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ORIGINAL ARTICLE

Spatial distribution of soil nutrient at depth in black soil of Northeast China: a case study of soil available potassium

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Abstract Spatial mapping of potassium is very urgently needed to develop economically and environmentally sound soil management plans, and deeper-layer soil available potassium (AK) resources on the farm are important for evaluating the long-term need for purchased K fertilizer. The objectives of this study are to analyze AK spatial distribution in deep soil depths from a small watershed, and to provide reference for farmers better managing fertilizer application and protecting environment in the farmland. In order to describe AK spatial distribution in deeper depths, six hundred and ten soil samples were collected from 122 soil profiles (0–60 cm) in a representative random sample method. Kriging procedures, correlation analysis and regression analysis were used to describe the spatial variability of soil AK in a small watershed from typical black soil of northeast China, and AK in cultivated field and forest (field returned to forest over 10 years) areas was compared. Gaussian models were recognized as the best for predicting AK in the soil at different layers. Spatial autocorrelations as influenced by human activities were weak for AK at 0–30, and 40–60 cm layers and was moderate at 30–40 cm, and autocorrelation distance ($A_0 = 3{,}110$ m) is uniform at all layers. AK heterogeneity was different among soil layers, and was influenced by soil parent material, landscape, slope position, land use, soil management and so on in the watershed. The content of AK was 21.1–428.4 mg kg^{-1} in the cultivated areas and 117.2–401.0 mg kg^{-1} in the forest (field returned to forest over 10 years) in the entire profile (0–60 cm). AK in the forest areas were larger 18, 3, 22, 16 and 5 % in 0–20, 20–30, 30–40, 40–50 and 50–60 cm, respectively than in the farmland. AK variance in space decreased from the 0–20 to the 50–60 cm depth. The spatial pattern of AK was similar in all layers, and typically decreased from forest to surrounding farmland. AK also deceased along the water flow direction. Furthermore, AK was influenced by steepness, aspect, elevation, leading to the big difference between the two banks of the hydrographic reaches. In the field, AK was negatively correlated to gross soil loss and steepness at all depths, and became significant at the 0–20 cm depth, while it was significantly positively correlated to elevation except at the 40–50 cm depth. Generally, AK is sufficient for crop production for at least 160 year with a little potassium fertilizer application needed during the growing season in the study area. However, crop residue management and fertilizer application, especially manure and nitrogen application in special conditions (dry seasons, intensive cropping without residue return and so on) and sensitive areas (such as Low elevation, closer forest and so on) is still necessary in order to increase potassium storage and promote the efficiency of AK for plants.

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Introduction

Soil nutrient spatial distribution is affected by many complex factors. The primary factors affecting nutrient distribution are soil loss and runoff (above ground and underground), as runoff from upslope areas carries topsoil and dissolved nutrients to lower slope positions, thus altering the spatial distribution of soil nutrient content in both affected areas (Zhang 2010; Balasundram et al. 2006; Noorbakhsh et al. 2008; Verity and Anderson 1990; Moulin et al. 1994). Many studies confirm that upslope positions are eroded areas and lower slope positions are depositional areas (Gregorich et al. 1998; McCarty and Ritchie 2002; Papiernik et al. 2005). Generally, soil erosion decreases chemical and physical soil fertility, affecting soil productivity and resulting in the degradation of the physical and chemical properties of the soil (Kaihura et al. 1999; Rhoton et al. 2002). It is apparent that the steepness of a slope influences the intensity of soil erosion and runoff thus affects soil nutrient distribution in the field, but soil erosion and nutrient loss as affected by slope also varies according to the type of soil (Agassi et al. 1990; Walson and Laflen 1986; Liu et al. 2006; Morgan 2005). Slope aspect can also be important in affecting nutrient distribution, as equatorial-facing slopes tend to be dryer than polar-facing ones because they have greater evapo-transpiration rates (Rundel 1981; Zhang et al. 2011), while the amount of rainfall, and thus runoff, tends to be greater on a windward slope than on the leeward side (Agassi et al. 1990).

