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Effects of vegetation and slope aspect on soil nitrogen mineralization during the growing season in sloping lands of the Loess Plateau

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ABSTRACT

The presence of vegetation has significant effects on soil nitrogen (N) turnover. However, whether these effects vary with slope aspect, vegetation type and time of season were not understood in previous studies, precluding our ability to understand how vegetation affects soil N cycling in sloping land. In this study, we investigated the effects of vegetation presence (plots with vs. without vegetation), vegetation type (grassland vs. woodland) and slope aspect (east vs. west slope) on soil N turnover during the growing season in sloping lands of the Loess Plateau, China. Soil metrics measured included concentrations of ammonium (NH_4^+), nitrate (NO_3^-) and total mineral N (Min-N) in soil solution and rates of ammonification (R_a), nitrification (R_n) and net N mineralization (R_m). We hypothesized that the presence of vegetation would deplete the soil Min-N pool and decrease R_m and that these effects would be greater in east slopes and woodlands than in west slopes and grasslands. In partial support of these hypotheses, vegetation presence decreased soil Min-N concentration but did not affect R_m. NH_4^+ and NO_3^- contributed similarly to Min-N, while R_n dominated R_m. The effects of vegetation presence on soil mineral N and N mineralization varied with the time of the season but were not related to the vegetation type and slope aspect. The soil Min-N and R_m were significantly higher in woodlands, east slopes and 0–10 cm depth than grasslands, west slopes and 10–20 cm depth, respectively. The R_a and NH_4^+ increased, while the R_n, R_m, NO_3^- and Min-N decreased with increasing soil moisture. These results indicated that soil Min-N and R_m in the sloping lands of the Loess Plateau consistently respond to vegetation presence across slope aspect and vegetation type, and were regulated by soil moisture.

1. Introduction

Sloping land is an important land position of the terrestrial ecosystem and is often used for agricultural production. Soil erosion due to tillage is the most important driver of land degradation in slopes (Basic et al., 2004; Wezel et al., 2002). Globally, the land area affected by soil erosion reached 1.643×10^7 km^2 (Lal, 2003), particularly in arid and semiarid climates (e.g., China's Loess Plateau, semiarid rangelands of Argentina) (Busso and Fernández, 2018; Fu et al., 2005). Generally, erosion results in the loss of nutrients and fine particles (Lal, 2003; Doetterl et al., 2016), leading to decreases in soil fertility and thus productivity of the ecosystem (Wezel et al., 2002). Establishing natural vegetation (grass or forest) is proven an effective way to prevent erosion and to improve soil quality of the slopes (Bennett, 2008). For example, the Grain for Green Program, aimed at rehabilitating the eroded lands in China, has decreased the sediment load from the Loess Plateau into the Yellow River from 1.34 ± 0.64 Gt yr^{-1} during the 1951–1979 period to 0.73 ± 0.28 Gt yr^{-1} during the 1980–1999 period, and further down to 0.32 ± 0.24 Gt yr^{-1} during the 2000–2010 period (Wang et al., 2016). In addition, this practice significantly increases soil organic carbon (C) and total nitrogen (N) concentrations in the Loess Plateau, with increasing rates of 0.23 and 0.03 g kg^{-1} yr^{-1}, respectively (Deng and Shangguan, 2017). The accumulation of soil organic matter and the reservation of soil nutrients could either increase N mineralization and availability due to the priming effects of the increased input of soil organic materials (Berhe et al., 2014; Doetterl et al., 2016) or decrease them due to the immobilization effect of increased microbial biomass and activities

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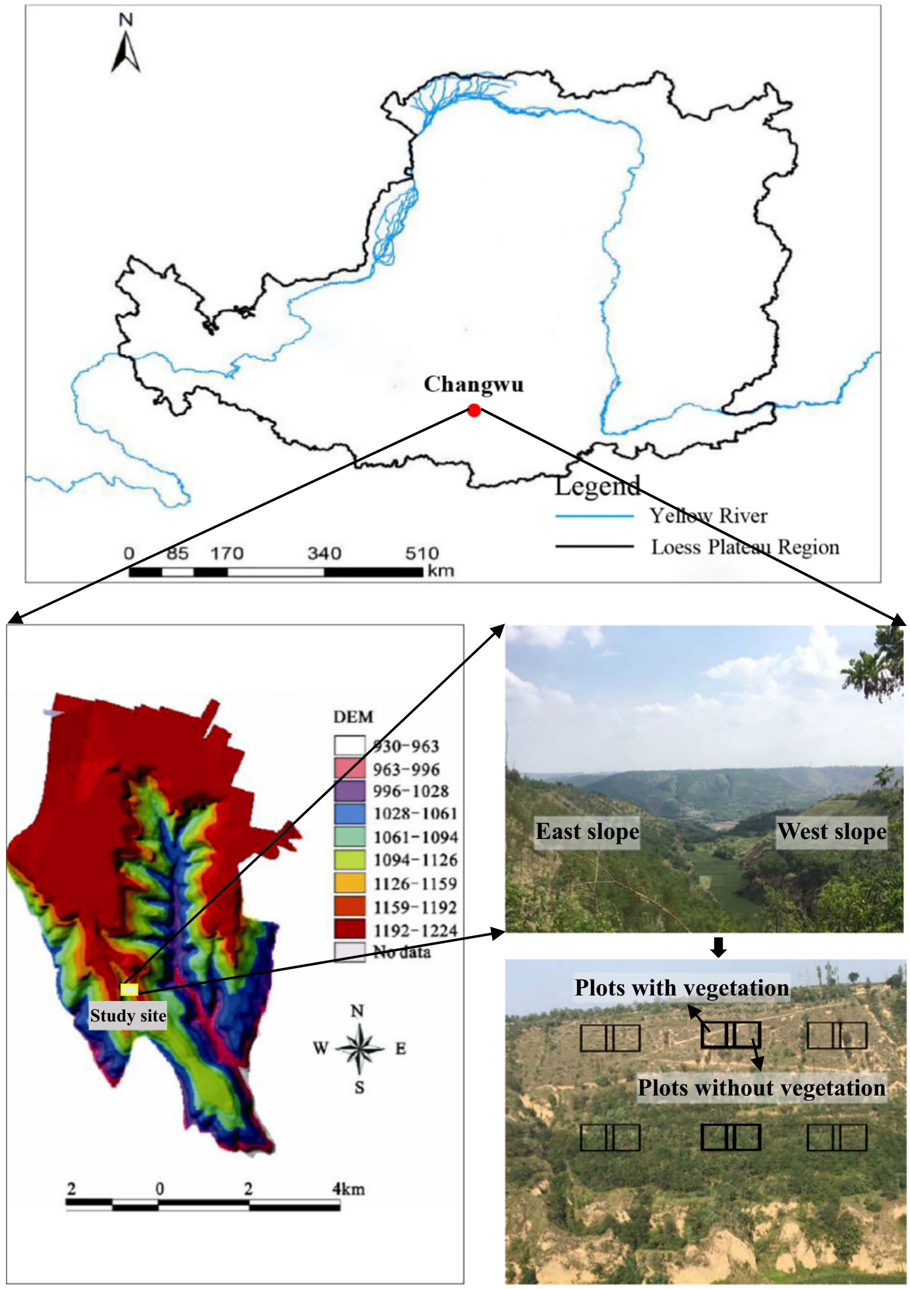

Fig. 1. Location of the study site and sampling scheme.

