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Original article

Seasonal variations in nitrogen mineralization under three land use types in a grassland landscape

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ABSTRACT

Soil nitrogen (N) mineralization is an important component of the N cycling process in ecosystems. In this study, we assessed the seasonal patterns of net soil N mineralization and nitrification using an intact soil core incubation method in the upper 0–10 cm soil layer in three representative land use types. These included a fenced steppe, an abandoned field and a crop field in a grassland landscape of Inner Mongolia, China. The study was conducted from September 2004 to August 2005. Our results demonstrate marked seasonal variations in inorganic N pools, net nitrogen mineralization and net nitrification. Net N mineralization was higher in the crop field than in the fenced steppe and the abandoned field. Daily rates of N mineralization and nitrification during the growing season were approximately twice their corresponding mean annual rates. Accumulative mineralization and nitrification of N during the growing season accounted for about 90 and 85% of that measured for the entire year. Rates of mineralization and nitrification were positively correlated with soil bulk density, but negatively correlated with soil pH. Net N mineralization and nitrification were strongly regulated by land use, precipitation, soil water and temperature.

1. Introduction

Nitrogen (N) mineralization is a major process supplying mineral N to plants in terrestrial ecosystems (Vitousek and Howarth, 1991). The seasonal pattern of soil N mineralization may regulate soil fertility (Pastor et al., 1984; Xu et al., 2007) and affect plant growth (Nadelhoffer et al., 1985; Antil et al., 2001) and is responsible for variations in primary production (Burke et al., 1997; Reich et al., 1997; Joshi et al., 2006). Soil N mineralization also affects trace gas production in natural ecosystems (Davidson et al., 1993), and alters N cycling routes. For example, by enhancing soil net N nitrification, soil N mineralization can result in increased nitrate losses (Aber et al., 1998; Wright and Rasmussen, 1998). The temporal pattern of soil N mineralization should be documented to gain a better understanding of the mechanisms underlying the role of N in the function of a particular ecosystem. Previous studies on soil N mineralization demonstrate that marked seasonal and temporal variation can occur in different ecosystems, such as grassland (Neill et al., 1997; Steltzer and Bowman,

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1998), forest (Pastor et al., 1984; Vitousek and Matson, 1985) and other ecosystems (Fisk and Schmidt, 1995; Schimel et al., 2004) during both the growing season (van Wijnen et al., 1999; Zhu and Carreiro, 2004) and non-growing season (Groffman et al., 2001; Schimel et al., 2004). However, we still lack a consistent conclusion about seasonal patterns of N mineralization. Some studies have reported that mineralization is lower during the growing season than during winter due to microorganisms immobilizing nutrients during summer while nutrients are released from lyzed cells of dying microbes during winter (Nadelhoffer et al., 1991; Schmidt et al., 1999). Others have found that greater N mineralization occurs during the growing season than during the non-growing season due to higher temperature coupled with greater soil moisture in the growing season (Ehrenfeld et al., 1997; Zhu and Carreiro, 2004). Two peak rates of N mineralization within a year have also been documented (Mladenoff, 1987; Uri et al., 2003). These variable results suggest site specificity in the temporal pattern of soil N mineralization.

Land use change has a great impact on soil N mineralization by modifying plant composition and abundance and soil physical, chemical and microbiological characteristics (Rhoades and Coleman, 1999). It has been widely recognized that cultivation results in carbon (C) and N losses in temperate soils (Post and Mann, 1990; Mikhailova et al., 2000; Bronson et al., 2004; Billings, 2006). These losses are caused either by increased rates of N mineralization, reduced N uptake by plants or increased loss by leaching and erosion (Vitousek et al., 1979). Increased N mineralization following disturbance can be due to changes in microenvironment and substrate quality. However, changes in levels of soil C and N and mineralization processes after agricultural abandonment are not well established and may be particularly site-specific (Compton et al., 1998).

Grassland in Inner Mongolia forms a large part of the contiguous Eurasia steppe. Severe land degradation in the Inner Mongolia plateau has occurred since the late 1970s, mainly due to growth of human populations and changes in land use practices, especially overgrazing and introduction of crop production. Recent investigation conducted in this region indicates that more than 42% of the steppe is moderately to heavily degraded. Productivity has decreased by 36–60% and more than 60% in the moderately and heavily degraded steppes, respectively (Tong et al., 2004). Heavy grazing has decreased soil organic C and N by up to 82% (Barger et al., 2004; Steffens et al., 2008). To restore degraded ecosystems and improve ecosystem functioning, new management practices have been enforced since 2000 including fencing grassland to exclude animal grazing and abandoning cropland to allow grassland to re-establish. Nitrogen will play a key role in grassland restoration because it is the most frequently limiting nutrient in this ecosystem. However, to our knowledge, there is no information about how these land use changes influence N cycling in this area.