The spatial distribution of soil nutrients under agricultural systems is affected by natural conditions as well as management practices (Lal 1998; Huang 2000; Barton et al. 2004; Atreya et al. 2008), while soil nutrient distribution in natural systems is mainly affected by topography, climate, biological activities and natural soil properties (DeBusk et al. 1994; Tang and Yang 2006; Brady and Weil 2000). Studies of the effect of land management on nutrients has shown that cultivation generally increases the potential for soil erosion due to the breakdown of soil aggregates and reduction of soil cohesion, and thus decreases soil nutrient content in the profile (Horn et al. 1995; Walson and Laflen 1986). By extension, since cross-slope tillage reduces soil loss compared to down-slope tillage (Voroney et al. 1981; Van Doren et al. 1950), it can be expected that nutrient levels would also be less affected. It is also reported that soil nutrient content varies considerably under different land covers (Huang 2000; Gardner and Gerrard 2003), and nutrient contents were also changed when a field was returned to forest (Peng et al. 2005). Fertilizer application rates can also affect soil nutrient content dynamics in the field (Lal 2004; Liu et al. 2006).

Spatial mapping of potassium is critical to the development of economically and environmentally sound soil management plans, especially in guiding farmers in terms of soil fertility management (Uygur et al. 2010). Soil analyses and available K resources on the farm are important for evaluating the need for purchased K fertilizer (Øgaard and Hansen 2010). Potassium (K) is one of three major elements required by crops, and it is necessary to feed growing crops, especially since available potassium (AK) can be directly absorbed by crops during the growing season and is regarded as realistic practical indicator of the soil's ability to supply potassium (Zhang et al. 2003). NH_4OAc-K (AK) is still the most widely used index of plant available K^+ (Mengel and Rahmatullah 1998).

Some K^+ fertilizer could increase K^+ concentration in the soil solution, some could be adsorbed on exchange sites and some might be fixed between adjacent phylosilicate layers as non-exchangeable forms (Øgaard and Krogstad 2005; Kovar and Barber 1990). Generally, intensive crop production might lead to exchangeable K^+ becoming depleted in certain regions (Jalali and Zarabi 2006). Depletion of soil K resulted in increasing K fixation capacity, and added K will be fixed in the inter layers of the sheet silicates and thereby will be less available for plant growth, but some deficit in the K balance is sustainable due to K release by weathering (Øgaard and Krogstad 2005). The available K content on the lower slope was not the highest even though it was the deposition position, which may be due to a relatively more vigorous plant growth on the lower slope resulting in considerably higher K absorption (Zhang et al. 2012). Some reports indicated that vailable K in the 0–60 cm layer was significantly and positively correlated with altitude (Gairola et al. 2012), and K application without N application did not increase the barley/pea yield

(Askegaard and Eriksen 2002). The leaching of K^+ is not considered a problem in soil with high clay content, but losses of K^+ in sandy soil with little clay are substantial due to their low cation exchange capacity (Jalali and Rowell 2003).

In recent years, geo-statistics, linear models, neural networks, regression trees, fuzzy systems and other analytical procedures have been used to analyze soil nutrient distributions and are considered good tools for use in understanding nutrient dynamics in the field (Zhang et al. 2007a; Srividya et al. 2002; Liu et al. 2006; DeBusk et al. 1994; Park and Vlek 2002), and generally geo-statistics was used to predict nutrient distribution in space (Oliver 1987; Yost et al. 1982; Zhang et al. 2007a, 2011).