(Seagle et al., 1992; Wang et al., 2010; Guo et al., 2018). The response of land surface processes to vegetation establishment would thus provide important regulation on biogeochemical cycles in the sloping lands.

The slope aspect plays a vital role in determining soil moisture and solar radiation and thus soil heat flux between the soil and atmosphere (Bennie et al., 2008; Chesson et al., 2004). Generally, the slope aspect alters radiation and soil evaporation, and thus influences plant composition (Clifford et al., 2013; Deák et al., 2017). These variations considerably affect soil biogeochemical cycles and vegetation patterns (Zhao and Li, 2017). For instance, Hishi et al. (2017) observed higher rate of net N nitrification in the north facing slopes than in the south facing slopes in the Ashoro Research Forest on the east side of inland Hokkaido, Japan. They attributed this effect to the differences in the C/N ratio, acidity and soil moisture between the two slopes. Gilliam et al. (2015) showed that N mineralization was dominated by ammonification in the southwest slopes but by nitrification in the northeast slopes at two forested sites of West Virginia. However, Westerband et al. (2015) and Zak et al. (1991) reported no response in nitrification and N mineralization with respect to the slope aspect in semiarid pinyon-juniper woodlands and upland pin oak forest, respectively. This inconsistency in the response of soil cycles to the slope aspect might be due to the variations in vegetation coverage and type. For example, Hishi et al. (2014) revealed that the rates of N mineralization and nitrification were higher in larch plantations than in natural broad-leaved forests, especially on south facing slopes. Although the effects of the slope aspect and the presence of vegetation were described in previous studies, the interaction of the two factors was rarely examined.

The turnover and the availability of soil N have important influence on terrestrial ecosystems, with higher soil N availability contributing to higher plant C assimilation and productivity (Vitousek and Howarth, 1991; Reich et al., 1997) but lower species diversity (Stevens et al., 2004; Isbell et al., 2013). In this study, we present the results of soil N mineralization during the growing season as affected by vegetation presence (plots with vegetation vs. without vegetation), vegetation type (grassland vs. woodland) and slope aspect (east vs. west slope) in the sloping land of China's Loess Plateau to test the following hypotheses: (H1) plots with vegetation have lower soil mineral N pools and net N mineralization rates than plots without vegetation due to the plant uptake of mineral N and the immobilization effects of new input organic materials (Knops et al., 2002; Wei et al., 2017a); (H2) soils in east slopes and woodlands have higher mineral pools and rates of N mineralization than those in the west slopes and grasslands because the soils under legume plants (black locust) have higher mineral pools and N mineralization rates than soils under non-legume plants (grasses in this study), and the productivity of the vegetation is smaller in the east slope than the west slope, while large productivity results in lower soil mineral N and mineralization rates due to the uptake and immobilization; (H3) the effects of vegetation presence would be greater in the east slope and woodland than in the west slope and grassland; and (H4) the effect of vegetation presence and its response to vegetation type and slope aspect would be regulated by soil moisture because soil moisture affects the availability of substrates to microbes (Wang et al., 2003; He et al., 2014). The Loess Plateau is one of the regions in the world that suffers severe soil erosion, and the ecosystem is highly vulnerable to human activities and global changes (Wei et al., 2006). In the past half century, the farmland in most slopes of the Loess Plateau has been converted to grassland or woodland to reduce soil erosion (Wang et al., 2016), and the vegetation coverage has been increased from 31.6% in 1999 to 59.6% in 2013 (Chen et al., 2015). These changes in vegetation on the slopes of the Loess Plateau provide a platform for us to test the interactive effects of the slope aspect and presence and type of vegetation on soil N turnover.

2. Materials and methods

2.1. Study site

This study was conducted at the Changwu Agri-ecological Station of the Loess Plateau, the Chinese Academy of Science, in the Wangdonggou watershed (107°41′E, 35°12′N) in Changwu Country, Shaanxi Province, China (Fig. 1). The watershed has an area of 8.3 km^2 and is located at an elevation of approximately 1200 m above mean sea level. The region has a warm temperate semi-humid continental climate with a mean annual temperature of 9.1 °C and mean frost-free period of 171 days. The mean annual precipitation is 584.1 mm, primarily occurring from July to September.

The watershed is characterized by sloping land, which accounts for 65% of the total land area. Most of the sloping land was converted from cropland to grassland and woodland approximately 30 years ago to prevent the soils from erosion. The soil in the sloping land is Calcic Kastanozems according to the FAO Soil Taxonomy with concentrations of clay, silt and sand of 14.7%, 74.4% and 10.9%, respectively. The contents of organic matter and total N of the soil are 10.50 ± 0.59 and 0.70 ± 0.04 $g\,kg^{-1}$, respectively. The C/N ratio and cation exchange capacity are 8.70 ± 0.12 and 17.86 ± 0.51 $cmol\,kg^{-1}$, respectively.

2.2. Experimental design, field investigation, and soil measurement

This study was designed to address the effects of the presence and type of vegetation, slope aspect and soil depth on soil N turnover. Two counter sloping lands (east and west slopes) with sloping gradients of 48.0 ± 1.9 and 48.3 ± 2.0° were selected in April 2017 to compare the effects of the slope aspect. The length and width were approximately 180 m and 150 m, respectively, for each sloping land. In each slope, grassland dominated the upper position (ca. 100 m in length) and woodland dominated the lower position (ca. 80 m in length), respectively. In the grasslands, the dominant grasses were *Leymus secalinus* and *Stipa bungeana* in the east slope, and *Phragmites communis* and *Leymus secalinus* in the west slope. Three 1 × 1 m^2 quadrats were established in each slope to measure the growth status of the grass. The average height, canopy cover and aboveground biomass were 13 cm, 80% and 163.8 $g\,m^{-2}$ in the east slope, and 18 cm, 90% and 181.7 $g\,m^{-2}$ in the west slope, respectively. In the woodlands, black locust (*Robinia pseudoacacia*) was the dominant species in both the east and west slopes. Fifteen trees were randomly selected in each slope to determine the height, canopy area, and diameter at breast height (DBH). The DBH was measured 1.3 m above the ground. The average height, canopy area, DBH and densities of trees were 6.5 ± 0.3 m, 3.0 × 3.0 m^2, 12.0 ± 0.5 cm and 2164 ± 377 stems ha^{-1} in the east slope and 4.8 ± 0.2 m, 1.7 × 2.0 m^2, 7.1 ± 0.5 cm and 2945 ± 470 stems ha^{-1} in the west slope, respectively. Three plots (10 m × 10 m) were established in either grassland or woodland in both slopes. Each plot was composed of two paired sub-plots (3 m × 3 m). In one sub-plot, all the vegetation was retained, and the soil was not disturbed with any agricultural activity. In the paired sub-plot, all the vegetation was removed, and the soil was ploughed to simulate tillage. This sub-plot was used as the control to examine the effect of the vegetation presence.

