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Spatial variation and soil nitrogen potential hotspots in a mixed land cover catchment on the Chinese Loess Plateau

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Abstract: Soil nitrogen (N) is critical to ecosystem services and environmental quality. Hotspots of soil N in areas with high soil moisture have been widely studied, however, their spatial distribution and their linkage with soil N variation have seldom been examined at a catchment scale in areas with low soil water content. We investigated the spatial variation of soil N and its hotspots in a mixed land cover catchment on the Chinese Loess Plateau and used multiple statistical methods to evaluate the effects of the critical environmental factors on soil N variation and potential hotspots. The results demonstrated that land cover, soil moisture, elevation, plan curvature and flow accumulation were the dominant factors affecting the spatial variation of soil nitrate (NN), while land cover and slope aspect were the most important factors impacting the spatial distribution of soil ammonium (AN) and total nitrogen (TN). In the studied catchment, the forestland, gully land and grassland were found to be the potential hotspots of soil NN, AN and TN accumulation, respectively. We concluded that land cover and slope aspect could be proxies to determine the potential hotspots of soil N

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at the catchment scale. Overall, land cover was the most important factor that resulted in the spatial variations of soil N. The findings may help us to better understand the environmental factors affecting soil N hotspots and their spatial variation at the catchment scale in terrestrial ecosystems.

Keywords: Soil biogeochemistry; Spatial heterogeneity; Multivariate statistical analysis; Environmental factors; Loess Plateau

Introduction

Soil nitrogen (N) is an important component of nutrient cycling and plays a critical role in enhancing soil fertility and plant productivity (Franzluebbers and Stuedemann 2009; Wang et al. 2012). However, large amounts of excess soil N are considered to be a nonpoint source of pollution and can pollute streams, rivers, and oceans via eutrophication (Aber et al. 1989; Causse et al. 2015). Therefore, studies related to soil N and its spatial variation are essential in agricultural production practices and environmental monitoring and management fields (Ihori et al. 1995; Foster et al. 2005; Córdova et al. 2012).

In recent decades, the concept of hot spots and hot moments (HSHM) has been developed to characterize biogeochemcial cycling and achieve better management of human and natural environments (McClain et al. 2003). Originally, the concept of HSHM was defined on the measurable field where the heterogeneity of soil biogeochemical processes can be described and analyzed statistically (Johnson et al. 2010). Recently, the concept of HSHM was adopted by Kuzyakov and Blagodatskaya (2015) and used to characterize microbial processes from the millimeter to meter scales. Hotspots generally refer to those special zones/microsites, e.g. swales, riparian zones, soil horizon interfaces, wetland and rhizosphere (Andrews et al. 2011; Frei et al. 2012; Gu et al. 2012; Morse et al. 2014), with significantly higher rates of biogeochemical cycling than the surrounding matrix and thus were assumed to the hotspots (Palta et al. 2014; Bernard-Jannin et al. 2017). Hot moments are defined as short time periods with remarkably high rates of biogeochemical cycles relative to the average long-term condition (Lescop et al. 2014). Thus, the methods of real-time monitoring and high-resolution sampling are generally used to determine the hot moments (Molodovskaya et al. 2012; Edokpa et al. 2015).

Soil hydrology is considered one of the primary processes that create hotspots in terrestrial ecosystems (Frei et al. 2012; Singer et al. 2016). The variation of soil hydrology can control redox conditions, dissolved N transportation and plant N uptake, which consequently results in the spatial heterogeneity of soil N and thus the HSHM of soil N cycling (Castellano et al. 2010; Keiluweit et al. 2017; Zhu et al. 2018). Moreover, organic matter input through plant litter and manure can also create hotspots in terrestrial ecosystems and the environment (Sørensen 2010; Kuzyakov and Blagodatskaya 2015). At the field scale, soil temperature and moisture are generally assumed to be the most important environmental factors that affect HSHM (Andrews et al. 2011; Brockett et al. 2012). However, when the scale increases (e.g. the catchment scale), the environmental impacting factors increase and their effects on HSHM become more complex (Burt and Butcher 2010; Gilliam et al. 2015; Huang et al. 2015; Lozano-García et al. 2016; Zhu et al. 2012). Currently, characterizing the spatial patterns of hotspots and their controlling factors at larger scales (e.g. catchment scale) is challenging due to the complex interactions of biological and environmental factors.

The spatial distribution of soil N in a catchment is an aggregative result of the interaction of multiple environmental factors which can provide potential indications of soil N hotspots. A number of environmental factors have been reported to influence the spatial variation of soil N, including land cover, topography, and soil moisture (Wang et al. 2001; Sajedi 2010; Schwanghart and Jarmer 2011; Cao et al. 2013; Liu et al. 2013; Yang et al. 2013; Zhu et al. 2014). Zhang et al. (2016) found that land cover could significantly affect the spatial variation of soil total and available N in the Fujiang River watershed of China. Topography has also been shown to significantly influence the soil N migration and deposition through erosion and sediment redistribution processes, which can influence the spatial distribution of soil N and hotspots in the catchment (Assouline and Ben-Hur 2006;

Armstrong et al. 2011). Soil moisture is closely related to the migration and redistribution of solutes as well as the turnover and transformation of soil N by affecting soil microbial communities and activities (Nielsen et al. 1997; Brockett et al. 2012). These results demonstrate that careful exploration of the relationships between the spatial variation of soil N and its environmental factors can greatly improve the understanding of soil N cycling and its hotspots in terrestrial ecosystems.

