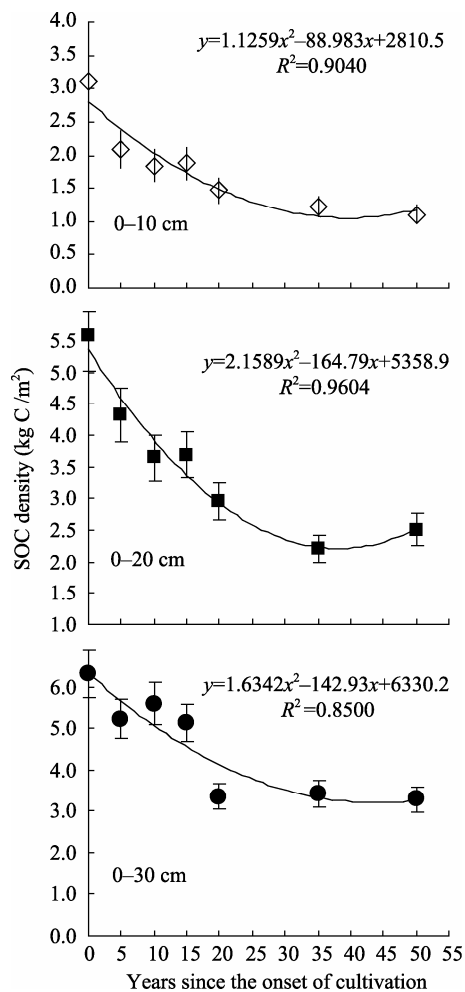
2.2 Changes in soil organic carbon density and total nitrogen density

The difference between the SOC contents of the grassland soils and the cropland soils was statistically significant ($F=64.1$, $P<0.0001$). There were pronounced differences in the SOC contents among the cropland soils of different ages ($F=61.4$, $P<0.0001$). We calculated the soil C and N density of up to a 30-cm depth using measured C and N concentrations (Table 5) and bulk density. The results for the SOC densities at 0–10 cm, 10–20 cm and 20–30 cm at the seven sites are shown in Fig. 1. For the 0–30 cm layers, the grassland soils had the highest value of 6.32 kg C/m². The SOC density of C5, C10, C15, C20, C35 and C50 decreased by 17%, 12%, 19%, 47%, 46%, and 48%, respectively, compared with the grasslands in the 0–30 cm soil depths (Fig. 1). These results are consistent with a previous report by Wu *et al.* (2003), which estimated an SOC loss of 10%–40% in the cultivated soils relative to their non-cultivated counterparts in China. Guo and Gifford (2002) found that soil carbon stocks, at a global scale, declined by 59% after the conversion of pasture to cropland. There is generally more SOC in grassland soil than in cropland soil (Cole *et al.*, 1993). In China, after alpine grassland soils were converted to arable land for 8, 16, and 41 years, the organic matter content in the soils decreased by 25%, 39%, and 55%, respectively (Wu and Tiessen, 2002). Celik (2005) reported that the soil organic matter of cropland soils decreased by 48% for the 0–10 cm soil depth and 50% for the 10–20 cm soil depth compared with pasture soils over 12 years. Lal (2002) also reported a carbon pool loss of 30%–50% in the mid-western USA due to land use changes from natural to agricultural ecosystems. Martin *et al.* (2010) tested that the amount of carbon loss from the soil was due only to changes in land use.