In situ soil net N mineralization was measured in each sub-plot using an undisturbed capped buried core method (Robertson et al., 1999), by incubating soil cores (20 cm long by 5 cm diameter) in the field for one month with two sub-replicates per sub-plot. This technology isolates a quantity of soil from its environment during the incubation period, which provides the opportunity to monitor the mineral N accumulation in the absence of plant uptake, leaching, and atmospheric N deposition that might otherwise affect mineral N pools. The measurement was conducted during the growing season of 2017 (May to October) with five incubation periods. The incubation was started on 21 May and was sampled on 18 June, 18 July, 16 August, 18 September and 23 October, respectively. Soil samples from the 0–10 and 10–20 cm depths before and after incubation were extracted with 2 M KCl, and nitrate (NO_3^-) and ammonium (NH_4^+) concentrations in extracts were measured using an Auto-analyzer 3 (SEAL Analytical, Norderstedt, Germany). The concentrations of NO_3^-, NH_4^+ and total min-N before incubation were used to assess the Min-N dynamics during the growing season. To link soil mineral N and N mineralization with soil moisture, we measured the gravimetric water content in both soil samples before incubation and in incubation cores using the oven drying method. The precipitation and air temperature at the experiment site were presented in Fig. 2.

2.3. Data analysis

The rates of ammonification (R_a), nitrification (R_n) and net N mineralization (R_m) during incubation were defined as the difference

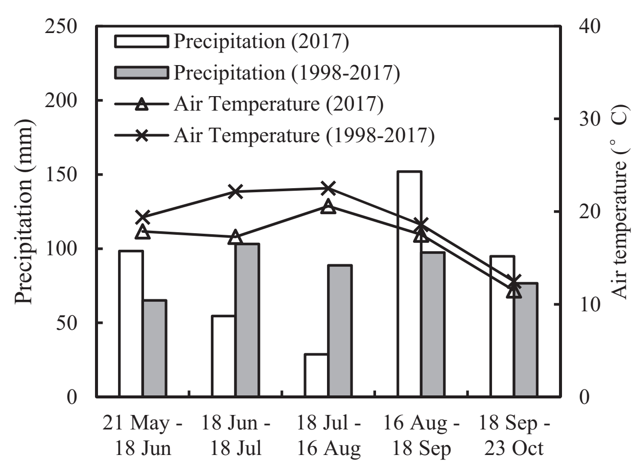

Fig. 2. Monthly mean precipitation and air temperature during the growing season in year 2017 and from 1998 to 2017 in the study site.

Table 1
ANOVA results for the effects of vegetation presence, vegetation type, slope aspect, soil depth and month on the concentrations of ammonium (NH_4^+), nitrate (NO_3^-), and total mineral N (Min-N) in soil solution and the rates of ammonification (R_a), nitrification (R_n) and mineralization (R_m) in sloping lands of the Loess Plateau.

	NH_4^+		NO_3^-		Min-N		R_a		R_n		R_m	
	F	*P*	*F*	*P*	*F*	P	*F*	*P*	*F*	*P*	*F*	*P*
VP	0.51	0.476	35.21	< **0.001**	24.03	< **0.001**	0.68	0.409	0.09	0.766	0.00	0.953
VT	0.81	0.370	12.98	< **0.001**	8.90	**0.003**	0.10	0.757	6.41	**0.012**	6.21	**0.014**
SA	41.52	< **0.001**	82.45	< **0.001**	34.03	< **0.001**	1.48	0.225	5.54	**0.019**	3.64	0.058
SD	1.38	0.242	12.91	< **0.001**	11.76	**0.001**	2.04	0.154	9.82	**0.002**	6.73	**0.010**
M	11.7	< **0.001**	6.85	< **0.001**	9.30	< **0.001**	18.73	< **0.001**	2.39	0.053	4.32	**0.002**
VP × VT	0.03	0.863	0.40	0.529	0.73	0.395	5.02	**0.026**	1.66	0.199	0.39	0.536
VP × SA	4.12	**0.044**	0.09	0.762	0.92	0.339	1.47	0.227	1.40	0.239	0.63	0.427
VP × SD	0.96	0.329	0.11	0.739	0.22	0.637	0.00	0.989	0.67	0.413	0.60	0.439
VP × M	0.64	0.673	7.70	< **0.001**	6.04	< **0.001**	2.99	**0.020**	2.91	**0.023**	2.57	**0.040**
VT × SA	1.61	0.206	1.80	0.181	1.00	0.318	0.00	0.958	1.14	0.287	1.06	0.304
VT × SD	0.34	0.561	0.25	0.617	0.00	0.962	0.06	0.813	1.87	0.174	1.53	0.219
VT × M	1.25	0.289	0.63	0.674	0.52	0.760	6.46	< **0.00**	0.68	0.606	0.46	0.764
SA × SD	3.89	**0.050**	5.01	**0.026**	1.75	0.187	0.16	0.691	2.02	0.157	2.13	0.146
SA × M	3.33	**0.006**	2.94	**0.014**	0.99	0.424	7.23	< **0.001**	3.81	**0.005**	2.49	**0.045**
SD × M	1.02	0.405	2.30	**0.046**	1.97	0.084	1.31	0.268	1.09	0.363	1.02	0.399
VP × VT × SA	5.02	**0.026**	0.00	0.982	0.07	0.786	1.61	0.207	0.29	0.593	0.73	0.395
VP × VT × SD	0.04	0.833	1.57	0.211	3.68	0.056	2.71	0.102	3.38	0.068	4.82	**0.030**
VP × VT × M	1.83	0.107	1.12	0.353	1.06	0.386	4.29	**0.003**	2.48	**0.046**	3.38	**0.011**
VP × SA × SD	0.09	0.763	0.99	0.320	0.60	0.439	0.18	0.672	2.44	0.120	1.88	0.172
VP × SA × M	1.88	0.099	0.26	0.935	0.39	0.856	0.42	0.792	0.29	0.885	0.18	0.949
VP × SD × M	0.34	0.887	0.62	0.685	0.24	0.946	0.92	0.453	0.80	0.529	0.81	0.521
VT × SA × SD	4.79	**0.030**	1.91	0.169	3.59	0.059	1.74	0.189	0.07	0.795	0.37	0.547
VT × SD × M	0.55	0.741	1.89	0.967	1.23	0.987	0.44	0.783	1.62	0.173	1.26	0.288
VT × SA × M	0.35	0.883	3.31	**0.007**	2.91	**0.015**	0.71	0.586	0.69	0.603	0.77	0.548
SA × SD × M	1.64	0.151	0.92	0.468	0.91	0.476	0.14	0.965	1.59	0.179	1.38	0.243
RMSE	0.74		2.18		2.37		0.04		0.15		0.15	
R^2	0.58		0.67		0.64		0.53		0.39		0.38	
P	< 0.0001		< 0.0001		< 0.0001		< 0.0001		0.0008		0.0018	
AICc	712		1296		1339		−716		−135		−113	

VP: vegetation presence (plots with vs. without vegetation); VT: vegetation type (grassland vs. woodland); SA: slope aspect (east vs. west slopes); SD: soil depth (0–10 vs. 10–20 cm depth); M: month (21 May, 18 Jun, 18 Jul, 16 Aug, 18 Sep and 23 Oct for NH_4^+, NO_3^- and Min-N concentrations; 21 May–18 Jun, 18 Jun–18 Jul, 18 Jul–16 Aug, 16 Aug–18 Sep, and 18 Sep–23 Oct for R_a, R_n and R_m, respectively); RMSE: root mean square error; AICc: corrected Akaike Information Criteria. Bold value indicates statistical significance.

between initial and final NH_4^+, NO_3^- and Min-N concentrations, respectively, as follows:

$$R_a = (NH_4{}^+{}_{i+1} - NH_4{}^+{}_i)/T$$

$$R_n = (NO_3{}^-{}_{i+1} - NO_3{}^-{}_i)/T$$

$$R_m = R_n + R_a$$

where NH_{4i}^+ and NO_{3i}^- are the concentrations of NH_4^+ and NO_3^- before incubation, NH_{4i+1}^+ and NO_{3i+1}^- are the concentrations of NH_4^+ and NO_3^- after incubation, respectively; and T is the days of the incubation period.

