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Soil Nutrient Variance by Slope Position in a Mollisol Farmland Area of Northeast China

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Abstract: In order to generate scientifically-based comparative information to improve fertilization efficiency and reduce nutrient loss, 610 samples of 122 soil profiles were collected at the 0–60 cm depth to compare soil nutrient contents including soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), available phosphorus (AP), and available potassium (AK) among different slope positions in a Mollisol farmland area of Northeast China. The contents of SOM and TN typically decreased with increased soil depth at back and bottom slope. Soil loss and deposition tended to decrease SOM and TN at the 0–20 cm soil depth on both the back slope and the slope bottom. The TP firstly decreased from 0–20 cm to 30–40 cm, and then not constantly increased at the back slope and the bottom slope. Due to the characteristics of soil nutrients and crop absorption, the contents of both AP and AK were typically the highest at the summit, followed by the slope bottom and the back slope in the 0–20 cm layer. Generally, in order to sustain the high soil productivity and protect the environment, attention should be paid to soil conservation on back slope; in addition, additional N and P fertilizer is necessary on the back slope.

Keywords: soil organic matter; soil nitrogen; soil phosphorus; soil potassium; slope position; Mollisols; China

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1 Introduction

Studies of nutrient variance in soils were carried in different regions, and the main driving factors of nutrient variance were not always coincidence. Generally, land use, topographical factors, hydrological factors and fertilization were recognized as the key factors influencing the variance of soil nutrients (Fang and Wu, 2014; Glendell *et al.*, 2014). In the Loess Plateau of China, soil organic matter (SOM) was significantly higher at the slope bottom where there is a relatively flat landscape, and was negatively correlated to the topographic index, stream power index and sediment transport index. Similarly, total nitrogen (TN) has a negative correlation with the sediment transport index and a significant negative correlation was found between total phosphorus (TP) and slope (Lian *et al.*, 2008a; 2008b; Li *et al.*, 2014). In the sloping land of the karst region, vegetation, land use, hydrographic conditions, topography, human disturbance and strong heterogeneity of microhabitats are recognized as the main factors, and the contents of soil organic carbon (SOC), TN, available nitrogen (AN) increase with the increasing altitude (Zhang *et al.*, 2008; Fan *et al.*, 2014). Guo *et al.* (2014) also reported that SOM was mainly influenced by elevation, followed by steepness and slope aspect in a watershed of Inner Mongolia Autonomous Region. In the black soil of Northeast China, the SOM and soil nutrients were mainly influenced by latitude when considering the whole black soil region (Zhang *et al.*, 2007), while

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they were mainly determined by topographical factors, hydrological factors and fertilization at the regional or watershed scale (Zhang *et al.*, 2010; Zhang *et al.*, 2011; 2014). However, the spatial distribution of nutrients was mainly qualitatively analyzed in a larger area in the previous study, and little attention was paid to quantitative comparison between slope positions in a complete watershed.

Generally, crop roots were predominant in the 0–45 cm soil layer in farmland (Jin *et al.*, 2007). Crop systems can also maintain normal yields if fields are fertilized and cultivated appropriately, even if the top 0–20 cm of soil was eroded (Sui *et al.*, 2009). As well, SOM and nutrient contents are typically higher at the bottom of a sloped area than at higher slope positions due to soil erosion (Malo and Worcester, 1975; Voroney *et al.*, 1981; Morgan, 2005; Soon and Malhi, 2005). Therefore, soil fertility in cultivated fields can not be accurately evaluated when only considering the 0–20 cm soil depth, especially when the surface layer was not homogeneous and eroded gradually (Brady and Weil, 2000). However, most reports were mainly focused on the plough layer (0–20 cm) in previous studies, while deep soil layers were neglected, despite the fact that deep soil layers with high-density roots also typically constrain crop yields (Costa *et al.*, 2010; Zhang *et al.*, 2011; Zhang *et al.*, 2012). In farmland, fertilizer application should be referenced to nutrient distribution because undesirable and excess nutrients can remarkably increase eutrophication in surface or underground water (Brady and Weil, 2000; Chen *et al.*, 2008). Thus, the clarification of the variability of soil nutrients in deep soil layers with high root densities at various slope positions is beneficial to help farmers improve their fertilization in order to increase crop yields while at the same time reducing nutrient loss.