In this study, a small catchment with mixed land cover on the Loess Plateau of China was selected as the study area, where the relationships between different environmental factors and the spatial variation and hotspots of soil N were determined. The protocols suggested by Bernhardt et al. (2017) and the multivariate statistical methods were used to determine the potential hotspots and dominant controlling factors of soil N in the studied catchment. The aims of this study were to 1) characterize the spatial distribution patterns of soil N and its hotspots, 2) determine the dominant environmental factors that influence soil N variation, and 3) evaluate the effects of the dominant factors on the spatial variation of soil N and its hotspots at a catchment scale.

1 Materials and Methods

1.1 Study area

The experiment was carried out in the Gutun watershed of Yan'an City, Shaanxi Province, China (Figure 1a). The area has a continental monsoon climate with a mean annual air temperature of 9.8°C and a mean annual precipitation of 541 mm. The dominant soil type is loessial soil, which is similar to the Calcic Cambisols (WRB 2006). The studied small catchment is a branch of the Gutun watershed, with an area of 47.0 ha and an elevation ranging from 964.2 m to 1185.4 m a.s.l. The "Grain for Green Project" has been implemented in the catchment since 1999, and the most of the land surface is now covered by trees, shrubs and grasses. The dominant tree, shrub, and grass species are *Robinia pseudoacacia*, *Sophora viciifolia* /*Hippophae*, and *Artemisia sacrorum*, respectively. The land cover of the catchment comprises 33.2% forestland, 34.0% shrubland, 30.2% grassland and 2.6% other land (Figure 2d). North-, south-, east- and west-facing slopes occupy 12.4%, 21.9%, 24.3% and 41.5% of the area of the catchment, respectively (Figure 2c).

1.2 Soil sampling and laboratory analysis

A total of 71 surface soil samples (0-20 cm) were collected in the small catchment using a hand-held auger in September 2015 (Figure 1b). In the area of slope and ridge, the sampling sites were selected based on an 80 m × 80 m grid; in the area of gully land, the sampling sites were distributed at approximately 30 m intervals. The precise location

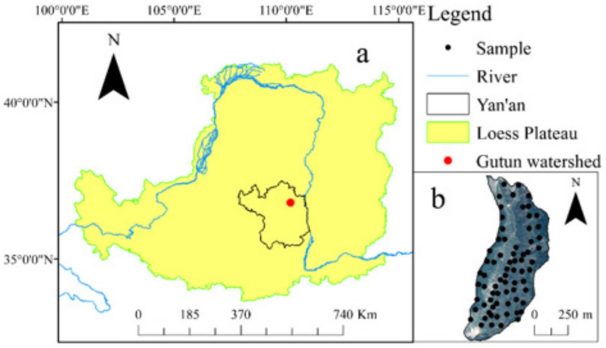

Figure 1 Location of the study area in the Gutun watershed of Yan'an City, Shaanxi Province, China: a) the Chinese Loess Plateau; and b) distribution of soil sampling sites in the studied catchment.

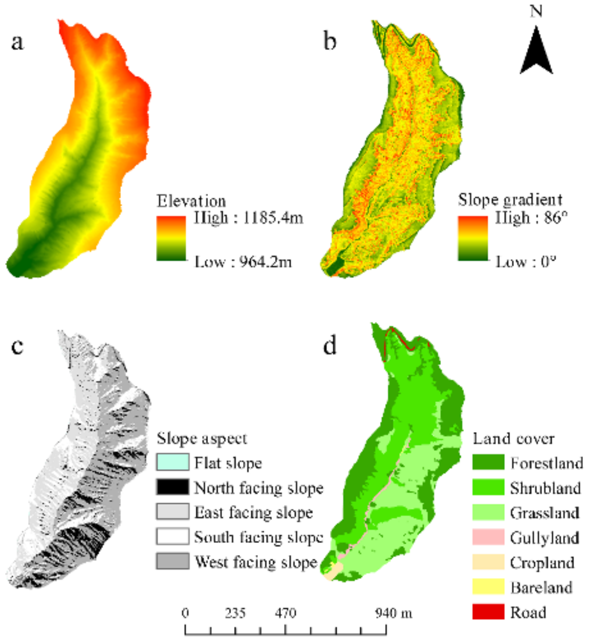

Figure 2 Elevation, slope gradient, slope aspect, and land cover in the studied catchment.

of each sampling site (elevation, longitude and latitude) was recorded using a hand-held GPS. In the area with deep slope, no soil samples were collected due to the difficulty of sampling. All the collected soil samples were divided into four parts. The first part was used for measuring the gravimetric content of soil moisture. The second part was used to measure the concentrations of soil nitrate (NN) and ammonium (AN) with a continuous flow analyzer (AutAnalyel, Bran + Luebbe GmbH, Germany) (Maynard et al. 2008). The third parts were used to determine the concentrations of total N (TN) with a Kjeltec auto analyzer (Kjeltec 8400, FOSS, Denmark). The last part was used to determine the soil bulk density.

The storages of soil NN, AN and TN were calculated based on the following equation:

$$Ns = d \times BD \times Nc/10 \qquad (1)$$

where d and BD represent the soil thickness (cm) and bulk density (g cm^{-3}), respectively. Ns indicates the storages of NN (kg ha^{-1}), AN (kg ha^{-1}) and TN: Mg ha^{-1}); and Nc indicates the concentration of NN (mg kg^{-1}), AN (mg kg^{-1}) and TN (g kg^{-1}).

1.3 Environmental factors

A total of 21 environmental factors were selected and divided into two groups. The first group consisted of quantitative factors, including elevations (GPS recorded and digital elevation model extracted), slope gradient, length and aspect, sine and cosine of the slope aspect (sin(aspect) and cos(aspect)), total curvature (a measure of flow convergence and divergence), profile curvature (a measure of flow acceleration or deceleration), plan curvature (a measure of topographic convergence and divergence), direction of runoff (flow direction, determined by the direction of steepest descent, or maximum drop), flow accumulation (calculated based on the value of flow direction in upslope), topographic wetness index (TWI, calculated based on the equation of ln(flow accumulation/tan(slope gradient))), and soil moisture (gravimetric soil water content). The second group was consisted of qualitative factors, including land cover (forestland, grassland and gully land) and slope aspect (north-, east-, south-, and west-facing slopes). The qualitative factors were then transformed to logical factors (binary response: 0 for absence and 1 for presence). Soil parent material and climatic factors were excluded because these factors varied little in the small catchment.