Table 5 Comparisons of SOC, TN, AK, AP, and pH of cropland and grassland soils

Treatment	Depth (cm)	Soil nutrient				
		SOC (%)	TN (g/kg)	AP (mg/kg)	AK (mg/kg)	pH
G	0–10	2.46±0.01	0.25±0.006	5.30±0.57	282±7.40	8.0±0.05
	10–20	2.22±0.05	0.23±0.005	3.09±0.28	205±4.00	8.1±0.02
	20–30	1.54±0.03	0.17±0.013	2.97±0.37	148±4.00	8.7±0.09
C5	0–10	1.58±0.05	0.17±0.010	7.15±0.35	189±8.14	7.6±0.08
	10–20	1.53±0.12	0.18±0.050	7.20±0.28	188±4.51	7.6±0.12
	20–30	1.31±0.07	0.16±0.001	4.15±0.35	138±6.08	7.6±0.07
C10	0–10	1.30±0.02	0.13±0.010	9.80±0.14	126±5.00	7.6±0.01
	10–20	1.31±0.03	0.13±0.020	5.30±0.18	97±2.52	7.6±0.05
	20–30	1.34±0.01	0.13±0.003	3.23±0.13	97±2.52	7.6±0.05
C15	0–10	1.41±0.02	0.14±0.004	5.15±0.64	172±5.69	7.7±0.02
	10–20	1.41±0.02	0.14±0.003	3.11±0.28	168±0.00	7.7±0.08
	20–30	1.38±0.09	0.13±0.007	3.17±0.58	145±7.02	7.8±0.11
C20	0–10	1.05±0.08	0.10±0.004	10.15±1.64	100±6.11	7.1±0.10
	10–20	1.03±0.09	0.11±0.004	5.41±1.13	96±5.13	7.4±0.04
	20–30	0.74±0.02	0.09±0.004	2.15±0.04	85±5.20	7.6±0.02
C35	0–10	0.79±0.07	0.08±0.004	9.10±1.56	112±0.19	6.9±0.06
	10–20	0.72±0.04	0.07±0.003	4.19±0.50	101±1.53	6.9±0.02
	20–30	0.77±0.10	0.08±0.004	3.16±0.66	93±2.31	7.3±0.02
C50	0–10	0.79±0.13	0.09±0.008	30.35±0.21	169±11.50	7.6±0.03
	10–20	0.93±0.11	0.09±0.007	18.30±1.41	138±6.93	7.6±0.11
	20–30	0.81±0.04	0.09±0.003	13.85±1.06	111±1.53	7.5±0.07

Note: Mean ± SD.

**Fig. 1** Correlation of SOC density and cropland reclamation age

Recent experiments in this area suggested that SOC stocks declined after land use changed from grassland to cropland for 10 years, 15 years, and 20 years in the 0–30 cm soil layers (Jiao *et al.*, 2009). There is generally more SOC under grassland than under cropland (Cole *et al.*, 1993) due to several factors, including the return of more plant residues, higher root biomass, the lack of mechanical disturbance, and erosion in grassland soil. For the cropland soils, the significant SOC losses were partly attributed to cultivation. Balesdent *et al.* (1998) reported that cultivation could also have contributed to the decrease of physical protection. The physical protection of soil organic matter (SOM) within stable aggregates may be reduced by soil tillage. Bouman (1990), Post and Mann (1990), and Lal *et al.* (1995) tested that agricultural management practices increased aeration and the loss of carbon to the atmosphere.

Our study proved that the conversion of grassland to cropland induced a significant loss of SOC in the ecotone between agriculture and grazing in Inner Mongolia.

A decrease of SOC density with increased cropland age was found as the age increased from 5 to 50 years. SOC loss was significantly correlated with the time of cropland reclamation in the study area, showing a marked decline in the inception years of cultivation. Afterward, the equilibrium in the new land could only

be reached after 50 years. This result is consistent with Guo's report (Guo *et al.*, 2002).

Land use change ($F=121.4$, $P<0.0001$) and cropland age ($F=194.0$, $P<0.0001$) distinctly affected soil TN content. The pattern of nitrogen storage with land use was similar to that of carbon storage. For the 0–30 cm layers, the lowest TN density (35 g N/m² for C50 soil) was found in the cropland. The grassland had the highest TN density (65 g N/m²). Compared with the grasslands, in the 0–30 cm soil layers, the C5, C10, C15, C20, C35, and C50 soils had a loss of 5%, 16%, 23%, 38%, 44%, and 44%, respectively (Fig. 2).

We applied a regression analysis and found that cropland reclamation age could explain more than 93%,