Most of the black soil region of Northeast China was famous for its high soil organic matter content and soil fertility, and it has been a major area of production for corn (*Zea mays* L.) and soybean (*Glycine max* L.). However, soil nutrients gradually decreased on sloped farmland during one hundred years of intensive cultivation, with serious soil erosion which threatens the sustainable development of agriculture (Zhang *et al.*, 2013). It is the premise of this study that the fertility of soil in cultivated fields can not be properly evaluated when the soil nutrients in only the 0–20 cm layer are considered, especially if the surface layer is facing severe erosion. In this study, we used both Kriging procedures and traditional analysis to describe the spatial variability of nutrients in farmland. A thorough understanding of the vertical and horizontal distribution of soil nutrients throughout the soil profile by slope position, and recognition of the relationships between nutrient distribution and soil loss and soil deposition, can enhance land management for better producer profits and environmental sustainability.

2 Materials and Methods

2.1 Study area

The study watershed (1.86 km^2) is located in Guangrong village (47°20′43″–47°21′29″N, 126°49′31″–126°50′54″E), Hailun City, Heilongjiang Province, Northeast China (Fig. 1), which is in the North Temperate Zone, and is in the continental monsoon area (cold and arid in winter, hot and rainy in summer). Average annual precipitation is 530 mm, with 65% falling from June to August. Total annual solar radiation is 113 MJ/cm^2 and average annual available accumulated temperature (≥ 10℃) is 2450℃. The average annual temperature is 1.5℃ and annual sunshine averages between 2600 h and 2800 h. Formation of soils in the study area began during the Quaternary period and occurred on loess deposits under natural grasses. The soils now have a rich, dark organic layer and are classified as Mollisols (black soil). These soils have a silty clay loam texture (Table 1), and most slopes are inclined at less than 5º, but are higher than 200 m in length.

2.2 Tillage and fertilization

The crop rotation was consisted of alternating one year of soybean with one year of corn for at least the last 6 decades. Fields were ridged-tilled at 65 cm intervals using a small tractor operating a roto-tiller after harvest in autumn, and both crops were planted in early May and harvested in October. Prescribed chemical fertilization on corn included 69 kg N/ha applied at planting with an additional 69 kg N/ha side dressed at the three-leaf stage. Soybean fertilization consisted of 20.25 kg N/ha, 51.75 kg P/ha and 15 kg K/ha was applied at planting.