1.4 Data analysis

A multivariate statistical method was used to determine the main environmental factors that affected the spatial variation of soil N. The statistical method consisted of correlation analysis, principal component analysis (PCA) and multiple linear regression (Figure 3). First, Spearman's correlation analysis was used to determine the factors that were significantly correlated with the variation of soil N ($p < 0.05$). Second, the method of PCA was used to determine the critical factors from among the factors identified in the first step. PCs with high eigenvalue and factors with high factor loading were assumed to be the critical factors that best represented the system attributes (Wang et al. 2012). In this study, the PCs with eigenvalues > 1 were selected (Brejda et al. 2000). Then, the factors with highest factor loading and these factors which the factor loading was within the 10% of variation of the absolute values of the highest factor loading in each PC were selected (Mandal et al. 2008). Third, the method of correlation coefficients and correlation sums was used to reduce redundancy and exclude spurious groupings among the highly weighted factors within a given PC. The strength of the relationships among those factors was determined based on Pearson's correlation coefficients, which was used to determine the collinearities among factors in the same PC (Andrews and Carroll 2001). The correlation sums were the sum of all correlation coefficients between a specific factor and all factors. The factors with the highest correlation sums best represent the group, and the factors with the lowest correlation sums imply relative independence from the group (Mandal et al. 2008). Then, a minimum dataset of environmental factors (MDS) was compiled from each PC, including (a) the factor with the highest factor loading; (b) the factors with the highest correlation sums but correlating minimally with the factor with the highest factor loading; and (c) the factors with the lowest correlation sums but correlating minimally with the factor with highest factor loading. Finally, multiple linear regression analysis was employed to quantify the total contribution and the contribution

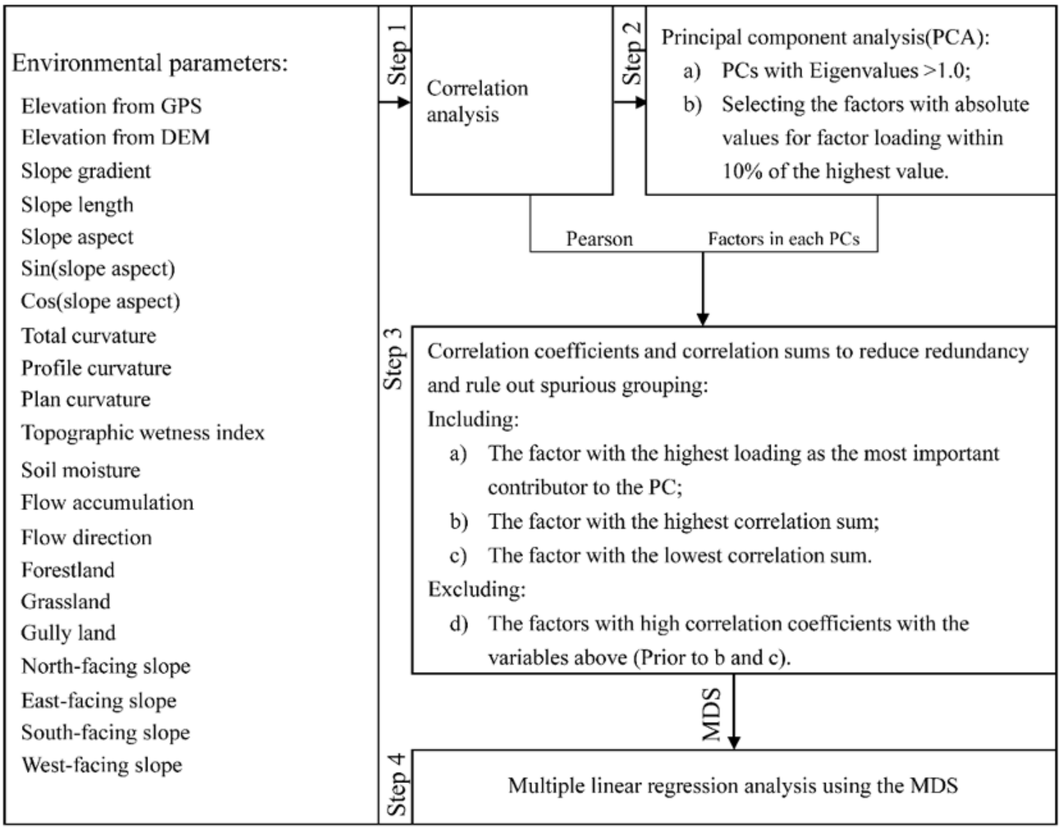

Figure 3 The multivariate statistical method that used in this present study. (MDS = Minimum data set)

of each component of the MDS to the dependent factor. In addition, the K-W and ANOVA tests were employed as auxiliary statistical methods to determine the qualitative factors (e.g. land cover factors) that affect the soil N variation (Wanshnong et al. 2013; Xiong et al. 2015).