This study investigates the seasonal variations in net soil N mineralization and nitrification, and the controlling factors of N mineralization for three contrasting land uses in Inner Mongolia, China. Questions that we addressed were: (1) what are the seasonal patterns of net soil N mineralization and nitrification under different land use? (2) Do changes in land use alter net soil N mineralization and nitrification? (3) What is the contribution to annual N mineralization and nitrification during the growing and non-growing seasons?

2. Materials and methods

2.1. *Site description*

The study was carried out in the permanent plots of the Duolun Restoration Ecology Research Station, which is located in Duolun County (42°02′N; 116°16′E; 1344 m a.s.l.), Inner Mongolia, China. This area has a typical semiarid monsoon climate. The growing season is from May to September and non-growing season from October to April. The mean annual temperature is 2.1 °C, with minimum in January (−16.7 °C), and maximum in July (24.3 °C). The mean annual precipitation is 385 mm, of which more than 80% falls between mid-June and late September (Xu and Wan, 2008). Over the period of field incubation (September 2004–August 2005), the monthly soil temperature at 5 cm depth ranged from −10.8 °C in January 2005 to 22.2 °C in July 2005, and the monthly precipitation peaked in July with 235.4 mm and was lowest with only 0.2 mm in January (Fig. 1). The soil is classified as Chestnut soil in the Chinese soil classification system, which is equivalent to Calcic Kastanozems in the FAO Soil Classification System, and Calciustolls in the US Soil Taxonomy (United

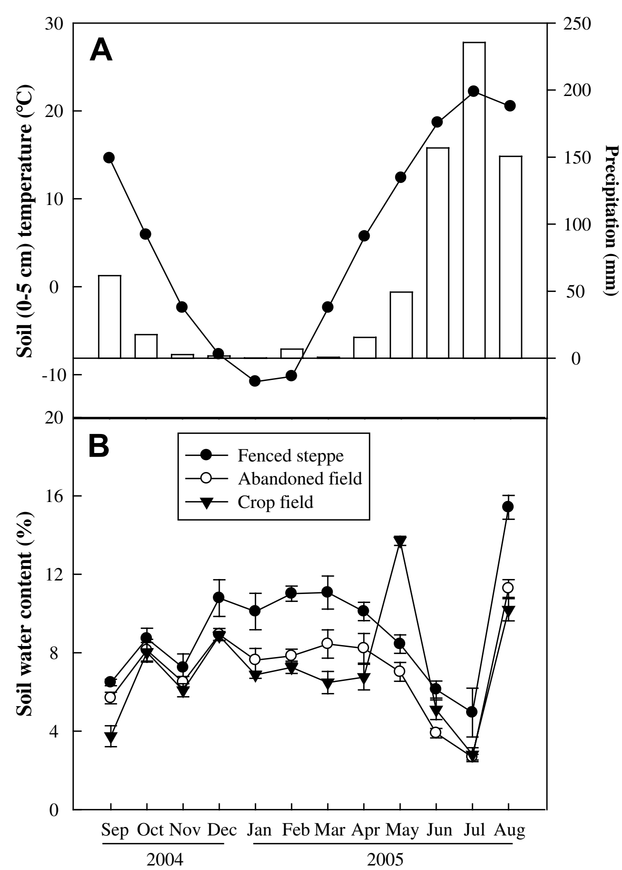

Fig. 1 – (A) Soil temperatures (0–5 cm depth, points) and precipitation (bars), and (B) soil moisture content from September 2004 to August 2005.