2.3 Soil sample collection and measurement

There were 126 soil profiles being dug by using a random

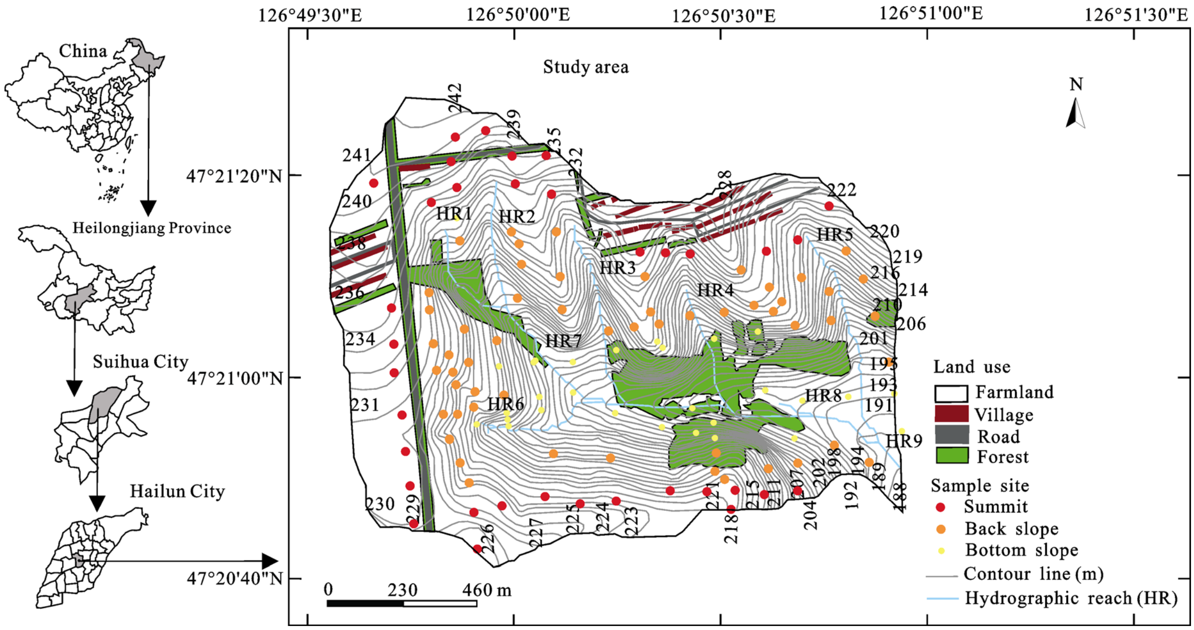

Fig. 1 Location of study area, distribution of sample sites, and land use in watershed. Hydrographic reach is the channel of the ground flow

Table 1 Soil physical and chemical properties

Soil depth (cm)	Bulk density (g/cm^3)	Total porosity (%)	Field capacity (w/w, %)	Saturated water (w/w, %)	Wilting point (w/w, %)
0–20	1.27	52.1	24.4	42.3	12.1
20–40	1.19	55.1	24.4	44.2	13.4
40–60	1.21	54.3	23.4	43.6	14.2

sampling method (Wang and Li, 2009), and soil samples were collected from 0–20 cm, 20–30 cm, 30–40 cm, 40–50 cm and 50–60 cm soil depths in autumn of 2012 after harvest. The samples were classified into summit (n = 34), back slope (n = 62) and bottom slope (n = 30) based on a Digital Elevation Model (DEM) (grid is 1 m^2) in ArcGIS 10.0 (ESRI, 2008) (Fig. 1) and the records in field (Fig. 2). The slope is relatively gentle on both the summit and bottom slope positions while the back slope position is little steeper (most slope were less than 5°). Each 0–20 cm soil sample was comprised of a mixture of five cores taken randomly from each 20 m^2 plot, while the soil samples at 20–30 cm, 30–40 cm, 40–50 cm and 50–60 cm were collected from the soil profiles which were taken in the central position of the sampling plots. Samples were air-dried and sieved at 0.25 mm for analyzing SOM, TN, TP, soil available phosphorus (AP), AK, and pH. Since the soils were free of carbonates, soil organic carbon (SOC) was assumed to be equivalent to total carbon (Liang *et al.*, 2009; Zu *et al.*, 2011). The SOM and TN were measured using an Elemental Analyzer (Vario ELIII, Germany) (Slepetiene *et al.*, 2008). The TP was determined with the molybdenum-blue method after digestion with concentrated $HClO_4$-H_2SO_4, and AP (Olsen-P) with the molybdenum-blue method after extraction with 0.5 mol/L $NaHCO_3$ at pH 8.5 (Bao, 2000). The AK was extracted with NH_4OAc and determined using a flame photometer. pH was measured using a pH meter with distilled water (Bao, 2000).

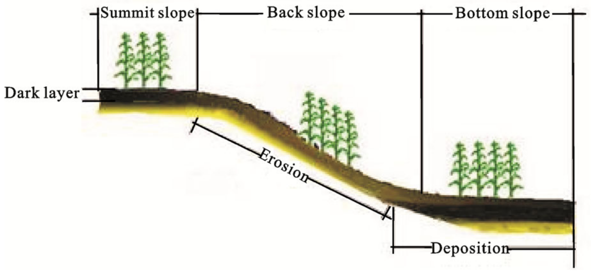

Fig. 2 Classification of slope position and deposition distribution

2.4 Statistical analyses

Pearson correlations, multiple comparisons using the least significant difference (LSD) method and regression equations were carried out by using SPSS 13.0 statistical software.