The mean and standard deviation of the data were calculated using SPSS 20 (IBM, USA). If the distribution of soil N was not normal, the data were transformed to a normal distribution to meet the prerequisites of semivariogram analysis and kriging interpolation. Semivariogram analysis was performed to evaluate the models of the spatial variation of soil N using GS$^+$ 9.0 software (Gamma Design, USA) (Walter et al. 2001; Mishra et al. 2009; Elbasiouny et al. 2014). Ordinary kriging and regression kriging are two of the most commonly used methods in soil mapping. However, if soil properties with nugget/sill ratio (N/S) are lower than 10%, R^2 of the regression with the auxiliary variables is lower than 0.6 and the target variable is stationary (Kravchenko 2003; Zhu and Lin 2009), the method of ordinary kriging is more accurate in soil mapping when compared with the method of regression kriging. Accordingly, the ordinary kriging method was used to map the spatial distribution patterns of soil N using ArcGIS 10.2 (ESRI, USA) in this study. The spatial dependence of soil NN, AN, and TN based on nugget/sill (N/S) values were determined as follows: weak (N/S $\geq$ 75%), moderate (75% > N/S >25%) and strong spatial dependence (N/S$\leq$ 25%) (Cambardella et al. 1994). The map of land cover types was manually interpreted based on a remote sensing image with an accuracy of 0.3 m. The topographic indices from a LiDAR DEM with a 0.5-m resolution were acquired through hydrological analysis and surface analysis. In ArcGIS 10.2, hydrological analysis can generate the hydrological factors through hydrology tools, such as basin area, flow accumulation, flow direction, and stream links and order; moreover, surface analysis can generate earth surface topographic factors, such as topographic slope, aspect, contour, curvature and hill shade through surface tools. Correlation analysis, PCA, multiple linear regression analysis, the K-W test and one-way ANOVA were performed using SPSS 20.

2 Results

2.1 Overview of soil N and moisture in the mixed land cover catchment

Table 1 shows the average storages of soil NN, AN and TN. Both soil NN and AN exhibited a high variation with coefficient of variation (CV) values ranging of 77% and 100%, respectively. However, the soil TN storage changed little, with a CV of 40%. The Box-Cox conversion of soil NN and AN and the log transformation of soil TN storage met the criteria of a normal distribution (p > 0.05). The quartile N values showed a clear statistical distribution of soil N storage. Hotspots were considered to occur in the areas with values equal to or greater than the 3rd quartile N value, which corresponded to the upper quartile distribution of the data. Therefore, the areas with values greater than 14.65 kg ha^{-1}, 9.58 kg ha^{-1} and 1.89 Mg ha^{-1} were considered the potential hotspots for soil NN, AN and TN, respectively. Figure 4a shows that soil moisture decreased in the following order: N-facing slope > E-facing slope > S-facing slope > W-facing slope. Land cover significantly affected soil moisture (p < 0.05), which was significantly higher in the area of gully land areas than in the forestland and grassland (Figure 4b).

2.2 Spatial variations of soil N in the mixed land cover catchment

Figure 5 presents the semivariograms of the storages of all soil N forms and the corresponding best fit models based on the normally transformed data. The shape of the experimental semivariogram of NN, AN and TN showed good fits according to the spherical models. The clear sills showed the values of 5.652, 0.014 and 0.166 for soil NN, AN and TN, respectively, which indicated that the data of soil N met the assumption of spatial stationarity and the demand of ordinary kriging. The N/S for all soil N storages were less than 10%, indicating strong spatial dependence of soil N, which further demonstrate that the method of ordinary kriging is more accurate than the regression kriging. Ranges of soil NN, AN and TN storages were greater than the sampling interval (80 m), which suggested that

Table 1 Descriptive statistics for soil nitrogen storages

Nitrogen type	Mean ±SD	CV (%)	Skew	Kurtosis	Quartile N value			Data-TM	Skew^{a}	Kurtosis^{a}	ND
					1st	2nd	3rd				
Nitrate (kg ha^{-1})	9.66±9.63	100	1.36	1.93	1.60	7.38	14.65	Box-Cox	-0.20	-0.62	No^{b} / Yes^{c}
Ammonium (kg ha^{-1})	8.50±6.51	77	2.44	5.79	4.81	6.35	9.58	Box-Cox	0.06	-0.60	No^{b}/ Yes^{c}
Total nitrogen (Mg ha^{-1})	1.42±0.57	40	0.68	-0.26	1.03	1.31	1.89	Log	-0.15	-0.47	No^{b} / Yes^{c}

Notes: SD: standard deviation; CV: coefficient of variation; Data-TM=Data transformation method; ND= Normal distribution;

^{a} shows the analysis of the transformation data; ^{b} represents whether the original data meet normal distribution; ^{c} represents whether the transformation data meet normal distribution.

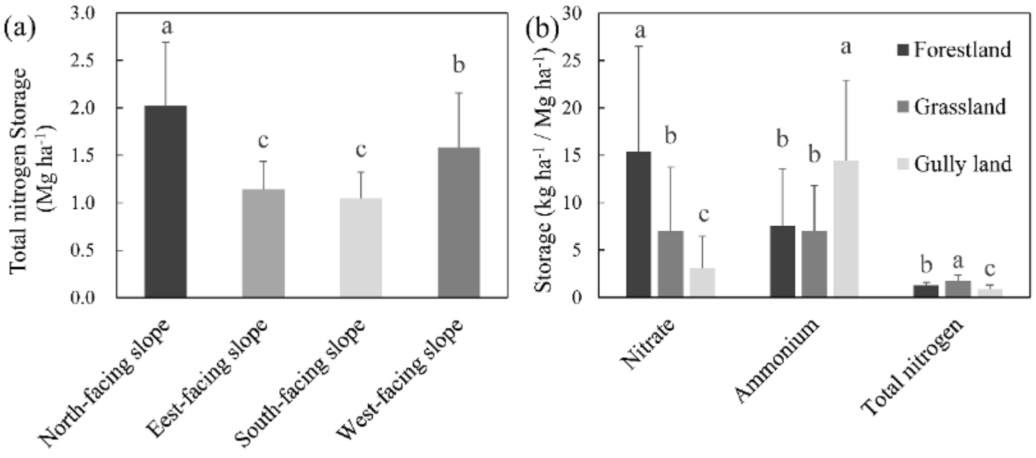

Figure 4 Differences of soil moisture among slope aspects and land covers in the studied catchment.