Table 1 – Soil (0–10 cm) characteristics measured in September 2004 in fenced steppe, abandoned field and crop field (values are mean ± SE). Different letters indicate statistical significance among the land use types at $p = 0.05$; $n = 3$ for bulk density, and $n = 5$ for other measurements

	Fenced steppe	Abandoned field	Crop field
Soil organic C (g kg^{-1})	15.26 ± 0.58^{a}	20.49 ± 0.39^{c}	18.88 ± 0.25^{b}
Total N (g kg^{-1})	1.57 ± 0.02^{a}	1.91 ± 0.02^{c}	1.67 ± 0.02^{b}
C:N	9.71 ± 0.35^{a}	10.72 ± 0.27^{b}	11.29 ± 0.18^{b}
NH_4-N (μg g^{-1})	4.60 ± 0.16^{a}	6.41 ± 0.25^{b}	6.22 ± 0.25^{ab}
NO_3-N (μg g^{-1})	1.19 ± 0.09^{a}	2.23 ± 0.10^{a}	3.51 ± 0.36^{b}
pH	7.17 ± 0.04^{b}	6.89 ± 0.05^{a}	6.92 ± 0.03^{a}
Bulk density (g cm^{-3})	1.24 ± 0.01^{a}	1.46 ± 0.03^{b}	1.47 ± 0.01^{b}

States Department of Agriculture, 2006). Soil properties under different land uses are presented in Table 1.

The entire region is situated in a typical agro-pastoral ecotone of China and different land use types coexist in the study area. We chose the three land use types, i.e., fenced steppe, abandoned field and crop field for this study. The fenced steppe was enclosed in 2000 and its dominant plant species included *Stipa krylovii* and *Artemisia frigida*. The abandoned field had been left since 2000 and was dominated by *Artemisia scoparia*. The crop field had a history of cultivation with *Zea mays* and *Linum usitatissimum*.

2.2. Incubation

Six sampling plots (2×2 m each) with separation distances of 10–20 m were randomly placed in each land use type. Net N mineralization and nitrification were measured monthly by an intact soil core *in situ* incubation technique (Raison et al., 1987). On the first day of each month during the growing season, a pair of 5.0 cm diameter by 15 cm long PVC tubes were driven 10 cm into the soil in each plot. One tube was taken out immediately from the soil for initial inorganic N (NH_4-N + NO_3-N) analyses. Another tube was left in the field for incubation. The top of the tube was covered by a piece of plastic film with eight 1 mm diameter holes in it. After 30 days of incubation, the tube and soil were retrieved and transferred to the laboratory for the final inorganic N (NH_4-N + NO_3-N) analyses.

During the non-growing season, because of difficulty in collecting soil samples from frozen soil, seven PVC tubes were driven into the soil in each plot as described above on October 1 2004, and one tube of each plot was removed immediately for initial NH_4-N and NO_3-N analyses. One of the remaining tubes was collected from each plot on the first day of each month from November to April for final NH_4-N and NO_3-N measurements.

2.3. Soil analysis

Both initial and field incubated soil samples were sieved through a 2 mm mesh to remove visible plant material. Inorganic N concentration was measured by extracting 10 g fresh weight sieved soil with 50 ml of 2 M KCl for 1 h on a reciprocal shaker. The filtered soil extracts were analyzed for NH_4-N and NO_3-N by a segment flow analyzer (Scalar SAN^{plus}, Netherlands) at the Institute of Botany, the Chinese Academy of Sciences.

At each sampling time, additional soil samples (0–10 cm) were taken to determine soil moisture content after drying at 105 °C for 24 h. Additional samples of soil (0–10 cm) collected in September 2004 were air dried and sieved for measurements of soil total nitrogen, soil organic carbon and pH. Total N was analyzed using the Kjeldahl acid-digestion method with an Alpkem autoanalyzer (Kjektec System 1026 Distilling Unit, Sweden) and soil organic carbon was analyzed using the H_2SO_4-$K_2Cr_2O_7$ oxidation method (Nelson and Sommers, 1996). Soil pH was determined by mixing fresh soil with deionized water (1:2 w/v).

2.4. Calculating net N mineralization and nitrification

During the growing season, N mineralization on a dry mass basis was defined as the difference in inorganic N concentrations before and after incubation, and net N nitrification as the difference between NO_3-N concentrations before and after incubation. Total annual net N mineralization and nitrification were calculated by summing the net amount of mineralized and nitrified N for all of the incubation periods (Subler et al., 1998; Trindade et al., 2001). For the non-growing season, net N mineralization and nitrification rates were calculated from the month-to-month accumulations of total inorganic N and NO_3-N in the incubated soil cores (Groffman et al., 2001). The conversion of annual net N mineralization and nitrification rates from soil mass to per area unit was made using the soil bulk density data.