3 Results

3.1 Vertical and horizontal variance of SOM, TN and TP

Except at 50–60 cm soil depth at the summit, the SOM (24.6–46.7 g/kg) and TN (0.79–1.79 g/kg) typically decreased with increasing soil depth at all slope positions (Table 2). Both SOM and TN were significantly higher in the surface layers than in the deeper layers at all slope positions. For instance, SOM was 64.7%, 78.5% and 41.4% higher at 0–20 cm than at 50–60 cm at the summit, back slope and the bottom of the slope, respectively. The TN was 92.5%, 112.7% and 59.8% higher at 0–20 cm than at 50–60 cm at the summit, back slope and the bottom of the slope, respectively. Except at 50–60 cm soil depth, the TP (0.41–0.73 g/kg) typically

Table 2 Vertical and horizontal distribution of soil nutrients by slope position

	Depth (cm)	Summit slope (n = 34)		Back slope (n = 62)		Bottom slope (n = 30)	
		Mean ± SD	CV	Mean ± SD	CV	Mean ± SD	CV
SOM (g/kg)	0–20	46.7±10.0aA	0.21	43.9±12.1aAB	0.28	41.3±12.0aB	0.29
	20–30	39.9±12.0bA	0.30	41.2±13.6aA	0.33	36.3±16.3aA	0.45
	30–40	35.9±13.2bA	0.37	28.2±16.7bB	0.59	34.3±16.5aAB	0.48
	40–50	26.1±11.6cA	0.44	26.8±18.7bAB	0.70	34.1±17.6aB	0.52
	50–60	27.9±16.8cA	0.60	24.6±15.8bA	0.64	29.2±18.8bA	0.64
TN (g/kg)	0–20	1.79±0.42aA	0.24	1.68±0.51aA	0.30	1.63±0.49aA	0.30
	20–30	1.41±0.53bA	0.38	1.43±0.56aA	0.39	1.33±0.65bA	0.49
	30–40	1.20±0.58bA	0.48	0.94±0.67bA	0.71	1.23±0.68bcA	0.56
	40–50	0.88±0.44cA	0.49	0.87±0.75bA	0.86	1.20±0.70bcB	0.59
	50–60	0.93±0.67cA	0.73	0.79±0.60bA	0.76	1.02±0.77cA	0.76
TP (g/kg)	0–20	0.67±0.23aA	0.34	0.55±0.17aB	0.32	0.73±0.36aA	0.49
	20–30	0.56±0.24abA	0.42	0.54±0.23aA	0.42	0.64±0.37abA	0.58
	30–40	0.57±0.31abA	0.54	0.44±0.28abB	0.64	0.55±0.25bcAB	0.45
	40–50	0.42±0.23cA	0.55	0.41±0.25bcA	0.62	0.61±0.31abcB	0.50
	50–60	0.49±0.28bcA	0.57	0.45±0.24abcA	0.53	0.54±0.30bcA	0.56
AP (mg/kg)	0–20	18.89±11.99aA	0.63	11.78±5.88aB	0.50	14.78±8.35aAB	0.56
	20–30	9.60±8.85bA	0.92	6.61±6.61bAB	1.00	5.69±4.92bB	0.86
	30–40	7.12±6.44bA	0.90	4.82±3.87bA	0.80	6.96±7.90bcA	1.13
	40–50	6.87±6.80bA	0.99	6.01±5.98bA	1.00	9.10±8.64bcA	0.95
	50–60	6.39±3.98bA	0.62	6.29±4.71bA	0.75	9.31±8.83cB	0.95
AK (mg/kg)	0–20	229.9±68.2aA	0.30	174.9±35.1aB	0.20	190.9±53.8abB	0.28
	20–30	195.7±46.7bA	0.24	172.7±39.9aB	0.23	177.6±45.1aAB	0.25
	30–40	196.4±43.3bA	0.22	192.2±40.9bA	0.21	175.4±36.5aB	0.21
	40–50	195.4±52.2bA	0.27	195.5±36.5bA	0.19	193.2±40.5abA	0.21
	50–60	210.2±47.7abA	0.23	201.6±35.1bA	0.17	207.9±48.4bA	0.23
pH	0–20	6.61±0.37aA	0.06	6.41±0.41aB	0.06	6.35±0.40aB	0.06
	20–30	6.83±0.35bA	0.05	6.78±0.40bA	0.06	6.72±0.45bA	0.07
	30–40	6.94±0.30bcA	0.04	6.81±0.43bA	0.06	6.83±0.39bA	0.06
	40–50	6.99±0.29cA	0.04	6.79±0.43bB	0.06	6.84±0.39bAB	0.06
	50–60	6.91±0.32bcA	0.05	6.71±0.41bB	0.06	6.78±0.40bAB	0.06