Outliers of soil mineral N concentrations or mineralization rates were assessed using Mahalanobis distance criteria (> 3.0 viewed as outlier). Among the total 288 measurements of Min-N, the outliers were 10 and 9 for NO_3^- and NH_4^+, respectively. Among the total 240 measurements of mineralization, the outliers were 6 and 4 for R_a and R_n, respectively. The proportion of the outliers was smaller than 3.5%, and thus the measurements were acceptable in this study. A multivariate analysis of variance was performed to evaluate the direct and three-way interactive effects of the vegetation presence (plots with vs. without vegetation), vegetation type (grassland vs. woodland), slope aspect (east vs. west slope), sampling date and soil depth (0–10 cm vs. 10–20 cm) on soil mineral N concentrations and mineralization rates. Pearson correlation analysis was conducted to test the relationships among soil variables. All analyses were conducted using a JMP 10.0 (SAS Institute, Cary, USA).

3. Results

3.1. Soil mineral N dynamics

Averaged across all the sources of variations, NH_4^+ and NO_3^- accounted for 46% and 54% of the Min-N pool in soil solution, and these proportions were consistent across soil depth, with 43% and 57% in the 0–10 cm and 48% and 52% in the 10–20 cm depth ($P = 0.1626$), respectively. However, these proportions varied with the vegetation type and slope aspect. For example, NH_4^+ accounted for 50% and 42% of the Min-N pool in the grasslands and woodlands ($P = 0.009$) averaged across soil depth and accounted for 30% and 61% of the Min-N pool in the east and west slopes ($P < 0.0001$), respectively. Furthermore, the proportion of NH_4^+ was significantly higher on 18 September but lower on 21 May compared with other sampling dates during the growing season.

The concentration of NH_4^+ was not affected by the vegetation presence (2.14 vs. 2.20 mg kg^{-1} in plots with and without vegetation) ($P > 0.1$, Table 1), while the concentrations of NO_3^- and Min-N were significantly lower in plots with vegetation (2.85 and 5.05 mg kg^{-1}) than without vegetation (4.84 and 7.17 mg kg^{-1}) ($P < 0.0001$, Table 1; Fig. 3). The effect of the vegetation presence on NH_4^+ was not affected by the month of the growing season ($P > 0.1$ for VP × M, Table 1), while the effects on NO_3^- and Min-N varied with the months, with significantly lower concentrations of NO_3^- and Min-N in the plots with vegetation than without vegetation in 18 Jun, 18 Jul and 16 Aug ($P < 0.05$), but similar concentrations in 21 May, 18 Sep and 23 Oct ($P > 0.05$) (Table 1; Fig. 3).

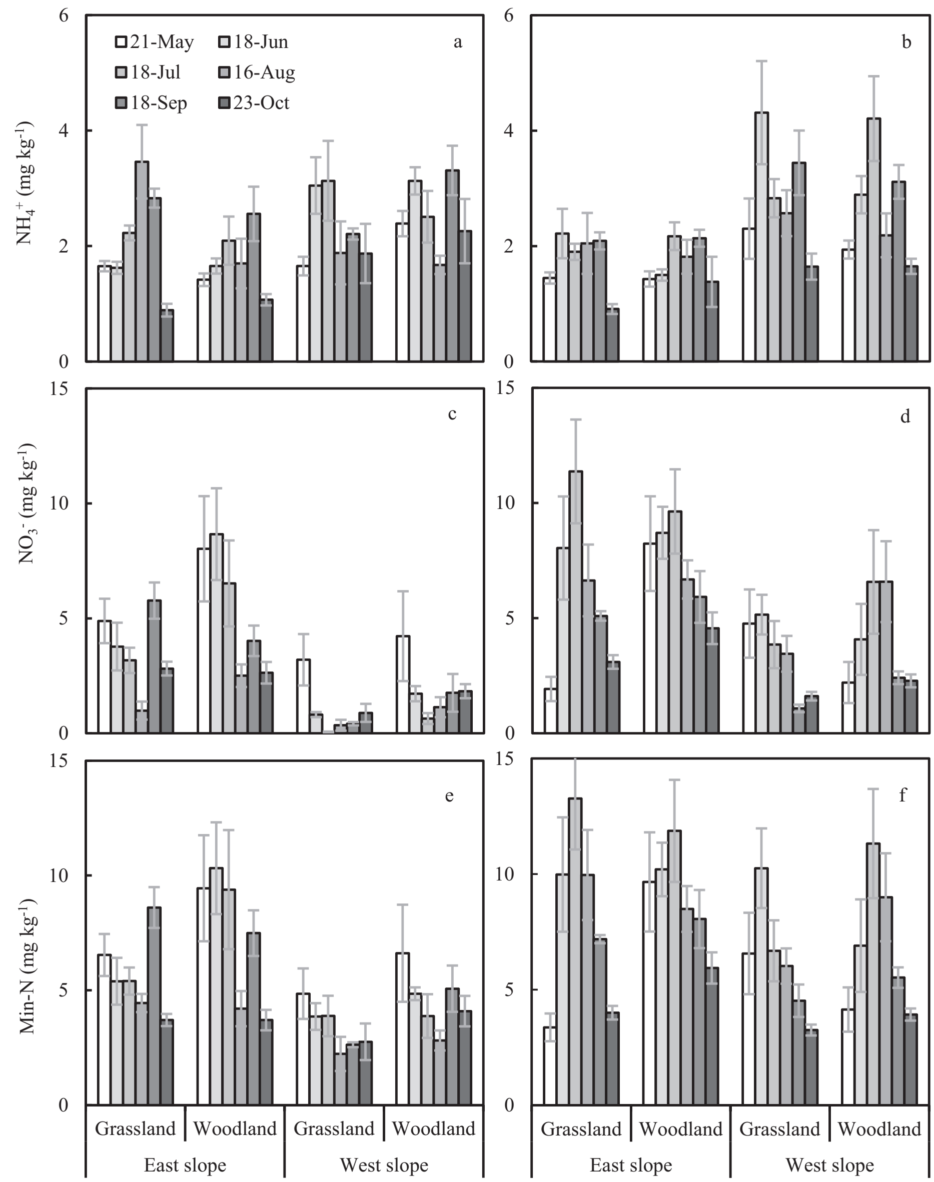

Fig. 3. Seasonal dynamics of soil ammonium (NH_4^+), nitrate (NO_3^-), and total mineral N (Min-N) concentrations in plots with vegetation (a, c, e) and without vegetation (b, d, f) as affected by vegetation type (woodland vs. grassland) and slope aspect (east slope vs. west slope) during the 2017 growing season. The values were averaged across 0–10 and 10–20 cm depth. Error bars are two standard errors of the means. n = 288.