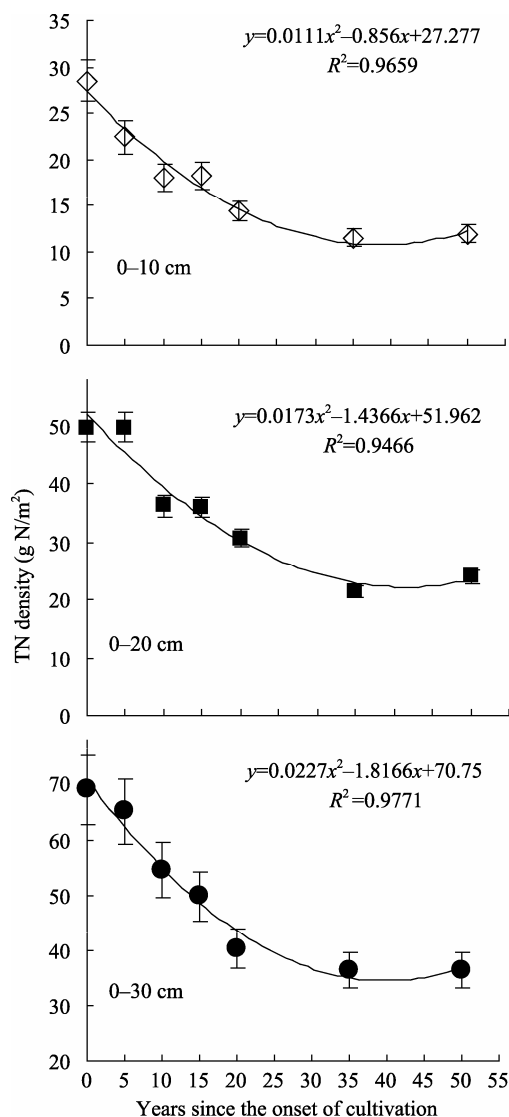


Fig. 2 Correlation of soil TN density and cropland reclamation age

90%, and 85% of the variability of SOC density in the 0–10 cm, 0–20 cm, and 0–30 cm soil depths, respectively (Fig. 1). The cropland age also explained more than 95%, 91%, and 96% of the variability of soil TN density in the 0–10 cm, 0–20 cm, and 0–30 cm soil depths, respectively (Fig. 2).

2.3 Changes in soil dissolved organic carbon

Figure 3 shows that land use type ($F=65.3$, $P<0.0001$) and cropland age ($F=4.6$, $P<0.001$) have pronounced effects on the soil DOC content. The DOC contents decreased in the order of grassland soils, cropland soils in the 0–10 cm, 10–20 cm, 20–30 cm, respectively. The DOC content of grassland was in the range of 9.1 to 17.8 mg/L in the 3 soil depths. The DOC value of C50 was 6.5 to 8.9 mg/L in the 3 soil depths. With increased soil depths, the soil DOC content of the cropland significantly decreased ($F=15.633$, $P<0.0001$), while that of the grassland soil increased ($F=52.7$, $P<0.0001$). Zsolnay (1996) reported that

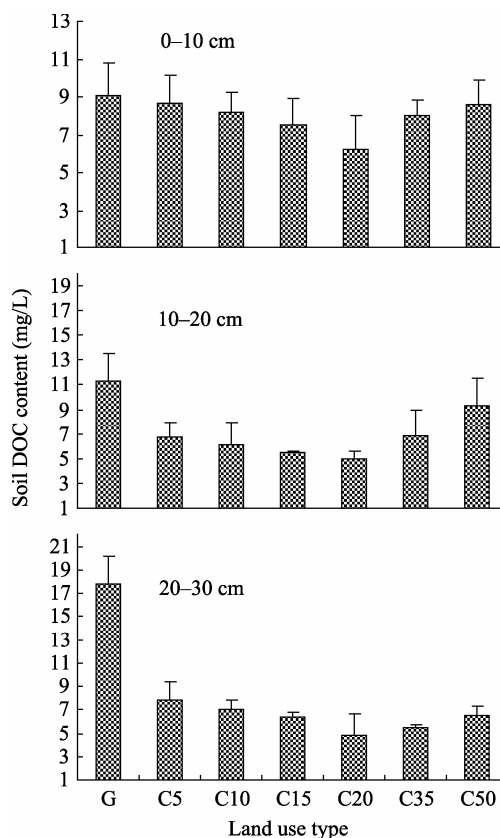


Fig. 3 Comparison of soil dissolved organic carbon (DOC) concentrations and the vertical distributions of croplands of different ages

agricultural soil DOC values varied from 10 to 70 mg/L. Other studies have also indicated higher DOC contents in grasslands than in cropland soils (Saviozzi *et al.*, 1994; Gregorich *et al.*, 2000; Haynes, 2000). Moreover, the extent of the decline in DOC appears to be more pronounced in the first 10 years after cropland reclamation. Gregorich *et al.* (2000) and Haynes (2000) found that DOC content obviously declined as cropland age increased. DOC production and content should be determined primarily by the amount of organic matter in the soil (Zsolnay, 1996; Kalbitz *et al.*, 2000). The factors that controlled the DOC content in the soil were complex because of their diversity, intensity, and heterogeneity in and between treatments. However, our results readily suggest that the difference is generated by land use and cropland age.

In the first 20 years after grassland was converted to cropland, the DOC content showed a decrease with increasing age of cropland at the same soil depths, the contrary is the case in the last 30 years. A possible explanation for this might be that older croplands were more influenced by agricultural practices.