Notes: SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; AP, available phosphorus; AK, available potassium. Values followed by the same lowercase letter within the same columns are not significantly different by LSD′s multiple range test ($P < 0.05$). Values followed by the same capital letter within the same rows are not significantly different by LSD′s multiple range test ($P < 0.05$)

decreased with increasing soil depth at all slope positions at the summit and back slope. In general, TP was also significantly higher in the surface layers than in deeper soil layers at the summit, back slope and the bottom. For example, it was 36.7%, 22.2% and 35.2% higher in the 0–20 cm layer than in the 50–60 cm layer at the summit, back slope and the bottom of the slop, respectively.

The coefficients of variation (CV) of SOM and TN generally increased with soil depth except at 50–60 cm on the back slope. The CV of TP increased with increasing soil depth at the summit, while it increased at first and then decreased on the back slope. The CV of TP increased from 0–20 cm to 20–30 cm then decreased to 30–40 cm, and then increased to 50–60 cm soil depth on bottom slope.

In the horizontal direction, SOM and TN were the highest at the summit, and notably SOM was 13.1% higher at the summit than at the bottom at 0–20 cm (Table 2). Compared to the summit and back slope, SOM and TN had the highest contents at the bottom at the 40–60 cm depth, especially SOM and TN were the highest and followed by summit and back slope in 50–60 cm. For example, TN was 37.9% higher at the bottom of the slope than on the back slope at the 40–50 cm depth. Generally, TP was the highest at the bottom slope, and was the lowest on the back slope, except at the 30–40 cm layer in the total soil profile. For example, TP was 32.7% higher at the bottom slope than on the back slope at 0–20 cm, and was 48.8% higher at the bottom slope than at the back slope at the 40–50 cm depth.

3.2 Vertical and horizontal variance of AP and AK

Compared to the total nutrient content, AP (4.82–18.89 mg/kg) and AK (172.7–229.9 mg/kg) were, relatively more complex. The AP decreased with increasing soil depth at the summit (Table 2), while first decreased and then increased with increasing soil depth on both the back and bottom slope. All slope positions had a significantly higher AP at 0–20 cm, while AP was the lowest at 50–60 cm at summit slope, 30–40 cm at back slope and 20–30 cm at bottom slope, respectively. The AP was typically higher in 0–40 cm layer at the summit, and was higher in the 40–60 cm layer at the bottom, while it was the lowest on the back slope at the 30–40 cm depth. The variance of AP was not consistent with increasing soil depth at the summit and on the back slope. The AP was 60.4% higher at the summit than on the back slope in the 0–20 cm layer, and was 45.7% and 48.0% higher at 50–60 cm at the slope bottom than on the summit and back slope, respectively.

The AK was not systematically changed with increasing soil depth, and was relatively lower at 20–50 cm soil depths on the summit (Table 2). The AK increased from 20–30 cm to 50–60 cm soil depth, and 30–60 cm layers were significant higher than 0–30 cm soil layers on the back slope. The AK decreased from 0–20 cm layer to 30–40 cm, and then increased to 50–60 cm soil layer at the bottom. The variance of AK at the summit and bottom decreased with increasing soil depth in the 0–40 cm depth and then not systematically changed (Table 2). The variance of AK on the back slope increased from the 0–20 cm depth to the 20–30 cm depth and then decreased with increasing soil depth. The AK was statistically higher at 0–20 cm than at 20–50 cm at the summit, and was significantly higher at 30–60 cm than at 0–30 cm on the back slope, as well as being significantly higher at 40–60 cm than at 0–20 cm or 30–40 cm at the slope bottom. The AK was typically higher at the summit in all depths except at 40–50 cm, and was typically lower on the back slope at 0–30 cm and 50–60 cm (Table 2). For instance, AK at the summit was 31.4% and 20.4% higher than on the back and bottom slope at 0–20 cm, respectively, and at 20–30 cm, AK was 13.3% higher at the summit than on the back slope. Furthermore, at 30–40 cm, AK was 10.7% and 8.7% lower at the bottom than on the summit and back slope, respectively.