2.5. Statistical analyses

Two-way ANOVA with incubation time and land use as the main factors was performed for the response variables: NH_4-N, NO_3-N, inorganic N (NH_4-N + NO_3-N), net N mineralization and nitrification rates. Difference in N mineralization between the growing and non-growing season was compared by paired *T*-test. One-way ANOVA was used to test the differences of annual accumulation of mineralized N and turnover rates among the three land-use types, and a Duncan test was used to distinguish differences at $p = 0.05$. Relationships between rates of N mineralization and climate or soil characteristics were tested using Pearson correlation analysis.

All analyses were performed using the SPSS 10.0 statistical software package (SPSS Inc., Chicago, IL, USA). All results are reported as mean ± standard error on a dry soil basis.

3. Results

3.1. Soil characteristics

The soil characteristics measured at the beginning of the study under three different land uses are presented in Table 1. There were significant differences in soil organic C content and total N among the three land use types (Table 1). For example, the highest values for both soil organic C and total N were found in the abandoned field soil (Table1). Other parameters such as NH_4-N, NO_3-N, C:N, pH, and bulk density were similar for the soil of the abandoned field and crop field, but significantly higher than those of soil from the fenced steppe. The one exception was for pH which was lower ($p = 0.05$) in the two disturbed soils (abandoned field and crop field, Table 1).

3.2. Extractable nitrogen

During the 12-month study, the KCl extractable inorganic N (NH_4-N and NO_3-N) pools ranged from 2.56 to 10.27 $\mu g\ g^{-1}$ for the fenced steppe, 2.07 to 8.39 $\mu g\ g^{-1}$ for the abandoned field, and 2.48 to 30.65 $\mu g\ g^{-1}$ for the crop field (Fig. 2 and Table 2). Nitrates were the largest component of the extractable inorganic N pools for the abandoned field and crop field, while NH_4-N and NO_3-N were almost equal in the inorganic N pool of the fenced steppe (Table 2).

Results from two-way ANOVA demonstrate that both land use and sampling time as well as their interaction had a significant effect on the extractable inorganic N concentration (Table 3). However, it is important to note that when the extractable inorganic N pool was partitioned into NH_4-N and NO_3-N pools, a different land use effect was observed (Table 2, Fig. 2). Over the course of the study, soil NH_4-N showed clear seasonal patterns (Fig. 2A). Amounts of NH_4-N increased from September 2004 and reached maximal values in November in the abandoned (6.0 $\mu g\ g^{-1}$) and crop fields (5.36 $\mu g\ g^{-1}$), whereas the highest values in the fenced steppe (5.21 $\mu g\ g^{-1}$) were obtained in December 2004. In contrast to the soil NH_4-N, the NO_3-N concentrations at all sites showed a different pattern (Fig. 2B) by increasing and peaking in June 2005. Soil inorganic N in the three land use types showed similar seasonal trends to NO_3-N concentration (Fig. 2C).

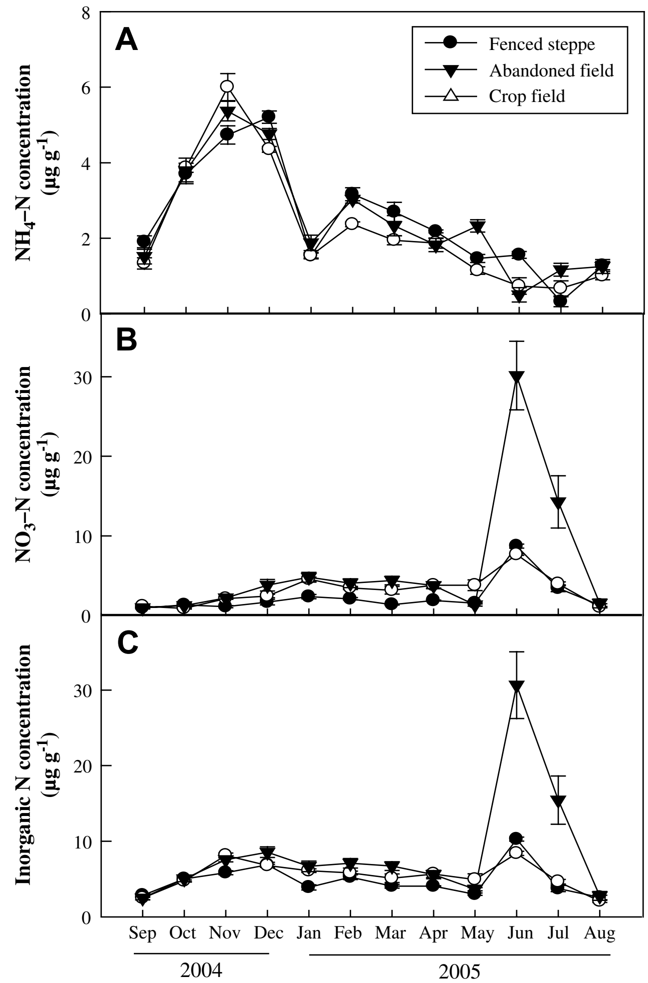

Fig. 2 – (A) Temporal variations in soil NH_4-N, (B) NO_3-N and (C) inorganic N concentrations in fenced steppe, abandoned field and crop field from September 2004 to August 2005. Values are mean ± SE, $n = 6$.