Most of the "black soil" region of North-eastern China has been a major production base for corn and soybeans for more than 100 years. The long, narrow fields generally have slopes of <6° and slope lengths from 500 to 2,000 m (Yan et al. 2008), and can suffer from extreme erosion under intense rainfall events. Currently, most studies of soil nutrient distribution in space are focused on the surface depth 0–20 cm named the plough layer (Zhang et al. 2007a, b, 2011), while few studies were carried on in deeper depth. Actually, crop roots were found deeper, over 70 cm underground, and were predominant in the 0–45 cm layer in black soils of northeast China (Jin et al. 2007). Also, soil nutrient movement was influenced by runoff (including above ground and underground) and soil structure (Such as soil aggregate, soil mechanical composition, rocks and so on), thus leading to the variance of soil nutrients along slope surfaces and within profiles (Zhang 2010). It was reported that corn (*Zea* mays L.) and corn-soybean (*Glycine* max L.) can also maintain a normal yield if the field was fertilized and cultivated appropriately, even though the 0–20 cm soil depth was eroded (Sui et al. 2009). Therefore, the fertility of soil in cultivated fields can not be properly evaluated when only the soil nutrients in the 0–20 cm layer were considered, especially when the surface layer was eroded gradually.

In our study, in order to describe the AK spatial distribution at various depths or within profiles, and ascertain the main driving factors, 122 soil profiles were dug using a representative random sample method, and 610 samples (one from each layer) were collected from the 0–20, 20–30, 30–40, 40–50 and 50–60 cm depths in the autumn of 2012 after harvest in a 1.86 km^2 region of typical Mollisols. Kriging procedures were used to describe the spatial variability of soil AK. At the same time AK in the field and the forest (field returned to forest over 10 years) areas was compared.

Materials and methods

The 1.86 square kilometre study area is located in Guangrong village (47.21–47.23°N, 126.50–126.51°E) in Hailun city, Heilongjiang province, Northeast China (Fig. 1). The area falls in the North Temperate Zone and has a continental monsoon climate of cold and arid weather in winter and hot and rainy conditions in summer. Average annual precipitation is 530 mm, with 65 % falling in June, July and August. Average precipitation from March to October in the 2002–2008 period was 472.3 mm. The average annual temperature is 1.5 °C and annual sunshine averages between 2600 and 2800 h. Total annual solar radiation is 113 MJ cm^{-2} and annual average available accumulated temperature (≥10 °C) is 2,450 °C. The prevailing wind is from the north-west in winter and spring and from the south-west in summer (Soil survey service of Hailun 1985). Formation of soils in the study area began during the Quaternary period on loess deposits under natural grasses and now have a rich, dark organic depth and are classified as Mollisols (Zhang et al. 2007a). These soils have a silty clay loam texture (Table 1), and most slopes are inclined at less than 5°, but are over 200 m in length. Farmland and forest were main land use types, and field returned to forest (predominant tree is *Populus*) over 10 years.

Farmland management

The study area is farmed by local villagers, but all cropping activities are prescribed and monitored by our team of researchers working with a local manager. Farmland are generally long and narrow and the orientation between up-and-down or cross-slope is essentially random. The crop rotation has consisted of alternating 1 year of soybean with 1 year of corn for at least the last 3 decades, so approximately 50 % of farmland were in each crop during the study year of 2012. Fields were ridged-tilled at 65 cm intervals using a small tractor operating a roto-tiller after harvest in the autumn of 2006, and both crops were