4 Discussion

4.1 Vertical and horizontal variance of SOM, TN and TP

In the study area, the vertical distribution of SOM, TN, TP and CVs are similar to the results from previous study (Yang *et al.*, 2012). Fertilizer application and incorporation of crop residue tend to increase nutrient content, while they decrease the variances in the surface layer (Greenwood *et al.*, 1980). In the watershed, soil loss was severe on the back slope and soil was heavily deposited in the lower slope position (Fig. 2). Soil with a low nutrient content being translocated downward from the back slope deceased both SOM and TN on the back slope and at the bottom of the slope in the 0–20 cm layer (Zhang *et al.*, 2013). This was also approved by the results from Fu *et al.* (2004) who carried out research on brown soil (classified as Eutriccambisol) in a typical warm temperature continental monsoon climate in the Taihang Mountains of China, and differed from the results of Liu *et al.* (2006) who reported that higher SOC concentrations were only associated with the lower slope positions in Dehui City for a black soil of Northeast China. It might be that the soil loss was severe at the summit, mainly caused by long-term tillage erosion (Morgan, 2005). Furthermore, high moisture content was beneficial for vigorous crop growth, which can absorb many soil nutrients at the bottom (Zhang *et al.*, 2006), and can also decrease SOM and TN. However, SOM and TN had relatively higher contents on the bottom slope at 30–60 cm. This was also attributed the distribution of soil loss and deposition in this watershed, which also influenced the vertical variance of nutrients (Zhang *et al.*, 2013). In this watershed, soil loss was correlated to most of the soil nutrients in soil depths and slope positions, but only the weak correlation was found, the exception being TP at the depths of 20–30 cm and 50–60 cm (Table 3). The results might be due to soil loss being calculated by a Universal Soil Loss Equation (USLE) model based on ArcGIS and thus could not include tillage erosion, wind erosion, thaw-melt erosion and so on. Also, fertilization influenced nutrient dynamics, thus decreasing the degree of correlation (Brady and Weil, 2000; Zhang *et al.*, 2013). In this study, regression equations between nutrient contents and soil deposition

Table 3 Correlation analysis between soil nutrients and soil loss, and between soil nutrients and soil deposition at different depths

	Depth (cm)	Soil loss (n = 68)	Soil deposition (n = 45)	Equation	R^2	Sig.
SOM (g/kg)	0–20	0.033	0.022			
	20–30	–0.025	0.211			
	30–40	0.051	0.294^{*}	$y = 0.0778x + 2.3882$	0.08	< 0.01
	40–50	0.006	0.307^{*}	$y = 0.1055x + 1.9544$	0.09	< 0.01
	50–60	0.098	0.407^{**}	$y = 0.1603x + 1.7057$	0.16	< 0.01
TN (g/kg)	0–20	0.063	0.036			
	20–30	0.026	0.219			
	30–40	0.073	0.308^{*}	$y = 0.0041x + 0.0773$	0.12	< 0.01
	40–50	–0.004	0.336^{*}	$y = 0.0052x + 0.0662$	0.11	< 0.01
	50–60	0.091	0.420^{**}	$y = 0.0068x + 0.0593$	0.13	< 0.01
TP (g/kg)	0–20	0.138	0.391^{**}	$y = 0.021x + 0.5318$	0.11	< 0.01
	20–30	0.252^{*}	0.517^{**}	$y = 0.031x + 0.4085$	0.25	< 0.01
	30–40	0.152	0.465^{**}	$y = 0.0214x + 0.3701$	0.18	< 0.01
	40–50	0.187	0.519^{**}	$y = 0.0286x + 0.3306$	0.23	< 0.01
	50–60	0.237^{*}	0.516^{**}	$y = 0.0272x + 0.3495$	0.20	< 0.01
AP (mg/kg)	0–20	0.042	0.101			
	20–30	0.029	0.011			
	30–40	0.044	0.462^{**}	$y = 0.4657x + 3.0176$	0.25	< 0.01
	40–50	0.041	0.400^{**}	$y = 0.5337x + 3.7903$	0.19	< 0.01
	50–60	0.085	0.437^{**}	$y = 0.5456x + 3.9905$	0.22	< 0.01
AK (mg/kg)	0–20	0.033	–0.166			
	20–30	–0.025	–0.005			
	30–40	0.051	–0.130			
	40–50	0.006	–0.014			
	50–60	0.098	–0.096			