3.3. Net N mineralization and nitrification

Monthly net mineralization and nitrification rates showed seasonal variations ranging from −0.093 (immobilization) to 0.98 $\mu g\ g^{-1}$ and −0.08 (immobilization) to 0.97 $\mu g\ g^{-1}$ respectively, across all land use types and sampling times (Fig. 3). Over the sampling period, the rates were higher in the growing

Table 2 – Mean soil NH_4-N and NO_3-N concentrations, mean net N mineralization and nitrification rates, and organic N turnover rate from September 2004 to August 2005 for the fenced steppe, abandoned field and crop field (values are mean ± SE, $n = 6$). Different letters indicate the significant difference among the three land use types at $p = 0.05$

	Fenced steppe	Abandoned field	Crop field
Soil water content (%)	9.20 ± 0.40^b	7.18 ± 0.31^a	7.15 ± 0.38^a
NH_4-N ($\mu g\ g^{-1}$)	2.48 ± 0.19^a	2.24 ± 0.21^a	2.48 ± 0.19^a
NO_3-N ($\mu g\ g^{-1}$)	2.30 ± 0.27^a	3.17 ± 0.25^a	6.03 ± 1.13^b
Inorganic N ($\mu g\ g^{-1}$)	4.78 ± 0.28^a	5.41 ± 0.26^a	8.51 ± 1.06^b
Net mineralization rate ($g\ m^{-2}\ year^{-1}$)	2.46 ± 0.55^a	5.00 ± 0.62^{ab}	5.50 ± 1.35^b
Net nitrification rate ($g\ m^{-2}\ year^{-1}$)	2.30 ± 0.56^a	5.13 ± 0.56^b	5.19 ± 1.18^b
N turnover rate (%)	1.27 ± 0.28^a	1.79 ± 0.22^a	2.23 ± 0.54^a

Table 3 – Summary of two-way ANOVA (land use (LU) and sampling time (ST)) for the concentrations of NH_4-N, NO_3-N and inorganic N and rates of net N mineralization and net N nitrification

Main effects	NH_4-N ($\mu g\ g^{-1}$)			NO_3-N ($\mu g\ g^{-1}$)			Inorganic N ($\mu g\ g^{-1}$)			Net mineralization rate ($\mu g\ g^{-1}\ day^{-1}$)			Net nitrification rate ($\mu g\ g^{-1}\ day^{-1}$)		
	d.f.	*F*-ratio	*p*-value	d.f.	*F*-ratio	*p*-value	d.f.	*F*-ratio	*p*-value	d.f.	*F*-ratio	*p*-value	d.f.	*F*-ratio	*p*-value
LU	2	7.33	0.001	2	49.92	<0.001	2	49.27	<0.001	2	3.04	0.051	2	3.36	0.04
ST	11	214.51	<0.001	11	53.28	<0.001	11	41.13	<0.001	11	41.04	<0.001	11	40.91	<0.001
LU × ST	22	4.93	<0.001	22	16.11	<0.001	22	14.58	<0.001	22	7.25	<0.001	22	5.49	<0.001
Residual	144			144			144			144			144		
Total	179			179			179			179			179		