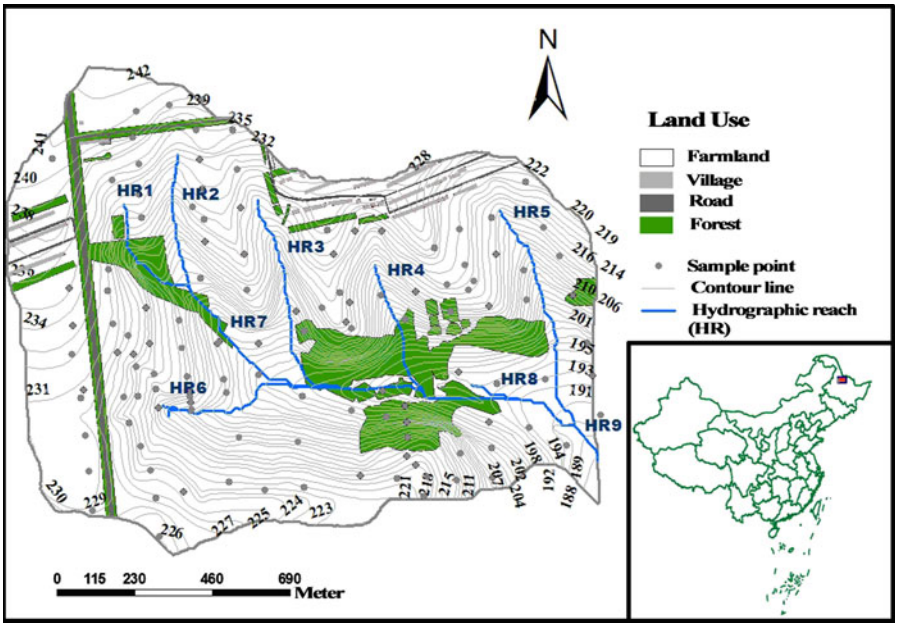

Fig. 1 Location of the study area, distribution of sample sites, and land use in the watershed

Table 1 Soil physical and chemical properties before planting on the experimental field in 2007

Soil depth (cm)	Organic matter content (g kg^{-1})	Bulk density (g cm^{-3})	Total porosity (%)	Field capacity (w/w, %)	Saturated water (w/w, %)	Wilting point (w/w, %)
0–20	42.1	1.27	52.1	24.4	42.3	12.1
20–40	28.4	1.19	55.1	24.4	44.2	13.4
40–60	18.6	1.21	54.3	23.4	43.6	14.2

planted in the first 10 days of May and harvested in October of 2007. Average crop yield for soybean, calculated by our research group, was 3,000 kg ha^{-1} and for corn 4,500 kg ha^{-1}. Prescribed chemical fertilization on soybean consisted of 20.25 kg N ha^{-1}, 51.75 kg P ha^{-1} and 15 kg K ha^{-1} applied at planting, and on corn 69 kg N ha^{-1} at planting and an additional 69 kg N ha^{-1} as side dressing at the three-leaf stage. Weeds were controlled with herbicides after emergence early in the growing season, and two or three between-ridge machine tillage operations were carried out before July.

Soil sample collection and measurement

122 soil profiles were dug using a representative random sample-method (Huang 2000), and soil samples were collected from 0–20, 20–30, 30–40, 40–50 and 50–60 cm depths in the autumn of 2012 after harvest (Fig. 1). Each soil sample at the 0–20 cm was comprised of a mixture of five cores taken randomly from within a 20 m^2 plot, and soil samples at 20–30, 30–40, 40–50 and 50–60 cm were collected from the soil profiles in the central position of each sampling plot. Samples were air-dried and sieved at 0.25 mm for analyzing soil available potassium (AK). AK was extracted with NH_4OAc and determined using a flame photometer (Bao 2000). Total nitrogen (TN) was measured using a Vario ELIII (Germany) (Vario EL operating instructions 2002; and Slepetiene et al. 2008).