Notes: SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; AP, available phosphorus; AK, available potassium. Soil loss was calculated by Universal Soil Loss Equation (USLE) based ArcGIS, and deposition was evaluated by SOM and TN (Zhang *et al.*, 2011; Zhang *et al.*, 2013). **, correlation is significant at the 0.01 level (2-tailed); *, correlation is significant at the 0.05 level (2-tailed). Nutrient contents were represented by 'y ', and soil deposition was represented by 'x (t/ha·yr)'. The equations were not listed when the correlation between nutrients and soil deposition were not significant were established when soil nutrients contents significantly positively correlated to soil deposition in Table 3. It is difficult to establish a model to predict nutrients based on soil loss, sediment transport factors and topographic factors, and this result is the same as that in the previous studies (Lian *et al.*, 2008 a; 2008b).

In the bottom slope areas, TP was generally high in the entire 0–60 cm depth except from 30 cm to 40 cm, while SOM and TN were only higher in the 40–60 cm layers (Table 2). This may be due to phosphorus (P) being strongly attracted by soils and causing difficulties for crop absorption (Brady and Weil, 2000). Furthermore, bottom lands have relatively higher soil moisture content and the subsequent vigorous crop growth can absorb available nutrients released from SOM and TN at depth of 0–30 cm (Zhang *et al.*, 2006).

4.2 Vertical and horizontal variance of AP and AK

In this watershed, AK was above sufficient levels for crop growth in most areas, so K fertilizer was seldom used (Han *et al.*, 2002; Han *et al.*, 2005) and the leaching of K was not considered a problem due to the high clay content of Mollisols (Jalali and Rowell, 2003). Furthermore, AK absorption is positively related to the root density in the soil profile through time (Zhang *et al.*, 2012). Crop roots were predominant from 0–45 cm and the root density decreased with increasing soil depth (Jin *et al.*, 2007). Thus, in the profiles of this watershed, AK had relatively consistent variance at all slope positions.

The AP on the slope summit typically decreased with increasing soil depth and differed from the back and bottom slope. The different results might be due to TP being relatively higher at the summit at all soil depths and P fertilizer application can satisfy crop needs for AP in the whole profile. However, TP content was low on the back slope, and AP was relatively insufficient for crop growth in the middle of the profile. At the bottom of the slope, absorption by vigorous crops can effectively change the vertical trend of AP, although high TP content and low pH are beneficial to increase AP in the entire profile (Moghimi *et al.*, 1978; Tang *et al.*, 2006). In this study area, pH was lower on the back slope and bottom slope than at the summit in the 0–60 cm profile (Table 2), and firstly increased with increasing soil depth and then decreased at all slope positions.

Generally, AP and AK were the highest at the summit and lower on the back slope and bottom slope in the 0–40 cm depth; notably AP was significantly lower in the 0–20 cm layer and AK was lower in the 0–30 cm layer on the back slope than that on the summit. This was also mainly due to erosion taking place on the back slope and available nutrients being absorbed by vigorous crop growth on the bottom slope (Zhang *et al.*, 2006; Zhang *et al.*, 2013).

The CV of AK and AP did not systematically change with changes of soil depth (Table 2). Generally, in the 0–20 cm layer, the CV of AP was lower than that at 20–50 cm depths for all slope positions, while the CV of AK was relatively higher on the summit and bottom slope except that was higher at 20–30 cm on the back slope. This result may be due to K fertilizer seldom being used in this area, and AK variance in the surface layer was heavily influenced by soil moisture and temperature which in turn influenced the weathering rate of the mineral (Øgaard and Krogstad, 2005). Conversely, the CV of AP in the surface layer tended to decrease after P fertilizer application.