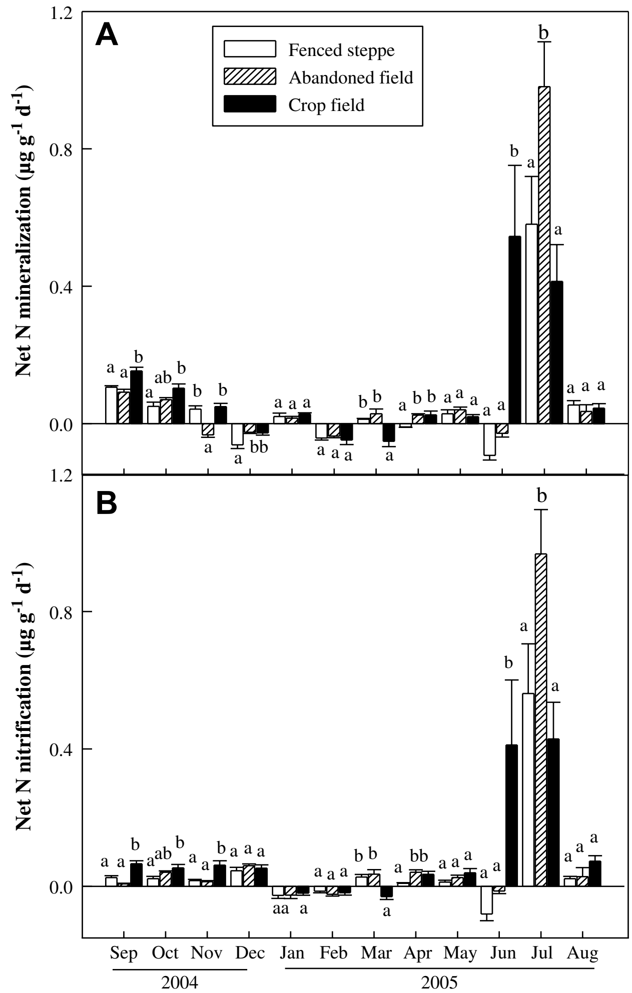

Fig. 3 – Temporal variations in net soil N (A) mineralization and (B) nitrification rates in fenced steppe, abandoned field and crop field from September 2004 to August 2005. Values are mean ± SE, $n = 6$. Different letters indicate statistical significances at different sampling times at $p = 0.05$.

season than in the non-growing season (Fig. 3A) and mean rates during the growing season in the fenced steppe, abandoned field and crop field were 2.36, 2.31 and 2.25 times as much as the annual mean daily rates, respectively. The patterns of net N nitrification rates in the three land use types were comparable to their rates of mineralization (Fig. 3B). The highest mean rate was obtained in July 2005 (0.65 $\mu g\ g^{-1}\ day^{-1}$) and the lowest in January 2005 (−0.02 $\mu g\ g^{-1}\ day^{-1}$). Mean net N nitrification rates during the growing season in the fenced steppe, abandoned field and crop field were 2.09, 2.10 and 2.12 times as much as their annual daily rates, respectively. Overall, net rates of N mineralization and nitrification and annual turnover were higher in the disturbed areas (abandoned field and crop field) than in the fenced steppe, although the N turnover rates were not statistically different among the three land use types (Table 2).

Apart from significant effects of sampling times on net N mineralization and nitrification (Table 2), soil bulk density,

Table 4 – Pearson's linear correlation coefficient (*r*) between soil characteristics and net N mineralization and nitrification rates (*n* = 15)

	Net mineralization rate (g m^{-2} $year^{-1}$)	Net nitrification rate (g m^{-2} $year^{-1}$)
Soil organic C (g kg^{-1})	0.49	0.56*
Total N (g kg^{-1})	0.39	0.47
C:N	0.37	0.40
pH	−0.50	−0.57*
Bulk density (g cm^{-3})	0.53*	0.58*

Significance at *p = 5%.

soil temperature, soil water content and precipitation significantly correlated with both soil N mineralization and nitrification (Tables 4 and 5). Despite this, soil pH and soil organic matter quality (including soil organic C, total N, and C:N ratio) did not affect net N mineralization and nitrification consistently. For example, pH and soil organic C correlated significantly with soil N nitrification but not with N mineralization (Table 4).

3.4. Accumulative N mineralization and nitrification

As expected, accumulation of mineralized N was higher in the growing season than in the non-growing season (Fig. 4A), and mean accumulation of N mineralized in the three land use types during the growing season accounted for up to 97% of their annual total fluxes. Nitrate-N produced during the growing season in the fenced steppe, abandoned field and crop field represented 87, 87 and 86% of the annual nitrification, respectively (Fig. 4B).

4. Discussion

This study demonstrates clear patterns of seasonal variation in soil inorganic N pools and both net soil N mineralization and nitrification in three contrasting land use types in a grassland landscape of Inner Mongolia, China. The highest rates of N mineralization and nitrification were observed in July and the lowest in January (Fig. 3). The daily rates of mineralization and nitrification in the growing season were about twice the annual mean rates. These results are consistent with previous studies in which significantly higher daily rates of mineralization and nitrification during the growing season than those in the non-growing season were reported (Pastor et al., 1984; Maithani et al., 1998; Zhu and Carreiro, 2004). Higher soil temperature and precipitation could account for these differences.