Statistics and Kriging analysis

Pearson correlations and multiple comparisons using the least significant difference (LSD) method were carried out using SPSS 13.0 statistical software. The spatial distribution of AK was determined by geostatistical analysis using GS$^+$5.0 and ArcGIS10 (ESRI 2008; Robertson 2000). Semivariograms were used in an autocorrelation analysis in order to evaluate the spatial dependence of the values, and best-fit models were optimized to predict AK (Oliver et al. 2000). Semivariograms were calculated according to the formula: $\gamma(h) = 1/2\ N(h) \sum[z(x_i + h) - z(x_i)]^2$ (Isaaks and Srivastava 1989), where $\gamma(h)$ is the experimental semivariogram value at distance interval h, $N(h)$ is the number of sample pairs within the distance interval h and $z(x_i)$, $z(x_i + h)$ is the sample value at two points separated by the distance interval h. The kriging algorithm was used to create an interpolated grid for development of isarithmic maps of SOM. Since the distribution of AK values based on the 122 sample points in the soil layers were not normally distributed except those in 50–60 cm layer, Kurtosis and skewness values were then used to determine the goodness of fit to a normal distribution. So, AK data for the 0–20, 20–30, 30–40, 40–50 and 50–60 cm depths was transformed by the logarithm method in order to satisfy the required normal distribution. Kurtosis values of SOM were close to 3, and skewness values were close to 0 (ESRI 2010; Robertson 2000).

Anisotropic analysis of AK indicated that variance (Semivariance value) was strongest at 0° (North–South), followed by 45° (Northeast–Southwest) and 90° (East–West), and 45° (Northeast–Southwest) equal to 135° (Southeast–Northwest) in the 0–20, 20–30, 30–40, 40–50 and 50–60 cm layers, respectively (Fig. 2).

The determination coefficient (r^2) provides an indication of how well a model fits variogram data, but this value does not serve as well as the residual sum of squares (RSS) value for best-fit calculations involving changes in a model parameter. The lower the RSS, the better the model fits (Robertson 2000). A Gaussian model was recognized as the best for predicting AK at all measured depths, respectively (Table 2).The Gaussian isotropic model can be depicted as follows:

$$\gamma(h) = C_0 + C\left[1 - \exp(-h^2/A_0^2)\right]$$

where h = lag interval, C_0 = nugget variance ≥ 0, C = structure variance $\geq C_0$, and A_0 = range parameter (Robertson 2000).

Results

Spatial distribution of AK in the 0–20, 20–30, 30–40, 40–50 and 50–60 cm layers

It is obvious that spatial pattern of AK was similar in the 0–20, 20–30, 30–40, 40–50 and 50–60 cm layers, and typically decreased from western forest, southwestern forest and the middle eastern forest to the surrounding farmland (Fig. 3a–e). Generally, the AK increased from up slope to down slope with northern aspects, while it decreased from up slope to down slope in slopes with southern aspects except in the 40–50 and 50–60 cm layers. However, there were differences between the two banks of the hydrographic reaches (HRs), especially in HR9.

The spatial distribution of AK on both banks was similar between HR1 and HR2, and gradually deceased along the water flow direction. AK was higher on the summit, and was 394, 353, 294, 287, 276 mg kg^{-1} at 0–20, 20–30, 30–40, 40–50 and 50–60 cm, respectively. AK was lowest at the intersection of two HRs, and was 122, 109, 137, 175, 133 mg kg^{-1} at 0–20, 20–30, 30–40, 40–50 and 50–60 cm, respectively.

Available potassium (AK) was lower in HR3 in all layers except in the 0–20 and 50–60 cm layers. The closer the distance to the HR, the higher AK was in the 0–20 and 50–60 cm layers. AK was higher at the intersection of HR9 and HR3, and the maximum value was 192, 212, 183, 195 mg kg^{-1}, 231 mg kg^{-1} at 0–20, 20–30, 30–40, 40–50 and 50–60 cm, respectively.

Available potassium was higher near HR4, and decreased from the HR to the surrounding region. AK gradually decreased from the middle area of HR4 to the village, and also from the middle area of HR4 to the intersection of HR4 and HR9. The minimum value was 189 mg kg^{-1}, 172 mg kg^{-1}, 184 mg kg^{-1}, 182 mg kg^{-1}, 182 mg kg^{-1} at 0–20, 20–30, 30–40, 40–50 and 50–60 cm, respectively.