The concentration of NH_4^+ was not affected by the vegetation type, with 2.16 mg kg^{-1} in grassland and woodland when averaged across vegetation type, slope aspect and soil depth. The concentrations of NO_3^- and Min-N were significantly higher in the woodlands (4.30 and 6.46 mg kg^{-1}) than the grasslands (3.26 and 5.41 mg kg^{-1}) ($P < 0.01$, Table 1; Fig. 3). The concentration of NH_4^+ was not affected by soil depth ($P > 0.05$, Table 1), while the concentrations of NO_3^- and Min-N were significantly higher at 0–10 cm than 10–20 cm depths ($P < 0.01$) (Table 1; Fig. S1). Soils in the east slope had significantly lower NH_4^+ but higher NO_3^- and Min-N than soils in the west slope ($P < 0.0001$, Table 1; Fig. 3) However, the effects of the vegetation presence on NO_3^- and Min-N were not influenced by the vegetation type ($P > 0.1$ for VP × VT), soil depth ($P > 0.1$ for VP × SD) and slope aspect ($P > 0.1$ VP × SA) (Table 1).

3.2. N mineralization

When averaged across all the sources of variations, R_a was −0.007 mg kg^{-1} d^{-1}, while R_n and R_m were 0.055 and 0.052 mg kg^{-1} d^{-1}, respectively. The R_a and R_n values were significantly positively correlated with R_m ($P < 0.0001$, n = 240), while the R^2 and slope of the relationship of R_a to R_m (0.08 and 0.09) were lower than those of the relationship of R_n to R_m (0.86 and 0.88) (Fig. S2). Therefore, the net N mineralization was dominated by nitrification in this study site. These patterns were consistent across vegetation presence, vegetation type and soil depth, but varied with the stages of the growing season (Table 1; Fig. 4). For example, R_n and R_m were positive in all five incubation periods, while R_a was negative in two of the five periods (18 Jul–16 Aug and 18 Sep–23 Oct).

When averaged across all the sources of variations, plots with and without vegetation had similar R_a (−0.009 vs. −0.006 mg kg d^{-1}), R_n (0.058 vs. 0.051 mg kg d^{-1}) and R_m (0.055 vs. 0.048 mg kg d^{-1}) (Table 1; Fig. 5). However, we observed significant interactions between the incubation periods and vegetation presence on N mineralization rate ($P < 0.05$ for VP × M, Table 1). The presence of vegetation significantly decreased R_n and R_m in the first two incubation periods but increased them in the following three incubation periods. R_a was more negative in plots with vegetation than plots without

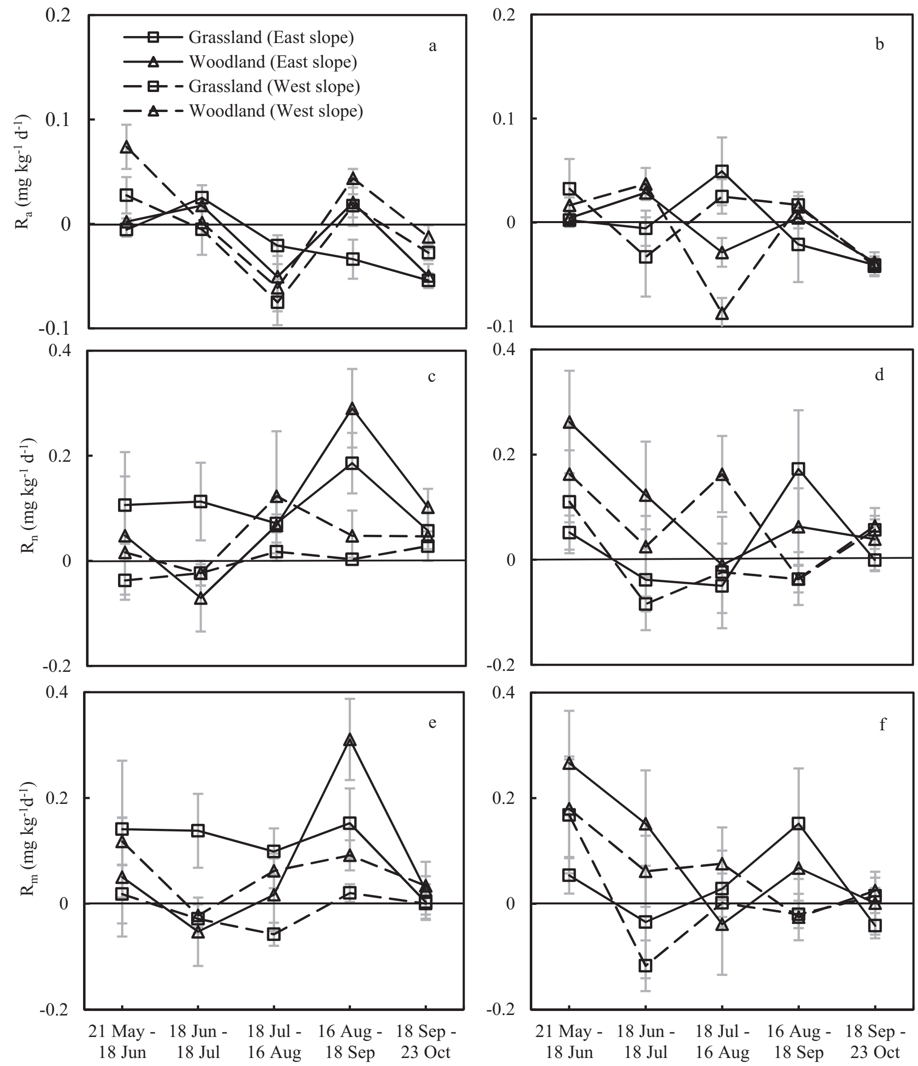

Fig. 4. Seasonal dynamics of soil ammonification (R_a), nitrification (R_n) and mineralization (R_m) rates in plots with vegetation (a, c, e) and without vegetation (b, d, f) as affected by vegetation type (woodland vs. grassland) and slope aspect (east slope vs. west slope) during the 2017 growing season. The values were averaged across 0–10 and 10–20 cm depths. Error bars are two standard errors of the means. n = 240.

vegetation in the 18 Jul–16 Aug period but was higher or less negative in the remaining four incubation periods (Fig. 5). R_a was not affected by vegetation type, slope aspect and soil depth ($P > 0.1$), while R_n and R_m varied significantly or marginally significantly with these factors (Table 1). For instance, R_n and R_m were 114% and 94% higher in woodlands than grasslands, 153% and 141% higher in the east slope than the west slope and were 327% and 334% higher at 0–10 cm than 10–20 cm depths, respectively (Figs. 4 and S1). However, R_a, R_n and R_m were not affected by the interactions of the vegetation presence with these factors ($P > 0.1$ for VP × VT, VP × SA and VP × SD, Table 1).

3.3. Soil moisture dynamics and its regulation on soil N transformation

Soil moisture was not affected by vegetation presence, vegetation type and soil depth but was significantly affected by the slope aspect, stage of the season and their interactions (Fig. 6). Generally, soil moisture was significantly lower at the middle stage of the growing season and was higher in the west slope than the east slope. In addition, the effect of the slope aspect on soil moisture was greater at the early stage than the middle and late stages of the growing season, and this effect was consistent across vegetation presence, vegetation type and soil depth (Fig. 6).