Temporal variations in plant growth and soil available N have been associated with plant composition and plant phenology (Warembourg and Estelrich, 2001). This in turn has been shown to affect microbial activity and to regulate the dynamics of soil N mineralization (Eviner and Chapin, 1997; Eviner, 2004; Eviner et al., 2006). During the non-growing season, plant growth was minimal, and uptake of N declined or ceased at the study sites. During the growing season, however, plant growth was stimulated by increasing soil temperature so that the demand for inorganic N increased. The period of plant uptake followed peak rates of soil microbial production of inorganic N and seasonal patterns of N mineralization matched the variation in plant growth (Eviner and Chapin, 1997; Eviner, 2004). The close coupling of N mineralization and plant uptake would constitute an important mechanism for nutrient conservation, implying that biogeochemical attributes such as available N or soil organic matter stocks can remain relatively stable.

Nitrogen mineralization and nitrification are microbe-governed processes. Soil temperature has been consistently reported to control soil microbial processes (Sierra, 1997; Dalias et al., 2002). Significant correlation between soil temperature and N mineralization observed in this study suggests that an increase in soil temperature is likely to stimulate soil mineralization by promoting microbial activity, while lower rates of mineralization in the non-growing season could be mainly attributed to lower temperatures which restrain microbial activities (Schimel et al., 2004), and inhibit soil N mineralization (Neilson et al., 2001).

Soil moisture regulates microbial processes and ecological interactions involved in nutrient cycling, and therefore affects N transformation (Amador et al., 2005). We observed significant relationships between soil moisture and N mineralization and nitrification with the maximal rates of net N mineralization and nitrification occurring when soil moisture peaked in July in this study. Soil moisture, N mineralization and nitrification shared a similar seasonal variation pattern. These results agree with previous findings in various ecosystems (Singh et al., 1991; Morecroft et al., 1992; Clein and Schimel, 1995).

The optimal soil moisture condition for microbial activity is at approximately field capacity, which corresponds to about

Table 5 – Coefficients of determination (r^2) and *p*-values in parentheses for correlations between net soil N mineralization parameters and climatic factors (*n* = 12)

		Soil (0–5 cm) temperature (°C)	Precipitation (mm)	Soil water (%)
Mineralization	Fenced steppe	0.23 (0.11)	0.43 (0.02)	0.25 (0.0.009)
	Abandoned field	0.24 (0.11)	0.50 (0.01)	0.28 (<0.0001)
	Crop field	0.46 (0.02)	0.63 (0.002)	0.13 (0.07)
	Mean	0.38 (0.03)	0.66 (0.001)	0.39 (<0.0001)
Nitrification	Fenced steppe	0.16 (0.20)	0.39 (0.03)	0.23 (0.002)
	Abandoned field	0.19 (0.15)	0.48 (0.01)	0.25 (<0.0001)
	Crop field	0.47 (0.01)	0.75 (0.001)	0.09 (0.02)
	Mean	0.28 (0.07)	0.61 (0.003)	0.37 (<0.0001)