Available potassium was high around HR5. The maximum value in the middle area of HR5 was 384, 273, 271, 323, 360 mg kg^{-1} at 0–20, 20–30, 30–40, 40–50 and 50–60 cm, respectively, and deceased toward the village and toward the intersection of HR5 and HR9 The minimum value was 112, 134, 127, 170, 133 mg kg^{-1} at 0–20, 20–30, 30–40, 40–50 and 50–60 cm, respectively.

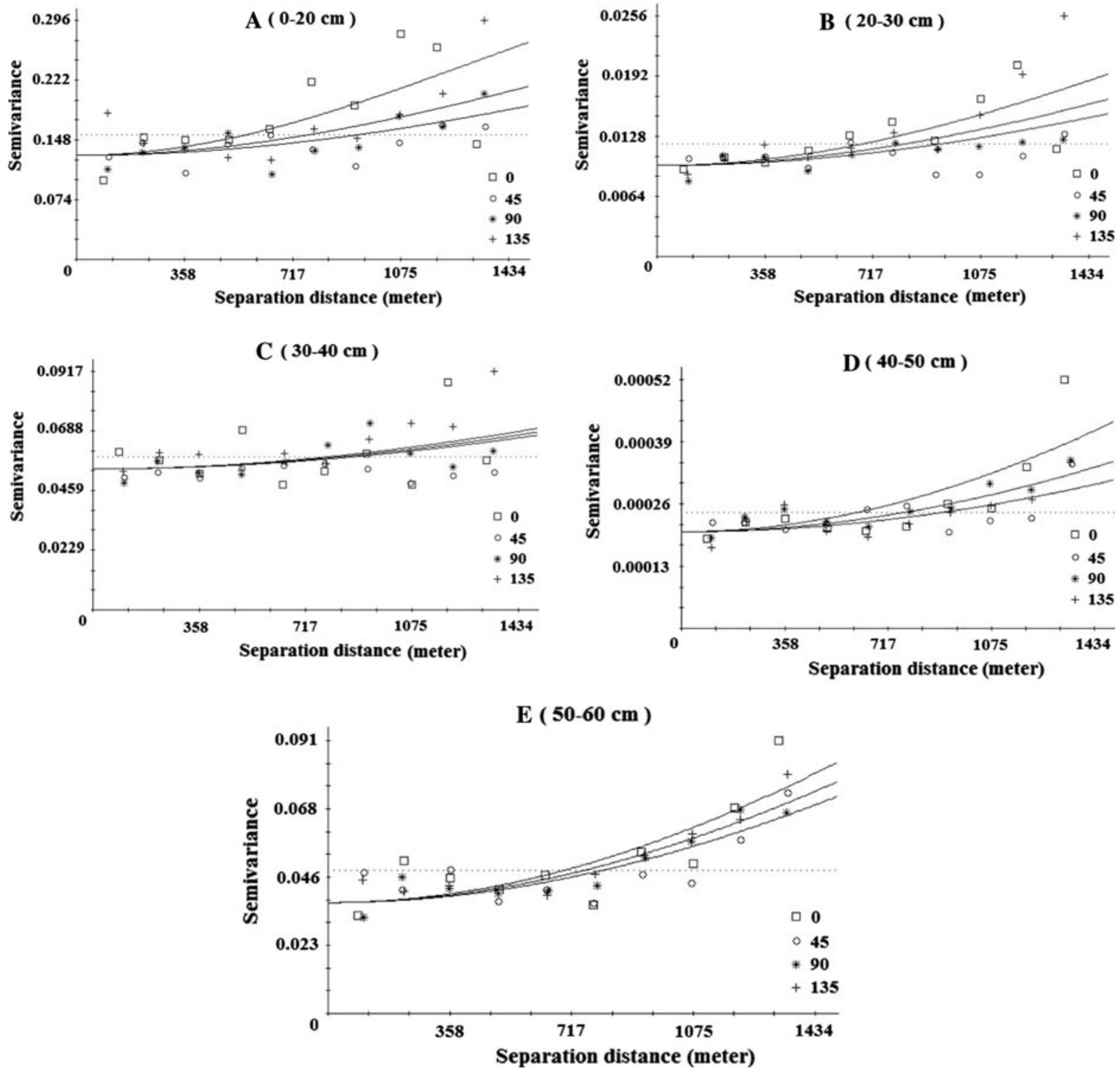

Fig. 2 Anisotropic semivariance of AK in soil layers

Table 2 Geostatistics parameters of AK in soil depths under isotropic

Depth (cm)	N	Transform	C_0	$C_0 + C$	A_0(m)	$C_0/C_0 + C$	Model	r^2	RSS
0–20	122	Y(Log)	0.1260	0.6040	3,110	0.21	Gaussian	0.851	1.32E − 03
20–30	122	Y(Log)	0.0098	0.0442	3,110	0.22	Gaussian	0.846	7.20E − 06
30–40	122	Y(Log)	0.0546	0.1167	3,110	0.47	Gaussian	0.722	6.44E − 05
40–50	122	Y(Log)	0.0002	0.0009	3,110	0.22	Gaussian	0.819	3.45E − 09
50–60	122	Y(Log)	0.0372	0.2165	3,110	0.17	Gaussian	0.864	1.66E − 04