The concentration of NH_4^+ increased significantly with increasing soil moisture ($P < 0.05$, Fig. 7), while NO_3^- and Min-N decreased significantly. The R_a increased, while the R_n and R_m decreased with increasing soil moisture, although these effects were not statistically significant ($P > 0.1$, Fig. 7). When the vegetation presence, slope aspect and soil moisture were included in the model, R_a and R_m were marginally significantly influenced by soil moisture ($P = 0.06$ and 0.05, respectively, Table 2) and R_a was significantly influenced by the interaction between the slope aspect and soil moisture ($P < 0.01$ for SA × SM, Table 2). The mineral N pool was significantly influenced by the interaction between the vegetation presence and soil moisture (on NO_3^- and Min-N) and the slope aspect (on NH_4^+) ($P < 0.05$ for VP × SM and VP × SA, Table 2). Therefore, soil mineral N pool and N mineralization was mediated by soil moisture.

4. Discussion

Examining the influence of vegetation on soil N dynamics and turnover in sloping land with different vegetation types provides essential information for the mechanistic understanding of soil biogeochemical cycles of N with respect to the management of sloping land. Our results demonstrated that mineral N pool in soil solution was decreased, while net N mineralization was not affected by the vegetation presence, and most soil metrics were higher in the woodlands and east

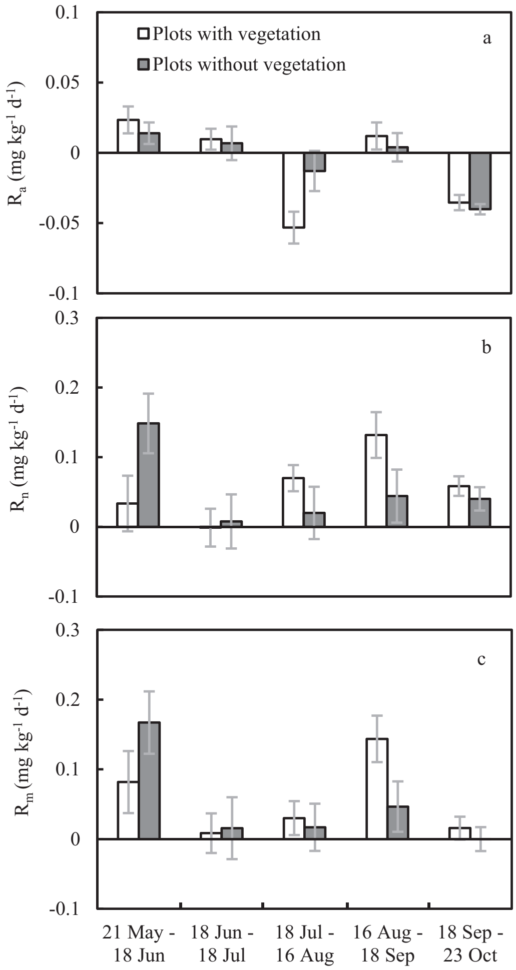

Fig. 5. Effects of vegetation presence (plots with vs. without vegetation) on the rates of ammonification (R_a), nitrification (R_n) and mineralization (R_m) in each incubation period during the 2017 growing season. The means were averaged across vegetation type (grassland vs. woodland), slope aspect (east slope vs. west slope) and soil depth (0–10 cm vs. 10–20 cm). Error bars are two standard errors of the means. n = 240.

slope than those in the grasslands and west slope, respectively, partially supporting (H1) and (H2). In addition, most of these responses were not correlated to the vegetation type and slope aspect, but related to changes in soil moisture, rejecting (H3), but supporting (H4).

4.1. Soil mineral N pool

Our results showed that both NH_4^+ and NO_3^- contributed to the Min-N pool in soil solution (46% vs. 54% when averaged across all sources of the variations), which is in contrast to the previous observation that NO_3^- dominated soil Min-N in this and other regions (Wei and Shao, 2007; Shan et al., 2011). The higher NO_3^- was assumed to be due to the dry soil environment in this region, which favored the nitrification of NH_4^+ (Schmidt, 1982; Zak et al., 1991). However, the relatively higher concentration of clay (Li et al., 2008) and cation exchange capacity (Wei and Shao, 2009) in the soils of this region might have resulted in the higher NH_4^+ concentration because of more cation exchange sites (Mueller et al., 2013; Wei et al., 2017a). Therefore, our results that NH_4^+ and NO_3^- contributed similarly to soil Min-N pool were expected.

Our observations showed that the proportion of NH_4^+ to Min-N pool varied with slope aspect and the stage of the growing season. The higher concentration and proportion of NH_4^+ in the west slope might be related to higher soil moisture in this slope compared to the east slope (Fig. 6), since higher soil moisture inhibited the nitrification of NH_4^+ (Stevenson and Cole, 1999), and thus resulted in the accumulation of NH_4^+ in soils, which was further supported by our results that soil NH_4^+ significantly increased with soil moisture (Fig. 7). In contrast, the lower soil moisture in the east slope led to the higher concentration and proportion of NO_3^- in this slope than the west slope. Additionally, soil moisture influenced the uptake of NO_3^- by the roots, with higher root activities and amounts of NO_3^- uptake by the roots in soils with relatively higher moisture.

The concentration and proportion of NH_4^+ to soil Min-N pool were lower in May, which was consistent with previous observations in the Inner Mongolia grasslands and the Loess Plateau (Shan et al., 2011; Wei et al., 2011). The concentration and proportion were higher in September due to the higher soil moisture (Fig. 7) and the leaching of NO_3^--N to deep soils when the precipitation was greater than the other months of the growing season (Fig. 2). In addition, the seasonal pattern of the NH_4^+ was not affected by the presence of vegetation.

The concentrations of NO_3^- and Min-N were significantly lower in plots with vegetation than without vegetation, and the effects of the presence of vegetation were more significant in the middle stage of the growing season. Variations in plant uptake might have caused the substantial differences in NO_3^- and Min-N because NO_3^- is the most available N in soils that could be absorbed by roots (Schmidt, 1982). In addition, the seasonal pattern of NO_3^- was affected by the presence of vegetation. In the plots with vegetation, soil NO_3^- and Min-N decreased gradually due to the plant uptake during the growing season. The absorption of mineral N by the plants declined or ceased, and the intermittent freezing (Scherer et al., 1992) contributed to the accumulation of the Min-N (Hu et al., 2015) in the non-growing season, and subsequently, relative higher NO_3^- concentration were observed in the early part of the growing season. Moreover, the amount of plant uptake was greater in the middle part than the early and later parts of the growing season (Bhuyan et al., 2014a). In plots without vegetation, the concentration of NO_3^- was highest in the middle part of the growing season (Fig. 3). Our results in the plots without vegetation were consistent with the observation that soil NO_3^- peaked in the middle part of the growing season (Hu et al., 2015), primarily due to the enhanced nitrification with higher temperatures and microbial activities in the middle part of the growing season (Wang et al., 2010). Therefore, in the sloping lands with vegetation, the effects of plant uptake were greater than the effect of nitrification on soil NO_3^- dynamics. In this study, the higher NO_3^- and Min-N in the woodland than the grassland was primarily due to the higher N contents in the roots and litters from *R. pseudoacacia*, which fixes N from the atmosphere (Cierjacks et al., 2013), than those from the grasses.