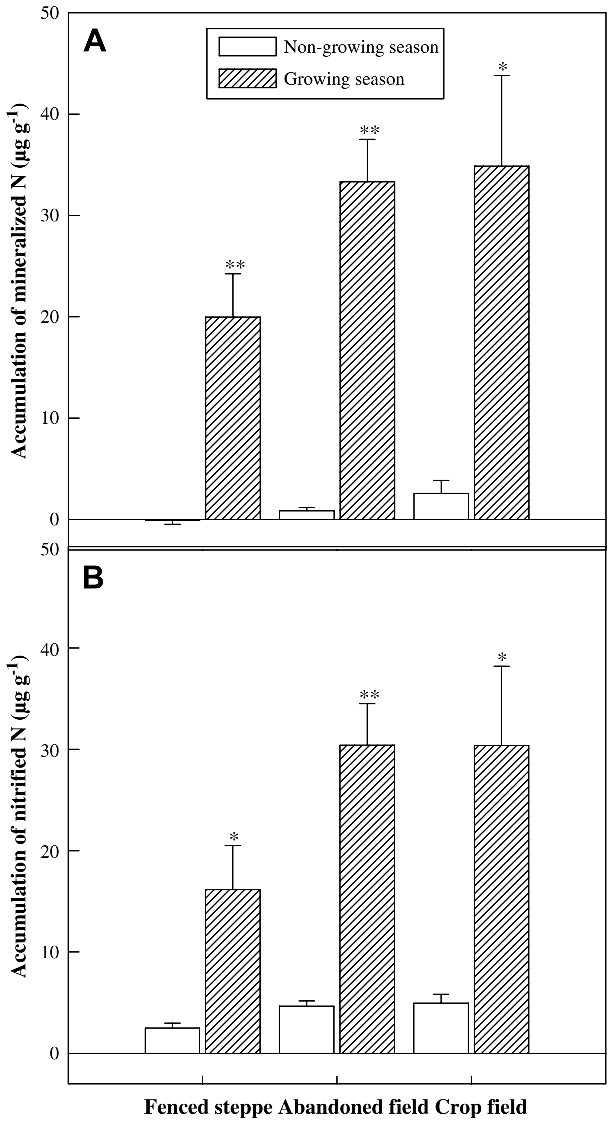

Fig. 4 – Comparisons of accumulative (A) mineralized and (B) nitrified N during the growing season with the non-growing season (October 2004–April 2005) in the fenced steppe, abandoned field, and crop field. Significance between non-growing season and growing season at $^*p = 0.05$ and $^{**}p = 0.01$.

60% of soil pore space filled with water (Linn and Doran, 1984). Wang et al. (2006) found that soil moisture content limited N mineralization when the moisture was less than 15% in Inner Mongolia grassland. Throughout the sampling period, soil water content was less than 15% which is below the limit reported and suggests that N mineralization and nitrification had been subjected to soil water limitation in our study sites.

Land use types can profoundly impact soil N cycling through the alteration of abiotic and biotic characteristics of soils and soil organic matter quality (Rhoades and Coleman, 1999; Mendham et al., 2004). In the study described here, differences in land use types resulted in variations in soil physical and chemical properties. However, total N, organic C, C:N ratio and pH of soil did not significantly correlate with N mineralization, therefore, they are not likely to be useful in explaining the pattern of mineralization among land use types. This again indicates that climatic conditions are a major factor influencing N cycling in the study area. Differences in inorganic N pools, such as the dominance of NH_4-N in undisturbed steppe and NO_3-N in abandoned and crop fields, suggest variations in microbial communities and may also explain differences in N mineralization among land use types. In contrast, net rates of N nitrification have previously been shown to relate to soil pH, ammonium supply and soil C:N ratio (Robertson, 1982; Vitousek et al., 1982; Pastor et al., 1984; Berendse et al., 1998) and these relationships were confirmed in our study. Given that disturbed fields are N-limited, higher rates of mineralization and nitrification provide more available N to plants, thus will facilitate vegetation succession in the abandoned field and enhance crop production in the crop field. Whether and how land use affects N balance is not clear and represents an important challenge for ecological research.

Many studies have demonstrated that different seasons need to be considered to fully account for the N cycling in terrestrial ecosystems (Morecroft et al., 1992; Burke et al., 1997; Maithani et al., 1998; Corre et al., 2002; Eviner et al., 2006). In particular, N transformations made during the non-growing season need to be addressed adequately (Henry, 2007). Throughout the year, mineralization and nitrification during the non-growing season accounted for about 10 and 15% of the annual accumulative N. The results suggest N biogeochemical processes during the growing season represent an absolutely dominant component of annual N fluxes in the Inner Mongolia grassland ecosystems. The contribution to annual inorganic fluxes during the non-growing season is much lower in our studies than in other systems such as about 40% in a taiga forest (Kielland et al., 2006). The lower contribution from the non-growing season is probably related to dryer soil and lower temperature and it is often assumed that microbial activity is minimal during a dry and cold non-growing season (Eviner et al., 2006).

5. Conclusions

We documented the seasonal variation patterns in soil inorganic N pools and the net N mineralization and nitrification in three contrasting land uses. Greater rates of N mineralization and nitrification in the disturbed fields suggest that rapid N turnover is due to the previous or current soil management practices and indicate that changes in land use alter net soil N mineralization and nitrification. Net soil N mineralization and nitrification were also influence by soil moisture, temperature and precipitation. Rates of mineralization and nitrification during the growing season were about twice the annual mean rates. Accumulative mineralization and nitrification during the growing season accounted for about 90 and 85% of the annual accumulative N transformed.

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