4.3 Nutrient content classification

According to the classification of Han *et al.* (2005), SOM, TN, AP and AK were all above 'rich' levels in the 0–20 cm layer (Table 4). It showed that the fertile Mollisols of Northeast China still maintain high potential productivity in the surface soil. The AK was sufficient in the whole 0–60 cm depth and potassium was not the limiting factor affecting soybean and corn yield (Han *et al.*, 2002). However, SOM, N and P were not consistent enough for crop growth, especially on the back slope where the thinner dark layer is facing a loss of 1–3 mm/yr (Liu *et al.*, 2008). The results from Zhang *et al.* (2009) indicated that conservation tillage can effectively reduce soil loss in the Mollisols region of Northeast China. Therefore, in order to reduce soil loss, environmental pollution and increase the efficient use of soil nutrients, N and P fertilizer applications are still necessary, especially in conjunction with conservation tillage in special conditions and in specific areas such as the back slope, where soil loss is severe and the deep soil that lacked TN is exposed at the surface (Askegaard and Eriksen, 2002; Wu *et al.*, 2002; Morgan, 2005). However, this study was only carried in a typical Mollisols watershed, and the results need to be proved by more case studies in other regions in the future.

Table 4 Soil nutrients classification in soil depths by slope position

	Very insufficient	Insufficient	Sufficient	Rich	Very rich
SOM (g/kg)	10 ≥	10–20	20–30	30–40	40 <
0–20 cm					ABC
20–30 cm				AC	B
30–40 cm			B	AC	
40–50 cm			AB	C	
50–60 cm			ABC		
TN (g/kg)	0.75 ≥	0.75–1.00	1.00–1.50	1.50–2.00	2.00 <
0–20 cm				ABC	
20–30 cm			ABC		
30–40 cm		B	AC		
40–50 cm		AB	C		
50-60 cm		AB	C		
AP (mg/kg)	5 ≥	5–10	10–20	20–40	40 <
0–20 cm			ABC		
20–30 cm		ABC			
30–40 cm	B	AC			
40–50 cm		ABC			
50–60 cm		ABC			
AK (mg/kg)	< 30	30–50	50–150	150–200	200 <
0–20 cm				BC	A
20–30 cm				ABC	
30–40 cm				ABC	
40–50 cm				ABC	
50–60 cm					ABC

Note: Summit, back slope, bottom were represented by A, B and C, respectively

5 Conclusions

Both Kriging procedures and traditional analysis were used to describe the vertical and horizontal distribution of soil nutrients throughout the soil profile by slope position, and the relationships between nutrient distribution and soil loss and soil deposition were analyzed. The horizontal and vertical distributions were different among SOM, TN, TP, AP and AK, and differed by slope position at the soil depths. As well, they were mainly influenced by soil loss, soil deposition, fertilizer application, crop growth and intrinsic characteristics of soil nutrients. It is difficult to establish models to accurately predict soil nutrient distribution according to soil loss by water. The SOM and TN typically decreased with increasing soil depth on the summit, back and bottom slopes. The SOM and TN were the highest on the summit followed by the back slope and the bottom slope in the 0–20 cm layer, while they were the highest at the bottom slope, followed the by summit slope and the back slope in the 50–60 cm depths. The TP was relatively higher at both summit and bottom locations, the bottom slope having nearly the highest values in all depths except at 30–40 cm soil depth. The AK at all slope positions and AP on the back and bottom slope displayed a coincident variance profile, first decreasing and then increasing with the soil depth. The AP on the summit slope typically decreased with increasing soil depth and the relationship differed from those on the back and bottom slope. The AP and AK were typically highest at the summit in the 0–40 cm layers, and were mainly the lowest on the back slope at the middle of the layers. Generally, in order to sustain the high soil productivity and protect the environment, more attention should be paid to soil conservation practices on the back slope, and additional N and P fertilizer on back slope is necessary. However, this study was only carried in a typical Mollisols watershed, and the results need to be proved by more case studies in other regions in the future.

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