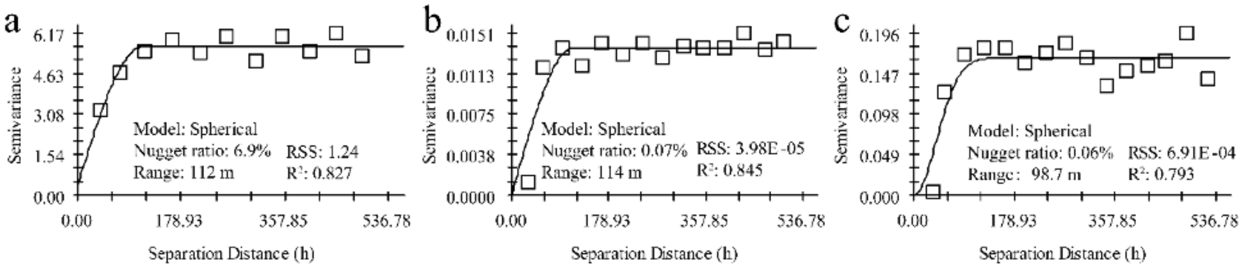

Figure 5 Semivariograms of data (square) on soil nitrogen across the studied catchment. The solid lines represent the best fit model. a) nitrate storage; b) ammonium storage; c) total nitrogen storage.

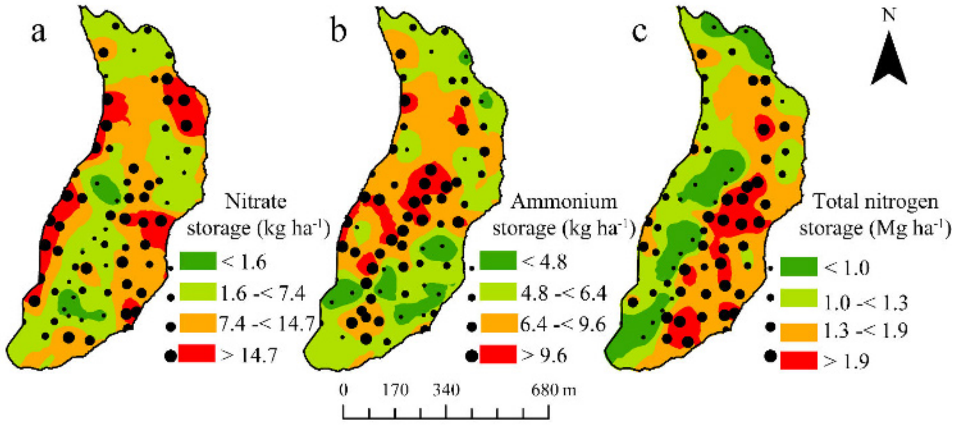

Figure 6 Spatial distributions of soil nitrogen in the studied catchment. • Soil samples with values.

the observations for the sampling sites were autocorrelated.

2.3 Spatial distribution of soil N and its potential hotspot

The spatial patterns of soil NN, AN and TN storages were first interpolated using the normal transformed data and then returned to the original values (Figure 6). Soil NN potential hotspots were mostly distributed on the forest ridges, while the lowest values were concentrated in the gully land (Figure 6a). However, the potential hotspots of soil AN were mostly distributed in the gully land, while the lowest soil AN storage were scattered in the forestland and grassland (Figure 6b). The highest values of soil TN (potential hotspots) were concentrated in the grasslands on the west- and north-facing slopes, while intermediate values of soil TN were continuously distributed in the forestland, and the lowest values were found in the gully land (Figure 6c).

2.4 Dominant factors that control the spatial variations of soil N

Table 2 shows that eleven environmental factors were found to exhibit significant correlations with soil NN ($p < 0.05$). Four environmental factors were found to be significantly correlated with soil AN and nine environmental factors with soil TN. Then, the PCA method was employed to identify the main factors among these correlated factors. For soil NN, PC1 was described by soil moisture (-0.813), elevation based on GPS (0.799), elevation based on DEM (0.803) and gully land (-0.780); PC2 was described by plan curvature (0.813) and total curvature (0.800), and PC3 was described by the flow accumulation (0.749) (Table 3). Regarding AN, soil moisture (0.926) and gully land together contributed to PC1 and east-facing slopes (0.991) to PC2 (Table 3). For TN, slope aspect (0.869), north-facing slopes (0.820) and south-facing slopes (0.900) were selected for PC1, PC2 and PC3, respectively (Table 3).

Pearson correlation coefficients and correlation sums analyses were then used to reduce redundancy and exclude spurious groupings among these factors. Regarding the soil NN in PC1, soil moisture was determined to constitute the

Table 2 Correlation coefficient between soil nitrogen and environmental factors

Factor	NN	AN	TN
Elevation from GPS	**0.319****	**-0.297***	0.119
Elevation from DEM	**0.317****	-0.229	0.103
Slope gradient	**-0.356****	0.232	-0.013
Slope length	**-0.266***	-0.191	-0.053
Slope aspect	-0.073	-0.179	**0.422****
Sin(A)	0.040	-0.001	-0.088
Cos(A)	0.028	0.074	-0.225
Total curvature	**0.310****	-0.076	0.163
Profile curvature	**-0.267***	0.076	-0.145
Plan curvature	**0.262***	-0.143	0.092
Topographic wetness index	-0.120	-0.188	-0.037
Soil moisture	**-0.294***	**0.244***	-0.012
Flow accumulation	**-0.234***	-0.195	-0.045
Flow direction	-0.071	-0.208	**0.499****
Forestland ^{a}	**0.498****	-0.170	-0.125
Grassland ^{a}	-0.204	-0.188	**0.491****
Gully land ^{a}	**-0.379****	**0.471****	**-0.486****
North-facing slope ^{a}	0.006	0.058	**0.331****
East-facing slope ^{a}	0.120	**0.238***	**-0.321****
South-facing slope ^{a}	-0.158	-0.057	**-0.294***
West-facing slope ^{a}	-0.001	-0.221	**0.295***

Notes: ^{a} logical factor (binary response: 0 for absence and 1 for presence).