2.4 Changes in soil AK, AP and pH

The characteristics of AP, AK, and pH at the seven sites as revealed by ANOVA analysis (Table 5) indicated that land use significantly affected AK content ($F=35.5$, $P<0.0001$) and pH ($F=37.5$, $P<0.0001$), but did not obviously affect AP content ($F=2.2$, $P>0.1$). There were pronounced differences in the AP content

($F=15.3$, $P<0.0001$), AK content ($F=30.8$, $P<0.0001$), and pH ($F=17.4$, $P<0.0001$) among cropland soils of different ages. The soil AK content of the grassland soil (between 148 to 282 mg/kg) was obviously higher than that of the cropland soil in the 0–30 cm soil depths. The soil AK content decreased after grassland conversion to cropland in the first 20 years, with a lesser increase in the last 30 years. There were no distinct correlations between AK content and cropland age ($R^2=0.3595$, $P>0.05$).

The AK ($F=6.1$, $P<0.01$) and AP ($F=3.9$, $P<0.0001$) contents of the grassland and cropland soils obviously decreased ($P<0.01$) as soil depth increased.

The soil AK loss after the conversion of grassland to cropland could be attributed to soil texture change. A Pearson coefficient correlation analysis shows that soil AK content is mainly negatively correlated with soil BD (Table 6). Kosmas *et al.* (1993) showed that the mineral composition and textural class of soil significantly affected other soil properties and plant growth. However, soil AP had no difference between the cropland and grassland soils. This result may be due to the fact that soil AP content had no significant correlation with other soil properties (Table 6), which needs to be further studied. Furthermore, there were significant differences in the AP contents among croplands of different ages. One possible explanation is that this discrepancy was the result of different cropland ages. A significant correlation exists between AP content and cropland age ($y=0.015x^2-0.3433x+8.0558$, $R^2=0.8626$, $P<0.01$), which means that higher cropland age indicated higher AP content.

Table 6 Matrix of Pearson's correlation coefficients for soil properties

	Cropland Age	TOC	TN	DOC	AK	AP	pH	BD
TOC	-0.840**							
TN	-0.858**	0.968***						
DOC	-0.062	0.194	0.225					
AK	-0.432	0.712**	0.767*	0.336				
AP	0.663**	-0.417	-0.382	0.255	0.039			
pH	-0.572	0.580*	0.653*	0.581*	0.417	-0.269		
BD	0.356	-0.542*	-0.593*	-0.267	-0.563*	-0.039	-0.602*	
Sand	0.603*	-0.721**	-0.837**	-0.245	-0.722**	0.073	-0.673**	0.730**
Clay	0.510	0.410	0.503	0.313	0.230	-0.373	0.637*	-0.323

Note: *, **, and *** mean significance at $P<0.05$, $P<0.01$, and $P<0.001$, respectively ($n=7$). TOC, total organic carbon; TN, total nitrogen; DOC, dissolved organic carbon; AK, available potassium; AP, available phosphorus; BD, bulk density; Sand, sand content; Clay, clay content.

Our results show that the grasslands had higher nutrient contents (except AP) than croplands, mainly because grasslands have higher clay content and lower bulk density, which is favorable for retaining nutrients.

Table 5 shows that the pH of the grassland soil was between 8.0 and 8.7 in the 0–30 cm soil depths. The differences between pH values are small among the 0–30 cm soil depths ($F=2.4$, $P>0.107$). A trend of decreasing pH values with increasing ages of cropland was detected, which was likely because the cropland soil tended to become acidic with the advance of reclamation time. However, the pH was not determined as a function of cropland age ($R^2=0.5507$, $P>0.05$). The long-term influence of land use change on pH was different in the study of Bronson *et al.* (2004), who compared intensive agricultural sites with grassland sites in the Southern High Plains, USA. The result showed that different types of cotton soils did not have a significantly different pH value compared with two types of native grassland soil. Strebel *et al.* (1988) demonstrated that reclaiming grassland and converting it to cropland did not affect soil pH.

3 Conclusions

The conversion of grassland to cropland led to soil degradation in the agro-pastoral ecotone of Inner Mongolia. We found that the conversion of grasslands to croplands induced a loss of soil C and N in the 0–30

cm soil depths. The conversion of grassland into cropland during the 50-year period decreased soil organic carbon density by 48% and total nitrogen density by 45%. Moreover, the soil organic carbon density and total nitrogen density revealed a positive correlation with cropland age.

The soil dissolved carbon content, available potassium content, clay content, and pH value were higher in the grassland than in the cropland soil. The soil available phosphorous content showed no differences between cropland soil and grassland soil. Our study demonstrates that grassland had a higher nutrient content (excluding available phosphorous content) than cropland. A longer cropland age was correlated with a lower soil nutrient content. A trend of higher soil sand content and lower clay content was observed with increasing cropland age.

How to improve soil quality will be a future concern in the study area. Based on our results, we conclude that frequent cultivation should be strictly avoided, and conservation tillage is expected to significantly prevent soil organic carbon loss and enhance soil organic carbon sequestration in the croplands.

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