Our results also indicated that NH_4^+ was relatively stable due to its association with the cation exchange sites of soil particles (Schmidt, 1982), while NO_3^- was responded to the vegetation presence, vegetation type, slope aspect and month because of the variable soil environment and plant uptake. Therefore, NO_3^- dominated the response of the mineral N in this region.

4.2. Soil N mineralization

Our results demonstrated that nitrification dominated the net mineralization in this study site, which was consistent with early observations in the Loess Plateau (Wei et al., 2011) or other regions (Liu et al., 2010; Zhou et al., 2009). This result was attributed to the relatively dry soil environment that favored nitrification, which is an aerobic process requiring oxygen for the oxidation of NH_4^+ to NO_3^- (Zak et al., 1991).

The net N mineralization in this study was not affected by the vegetation presence, which was in contrast to the results that the vegetation had a significant effect on soil N turnover (Knoepp and Swank, 1998; Wei et al., 2017a). For example, Wei et al. (2017a) reported

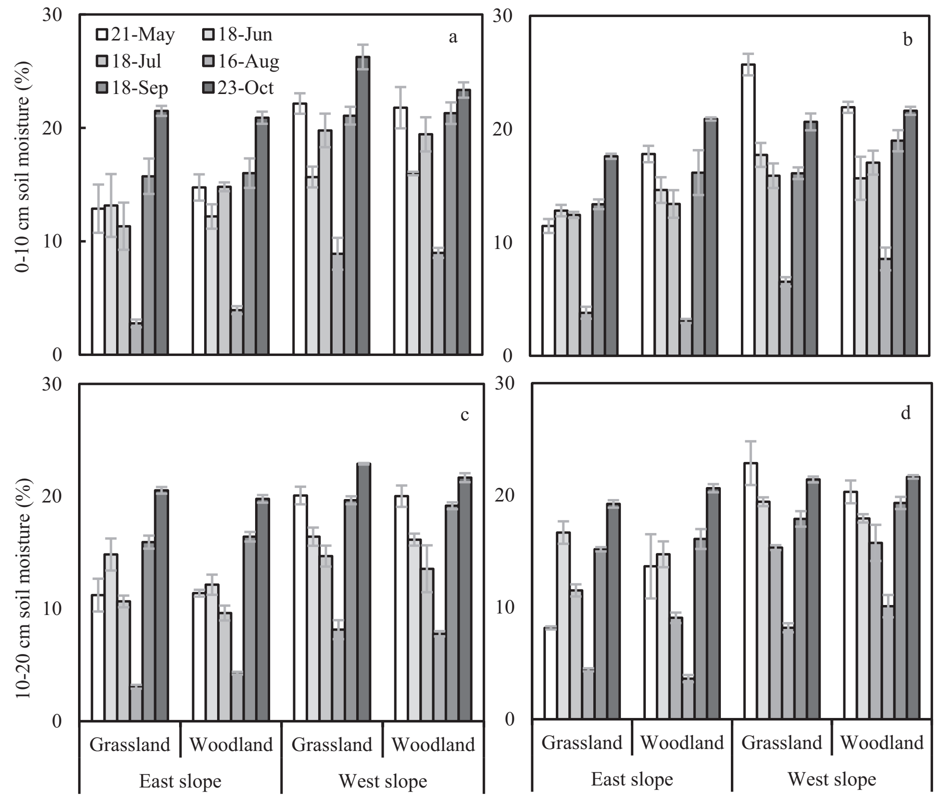

Fig. 6. Seasonal dynamics of soil moisture at 0–10 and 10–20 cm depths in plots with vegetation (a, c) and without vegetation (b, d) as affected by vegetation type (grassland vs. woodland) and slope aspect (east slope vs. west slope) during the 2017 growing season. Error bars are two standard errors of the means. n = 288.

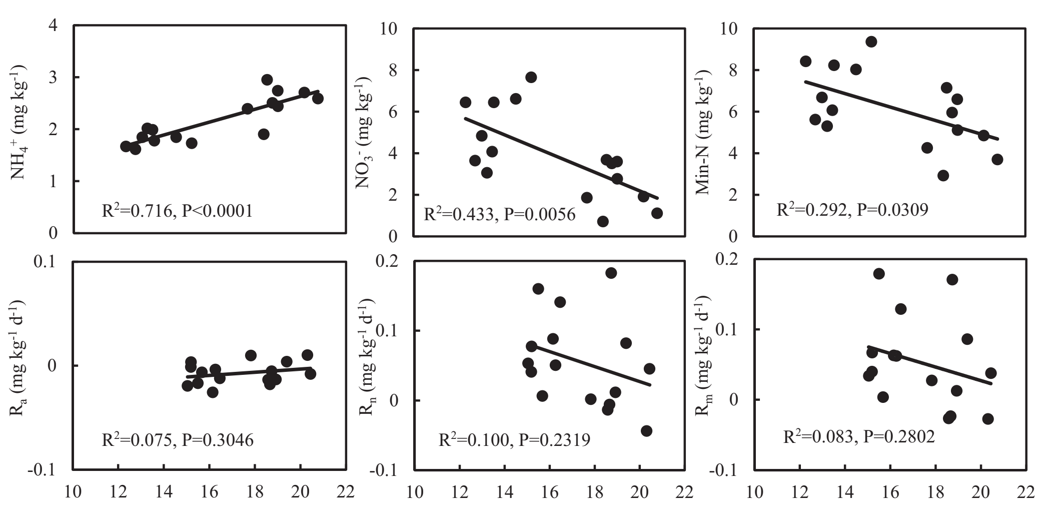

Fig. 7. The relationships of soil moisture to ammonium (NH_4^+), nitrate (NO_3^-) and total mineral N (Min-N) concentrations and rates of ammonification (R_a), nitrification (R_n) and mineralization (R_m). The means were averaged across vegetation presence, vegetation type, soil depth and slope aspect.

decreased net N mineralization with rising functional group richness in a temperate grassland at the Cedar Creek Ecosystem Science Reserve in east central Minnesota, USA. Hamilton and Frank (2001) found that grazing might lead to an increase in soil net mineralization. They ascribed the effects of vegetation on the net soil N mineralization to the changes in the root biomass, root N concentrations and microbial activities (Holland et al., 1996; Wei et al., 2017a). However, in this study, the effect of vegetations's presence on soil N mineralization varied with the stages of growing season. We showed that the vegetation enhanced R_a in most stages of the growing season, decreased R_n and R_m at the early stage but increased R_n and R_m at the middle and later stages. The enhanced R_a by vegetation might be related to the plant roots, which have priming effects on rhizosphere microbial activities associated with ammonification by the root secretions (Berendsen et al., 2012; Caravaca et al., 2005). The decreased R_n and R_m at the early stage of the growing season were due to lower temperature and microbial activities (Sierra, 1997), while the increased R_n and R_m at the middle and later stage of the growing season were due to the higher temperature and root biomass, as well as the higher activities of soil nitrifiers (Maithani et al., 1998; Schmidt, 1982). Moreover, the elimination of vegetation and

Table 2
ANOVA results for the effects of vegetation presence, slope aspect, and soil moisture on the concentrations of ammonium (NH_4^+), nitrate (NO_3^-), and total mineral N (Min-N) in soil solution and the rates of ammonification (R_a), nitrification (R_n) and mineralization (R_m) in the sloping lands of the Loess Plateau.