Correlation coefficients in bold represent there are significant correlations between soil nitrogen and environmental factors. * Significant at 0.05 level; ** significant at 0.01 level.

NN=nitrate; AN=ammonium; TN=total nitrogen.

MDS, as it showed the highest factor loading (Table 4). Although the gully land was considered to represent an independent group, it was excluded from the MDS due to its strong correlation with soil moisture ($r = 0.856$) (Table 4). In addition, elevation derived from GPS, which exhibited the highest correlation sums, was determined for the MDS, whereas elevation derived from DEM was excluded from the MDS due to its strong correlation with elevation derived from GPS ($r = 0.943$) (Table 4). Likewise, plan curvature was selected for the MDS for PC2. Finally, the MDS of soil NN consisted of soil moisture, elevation from GPS, plan curvature and the flow accumulation. Regarding PC1 of soil AN, gully land showed the highest factor loading (0.940) and was selected, while soil moisture was excluded because of its strong correlation with gully land ($r = 0.856$) (Table 4). Ultimately, gully land and east-facing slopes were selected for soil AN MDS. In addition, the soil TN MDS includes slope aspect, north- and south-facing slopes.

Multiple linear regression analysis was carried out to evaluate the contributions of the above MDSs to soil N variation (Table 5). The regression models explained 14%, 23% and 30% (R^2) of the variance for soil NN, AN and TN storages, respectively (Table 5). Elevation (with the highest high coefficient value: 0.288), plan curvature (the second-highest coefficient value: 0.104), soil moisture (coefficient value: -0.100) and flow accumulation (coefficient value: -0.028) were determined to be the most important factors in the fitting model of soil NN. Gully land (coefficient value: 0.369, land cover factor) was considered to be the crucial factor for soil AN storage, followed by east-facing slopes (coefficient value: 0.248), based on the soil AN model. Slope aspect, north- and south- facing slopes, was the dominant factors for soil TN storage. The results of the K-W and one-way ANOVA tests further indicated that soil TN storage ($p < 0.001$) differed among different slope aspects, and land cover significantly affected soil NN, AN and TN storage ($p < 0.001$) (Table 6 and Figure 7). The results demonstrated that the level of soil NN in the forestland was significantly higher than that in the grassland and gully land (Figure 7b). Moreover, a remarkably higher AN level was found in the gully land, and TN was significantly higher in the grassland than in the other land covers. The statistical analysis suggested that land cover, soil moisture, plan curvature, elevation and flow accumulation were the dominant environmental factors for soil NN, while soil AN and TN were primarily influenced by land cover and slope aspect.

3 Discussion

3.1 Effects of nontopographic factors on soil N variation and its potential hotspots

The spatial variation and hotspots of soil N are influenced by various nontopographic factors, including land cover, organic matter, soil moisture and temperature, etc. (Zhang and Wienhold 2002; Wang et al. 2009; Wiesmeier et al. 2013; Schütt et al. 2014). Our results demonstrated that land cover with different soil water content was the dominant

Table 3 Factor loading in principal component analysis for the selected environmental factors of soil nitrate, ammonium and total nitrogen storages

Factors	Nitrate			Ammonium		Total nitrogen		
	PC1	PC2	PC3	PC1	PC2	PC1	PC2	PC3
Elevation from GPS	**0.799**	-0.430	0.062	-0.839	0.149	-	-	-
Elevation from DEM	**0.803**	-0.426	0.043			-	-	-
Slope gradient	-0.489	-0.223	-0.622	-	-	-	-	-
Slope length	-0.073	-0.276	-0.297	-	-	-	-	-
Slope aspect	-	-	-	-	-	**0.876**	-0.155	0.120
sin(A)	-	-	-	-	-	-	-	-
cos(A)	-	-	-	-	-	-	-	-
Total curvature	0.560	**0.800**	-0.191			-	-	-
Profile curvature	-0.593	-0.646	0.236	-	-	-	-	-
Plan curvature	0.434	**0.813**	-0.116	-	-	-	-	-
Topographic wetness index	-	-	-	-	-	-	-	-
Soil moisture	**-0.813**	0.301	0.067	**0.926**	-0.095			
Flow accumulation	-0.140	0.255	**0.749**	-	-			
Flow direction	-	-	-	-	-	0.768	0.437	-0.073
Forest land [a]	0.687	-0.158	0.275	-	-	-	-	-
Grass land [a]				-	-	0.705	0.073	-0.041
Gully land [a]	**-0.780**	0.305	0.182	**0.940**	0.130	-0.429	0.079	0.220
North-facing slope [a]	-	-	-	-	-	0.4442	**0.832**	0.175
East-facing slope [a]	-	-	-	0.091	**0.991**	-0.767	0.263	-0.544
South-facing slope [a]	-	-	-			-0.278	-0.169	**0.903**
West-facing slope [a]	-	-	-			0.627	-0.686	-0.272
Eigenvalue	4.144	2.483	1.261	2.453	1.030	3.294	1.488	1.285
% of variance	37.68	22.58	11.46	61.33	25.76	41.17	18.60	16.07
Cumulative variance %	37.68	60.26	71.72	61.33	87.09	41.17	59.77	75.84

Notes: Factors loading in bold are considered highly weighted when 10% of variation of the absolute values of the highest factor loading in each principal component (PC). [a] logical factor (binary response: 0 for absence and 1 for presence).