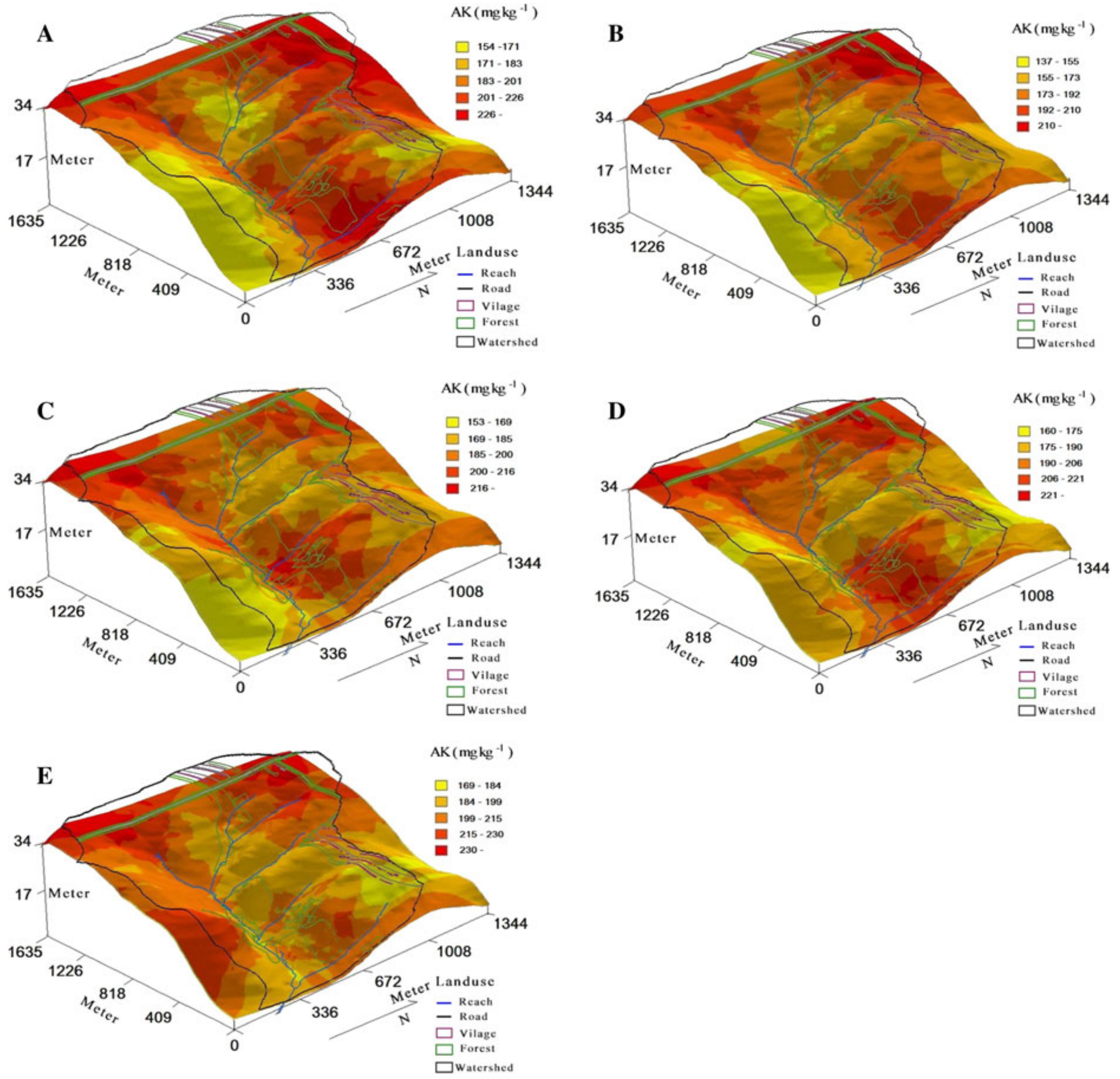

Fig. 3 AK special distribution in horizons of study area (**a**, **b**, **c**, **d** and **e** is 0–20, 20–30, 30–40, 40–50 and 50–60 cm layers, respectively). Reach means hydrographic reach (HR)

Available potassium was high near HR6 and the farther the distance from the HR, the lower the AK was. AK decreased from the summit to down slope along water flow direction in depth of 0–20, 20–30 and 30–40 cm, while AK increased from summit to down slope along water flow direction in the 40–50 and 50–60 cm layers.

Eight HRs intersected at HR9, and AK deceased from west to east along the water flow direction in all layers, and was lowest at the watershed outlet.

AK and TN in farmland and forest

In the cultivated farmland, the content of AK was between 21.10 and 428.36 mg kg^{-1} in the total profile (0–60 cm) (Table 3). AK was highest at 50–60 cm and then decreased through 0–20, 40–50, 30–40 and 20–30 cm. The mean of AK was 8.9 % greater in the 0–20 cm layer than in the 20–30 cm layer, and then increased from 20–30 to 50–60 cm. Compared to 20–30 cm, AK increased by 7.1 and 13.1 % at 30–40 and 40–50, respectively. AK at 50–60 cm was significantly greater 9.1 % than at 30–40 cm. Coefficient of variation (CV) decreased from 0–20 to 50–60 cm, with a large decline from 0–20 to 30–40 cm.