	NH_4^+		NO_3^-		Min-N		R_a		R_n		R_m	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
VP	1.92	0.167	30.59	< **0.001**	30.45	< **0.001**	0.05	0.832	0.02	0.894	0.00	0.950
SA	46.71	< **0.001**	66.19	< **0.001**	29.44	< **0.001**	0.02	0.878	5.76	**0.017**	5.03	**0.026**
SM	6.43	**0.012**	0.14	0.707	1.24	0.266	3.46	0.060	2.08	0.151	3.75	0.054
VP × SA	4.48	**0.035**	1.14	0.286	2.65	0.105	0.88	0.348	0.82	0.367	0.33	0.565
VP × SM	2.94	0.087	13.07	< **0.001**	14.83	< **0.001**	0.38	0.540	0.27	0.602	0.10	0.755
SA × SM	1.02	0.314	0.07	0.785	0.00	0.957	13.58	< **0.001**	2.05	0.153	0.06	0.802
VP × SA × SM	7.17	**0.008**	0.25	0.616	1.63	0.203	0.09	0.767	0.33	0.568	0.21	0.650
RMSE	0.90		2.73		2.97		0.05		0.16		0.17	
R^2	0.19		0.33		0.25		0.08		0.05		0.04	
P	< 0.0001		< 0.0001		< 0.0001		0.0098		0.1156		0.2950	
AICc	717		1315		1359		−705		−177		−155	

VP: vegetation presence (plots with vs. without vegetation); SA: slope aspect (east vs. west slope); SM: soil moisture; RMSE: root mean square error; AICc: corrected Akaike Information Criteria. Bold value indicates statistical significance.

tillage prior to the experiment may increase R_n and R_m in non-vegetative plots at the early stage of the growing season, and thus resulted in the decreased R_n and R_m by the presence of vegetation.

We also showed that R_a was not affected by vegetation type, slope aspect and soil depth, while R_n and R_m were higher in the woodland than the grassland, higher in the east slope than the west slope and higher in the 0–10 cm depth than the 10–20 cm depth. The responses of R_n and R_m to these factors might be related to the variation in soil moisture among these factors. In addition, the higher R_n and R_m in the woodlands than the grasslands were related to the N fixation by the legume tree, consistent with previous reports that soils under leguminous plants have higher R_m than soils under non-leguminous plants (Mendham et al., 2004; Wei et al., 2011). These results suggested that ammonification was relatively stable, while nitrification, and thus net N mineralization were responsible to the vegetation type, slope aspect and soil depth.

4.3. The regulation of soil moisture on soil N dynamics

We observed increased R_a but decreased R_n and R_m with increasing soil moisture (although not always significantly), which was consistent with the hypotheses that soil moisture regulates soil N turnover in highland soils (Borken and Matzner, 2009) and with previous observations in various ecosystems (Bhuyan et al., 2014b; Hu et al., 2015). Soil moisture influences N mineralization by directly changing the availability of the water to microbial activities (Orchard and Cook, 1983) and indirectly altering the aerobic microbial activities by regulating oxygen diffusion (Bhuyan et al., 2014a; Sierra, 1997). In our study, the increase in R_a with increasing soil moisture might be due to the increased activities of the microbes involved in ammonification. Additionally, both aerobic and anaerobic microorganisms are involved in ammonification, while only aerobes oxidize NH_4^+ to NO_3^- (Stevenson and Cole, 1999; Wei et al., 2017b). The decreased R_n and R_m with increasing soil moisture might be related to the reduced aeration and the restriction on the activities of nitrification-related aerobes (Stevenson and Cole, 1999), and thus increased denitrification (Zhu et al., 2013). In addition, soil moisture could affect the N mineralization by regulating soil temperature (Maithani et al., 1998). For example, Craine and Gelderman (2011) reported that soil moisture affected the temperature sensitivity of soil organic matter decomposition. Knoepp and Swank (2002) suggested interactions between temperature and moisture in influencing soil net N mineralization. However, soil temperature was not measured in this study but was investigated in situ N dynamics in many other field experiments (Dessureault-Rompré et al., 2010; Schütt et al., 2014). We therefore recommended that the effects of soil temperature and its interaction with soil moisture should be considered when considering changes in vegetation.

We did not observe a significant interaction between the vegetation presence and soil moisture on net N mineralization, indicating that the response of soil N turnover to vegetation presence was primarily dependent on plant growth ($P < 0.05$ for VR × M, Table 1), rather than changes in soil moisture.

The regulation of soil moisture on the mineral N pool in soil solution and its response to vegetation presence were ascribed to the changes in mineralization and thus the release of mineral N (Bhuyan et al., 2014a; Maithani et al., 1998). This explanation was supported by the similar response patterns of mineral N and mineralization rate to soil moisture in this study (Fig. 7). Such a regulation could also be related to the uptake of mineral N by roots because soil moisture had a significant impact on the activity and ability of roots to absorb mineral N in soil solution, which was indirectly supported by our observation that Min-N was significantly lower in plots with vegetation than without vegetation, particularly in the middle stage of the growing season (Fig. 3).

In this study, we studied the growing season dynamics of soil mineral N and N mineralization in two contrasting slope aspects as affected by the presence and type of vegetation. Soils in the non-vegetative plots were disturbed to remove plants (both above- and belowground biomass) prior to the experiment. This disturbance may have had an extra effect on soil N mineralization. Such effects decreased over time but influenced the evaluation of vegetation's effect on soil N. In addition, the contents of the mineral N and the rates of mineralization in this study were highly variable at different spatial and temporal scales. Therefore, long-term observations combined with large sampling sizes should be conducted to understand the difference between the growing and non-growing season, and the variations among years, so as to extend the results to a larger spatial scale.

Generally, the effect of plant on soil N metrics was related to the plant biomass. In the grassland of this study, the biomass was relatively small. The results of this study thus provided the effects of the presence of grass on soil N dynamics under very harsh conditions. The effect of vegetation presence in various habitats should be further investigated to link plant growth to its effect on soil N cycling.

5. Conclusions

In this study, we examined the effects of vegetation presence on soil mineral N and N mineralization during the growing season in the sloping lands of the Loess Plateau. We also tested whether these effects varied with the vegetation type and slope aspect. We found that soil mineral N pool was significantly lower in plots with vegetation than plots without vegetation, while the net N mineralization was not affected. The effects of the presence of vegetation on soil mineral N pool varied with time of the season, with increased NO_3^- and Min-N in the middle growing season but no effect in the early or late growing season. Vegetation presence significantly decreased R_m in the first two incubation periods but increased it in the following three incubation periods. However, the effects of vegetation presence were not related to the vegetation type and slope aspect. Soil mineral N and N mineralization rates were significantly higher in the woodland than the grassland, higher in the 0–10 cm than the 10–20 cm depth, and higher in the east than the west slope. R_a and NH_4^+ increased, while R_n, R_m, and the concentrations of NO_3^- and Min-N decreased with increasing soil moisture. These results indicated that slope aspect and vegetation type could be neglected when evaluating the effects of vegetation presence on soil N turnover in the sloping lands of the Loess Plateau. In addition, lower soil N availability in the plots with vegetation compared to the plots without vegetation was primarily due to the plant uptake, indicating that the N supply might limit this specific ecosystem. Appropriate amounts of N fertilizer were therefore recommended in the re-vegetated sloping lands in the Loess Plateau.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2018.09.037.

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