Table 4 Pearson correlation coefficient and correlation sums for highly weighted factors with high factor loading under the PCs of soil nitrate (NN), ammonium (AN) and total nitrogen (TN) storage

NN and **AN**	PC1 [a]				NN	PC2	
	EG	ED	**SM**	**Gy**		Tc	Pc
Elevation from GPS (EG)	1.000	0.943	-0.647	-0.663	Total curvature (Tc)	1.000	0.918
Elevation from DEM (ED)	0.943	1.000	-0.662	-0.615	Plan curvature (Pc)	0.918	1.000
Soil moisture (SM)	-0.647	-0.662	**1.000**	**0.856**			
Gully land (Gy)	-0.663	-0.615	**0.856**	**1.000**			
Sum	3.253	3.220	3.165	3.134			

Notes: [a] The factors including EG, ED, SM and Gy were both the main factors of NN, and the factors in bold font (SM and Gy) were only the main factors of soil AN.

nontopographic factor that affected the spatial distribution of soil N and its potential hotspots. In the studied catchment, the forestland showed a significant higher soil nitrate storage than that the other land cover types, which could be attributed to the biological N fixation in the planted trees. In the catchment, the dominant plantation species is *Robinia pseudoacacia,* which is well known to be a symbiotic N fixer and thus shows high rates of biological N fixation (Boring and Swank 1984; Ska et al. 1995). Jin et al. (2016) reported that the forestland with *Robinia pseudoacacia* plantation on the Chinese Loess Plateau showed higher soil NO_3^- levels than of grassland, and the higher soil nitrate was probably derived from soil nitrification. Moreover, the relatively dry environment in the forestland would suppress the soil nitrate loss through runoff, which would also lead to the accumulation of soil nitrate in the surface soil layer. The forestland generally has higher evapotranspiration and lower runoff and soil moisture on the Chinese Loess Plateau, which is beneficial to soil nitrate accumulation (Jin et al. 2016; Jin et al. 2018; Zheng et al. 2019). Therefore,

Table 5 Multiple regression analysis for soil nitrate (NN), ammonium (AN) and total nitrogen (TN) storages with the final minimum data set (MDS)

Nitrogen form	Predictive factor	Coefficients	t	F test		
				F	P	R^2
NN	Constant	-8.84E-16	0.000	2.742	0.036	0.143
	Elevation from GPS (EG)	0.288	1.927			
	Plan curvature (Pc)	0.104	0.904			
	Soil moisture (SM)	-0.100	-0.659			
	Flow accumulation (Fa)	-0.028	0.244			
Model	NN = (-8.84E-16) + 0.288 × EG + 0.1048 × Pc – 0.100 × SM – 0.028 × Fa					
AN	Constant	6.44E-16	0.000	10.252	< 0.001	0.232
	Gully land (Gy)	0.369	3.413			
	East-facing slope (E)	0.248	2.291			
Model	As = (6.44E-16) + 0.369 × Gy + 0.248 × E					
TN	Constant	2.75E-16	0.000	9.445	< 0.001	0.297
	Slope aspect (Sa)	0.313	2.848			
	North-facing slope (N)	0.270	2.471			
	South-facing slope (S)	-0.181	-1.729			
Model	TN = (2.75E-16) + 0.313 × Sa + 0.27 × N – 0.181 × S					

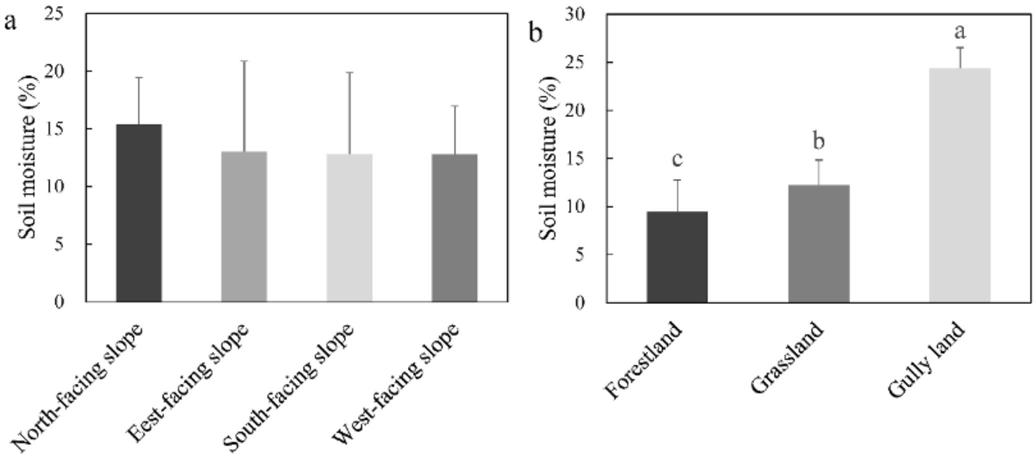

Figure 7 Effects of slope aspect and land cover on soil nitrogen storage in the studied catchment.

the land cover of forestland with *Robinia pseudoacacia* plantation is a potential hotspot of soil nitrate accumulation in the studied catchment.

In this study, the lowest soil nitrate storage occurred in the gully land, whereas the gully land showed the highest storage of soil ammonium among the three land cover types. We hypothesize that soil moisture is the primary factor that leads to the difference in soil nitrate and ammonium storage. Many previous studies have demonstrated that soil moisture can significantly influence the soil N cycling (Breuer et al. 2002; Lewis 2010). In the studied catchment, the soil water content in the gully land was significantly higher than that in the forestland and grassland (Figure 4b). Soil nitrification in the gully land could be significantly constrained by the high soil water content, while ammonification and denitrification would be promoted (Vernimmen et al. 2007). Jackson-Blake et al. (2012) also found that soil ammonification was less influenced by high soil water content, however soil nitrification was limited in high soil moisture. The high soil ammonium level observed in the high soil water environment would probably result from a high net mineralization input (Jackson-Blake et al. 2012). Thus, the gully land with a relatively high soil water content would likely be a potential hotspot of soil ammonium accumulation.

Soil TN showed a decreasing trend in the following order: grassland > forestland > gully land. The phenomenon can be attributed to the effects of an altered supply of plant litters and root function due to land cover change. Soil TN in the gully land

Table 6 Significant differences of soil nitrate (NN), ammonium (AN) and total nitrogen (TN) storages among slope aspects and land covers through Kruskal-Wallis χ^2 (K-W) test analysis

Factor	Test statistics	NN	AN	TN
Slope aspect	K-W	2.173	5.149	20.386
	df	3.000	3.000	3.000
	P	0.537	0.161	<0.001
Land cover	K-W	20.495	15.548	23.891
	df	2.000	2.000	2.000
	P	<0.001	<0.001	<0.001

was lower than that in the forestland and grassland because of the low vegetation cover and low above- and belowground litterfall input in the gully areas. In addition, the grassland showed the highest TN storage because 75% of the roots of *Artemisia sacrorum* were found to concentrate in the 0-20 cm soil layer (Zhang 2009). Wei et al. (2009) also found that soil TN concentration and storage in the native grassland, where 94% of the fine roots of the grasses were distributed in the surface soil layer, were significantly higher than that in the Chinese pine and *Korshinsk* peashrub soils. Therefore, the grassland would be a potential hotspot of soil TN accumulation.

3.2 Effects of topographical factors on soil N variation and its potential hotspots

Many studies have demonstrated that soil organic matter increases with the increase of elevation due to the restraining effects of increased precipitation and decreased air temperature in the high-elevation areas (Ping et al. 2015). In this study, the elevation difference of the studied catchment was only approximately 200 m, and precipitation and air temperature would change little under such a small elevation difference. However, elevation was determined as an important factor that led to the spatial variation of soil nitrate. We believe that the effects of elevation on soil nitrate would result from the land cover and soil moisture change under different elevation levels of the catchment. In the small catchment, we found that land cover significantly changed with the elevation of the catchment, which ranged from the gully land at the lowest elevation to the grassland/shrubland in the middle, and then to the forestland at the highest elevation (Figure 2). We believe that the land cover change has not been caused by the elevation difference, which is mostly caused by the human manipulation, e.g. the Grain for Green Project. Therefore, it is land cover, not elevation, affected the spatial variation of soil nitrate storage. Moreover, soil moisture significantly decreased with the increase of elevation ($p < 0.01$), which is actually controlled by the topography. Thus, we should pay attention that some nontopographic factors are controlled by topography, e.g. soil moisture. Therefore, nontopographical and topographical factors interactively controlled the soil N variation and its potential hotspots.

In this study, we found that plan curvature and flow accumulation were significantly correlated with soil nitrate storage ($p < 0.05$). Previous studies have demonstrated that plan curvature could influence soil moisture (Sulebak et al. 2000; Burt and Butcher 2010). However, we found no significant relationship between soil moisture and plan curvature ($p > 0.05$). Yang et al. (2017) obtained the similar results in a small catchment on the Chinese Loess Plateau, showing that there was no significant relationship between soil moisture and plan curvature. In the studied catchment, the convex area was occupied by the forestland (the plantation of *Robinia pseudoacacia*), while the gully land was located in the concave area. In addition, sites with large values of flow accumulation represent a fully connected drainage network (i.e. the gully), while sites with a flow accumulation value of zero generally correspond to the ridges (Jenson and Domingue 1988; Tarboton et al. 1991). In this study, the highest nitrate content occurred in the forestland, while the lowest occurred in the gully land. Therefore, the combination of plan curvature, flow accumulation and land cover affected the spatial variation of soil nitrate.

Slope aspect is an important topographical factor that affects the spatial variation of soil N (Yimer et al. 2006). Our results showed that the highest storage of soil TN and AN occurred on the north- and east-facing slopes, respectively. Klemmedson and Wienhold (1991) concluded that soil temperature and moisture on the north-facing slope were of benefit to the soil N accumulation and thus the north-facing slope showed higher storage of soil TN. However, south- and east-facing slopes generally receive more solar radiation than north-facing slopes in the Northern Hemisphere, which could lead to a higher soil temperature and a greater soil N loss than that on the other slope aspects (Agehara and Warncke 2005; Bennie et al. 2008; Leonelli et al. 2009). Gong et al. (2008) showed that microbial activities on the north-facing slopes were generally constrained by the relatively low soil temperature and thus the north-facing slopes showed higher soil TN content than the south-facing slopes. Schütt et al. (2014) demonstrated that soil ammonium storage could increase under a high ammonification rate due to the relatively high soil temperature on an east-facing slope.

4 Conclusions

The spatial distribution patterns of soil NN, AN, and TN differed in the studied catchment. Land cover, soil moisture, and topography were determined to be the most important environmental factors that affected the spatial variation of soil N. Land cover, soil moisture, elevation, plan curvature and flow accumulation significantly affected the spatial distribution of soil NN and its potential hotspots. Land cover and slope aspect were selected as the dominant factors affecting soil AN and TN and their potential hotspots. In the mixed land use catchment, the forestland is considered to be the potential hotspot of soil NN, and the gully land is the potential hotspot of soil AN. The grasslands and areas on the north-facing slopes could be potential hotspots of soil TN.

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