In the forest area, AK content was between 117.19 and 400.99 mg kg^{-1} in the 0–60 cm profile. AK was highest at 0–20 cm and then followed 30–40, 40–50, 50–60 and 20–30 cm. The mean of AK differed among layers, but was not significant. CV decreased from 30–40 to 50–60 cm, and was highest at 0–20 cm and lowest at 20–30 cm. Generally, AK was higher in the forest than in the farmland in the same layer, and was larger by 18, 3, 22, 16 and 5 % in the 0–20, 20–30, 30–40, 40–50 and 50–60 cm layers, respectively.

Total nitrogen (TN) ranged from 0.9 to 1.7 in farmland layers, and declined from 0–20 to 50–60 cm, while AK/TN increased from 0–20 cm to 50–60 cm. There were no obvious trends found for TN and AK/TN in the forest layers.

AK correlated with main driving factors in the various layers

In the farmland, AK was negatively correlated to gross soil loss) and steepness, and became significant at 0–20 cm, while it was significantly positively correlated to elevation except in the 40–50 cm layer (Table 4). Net soil loss (NSL) was negatively but not significantly correlated to AK. The correlation of AK i was very significant among the depths.

In the forest, the negative or positive correlation was not consistent between AK and soil loss, AK and soil loss-deposition, AK and steepness, or AK and DEM in the layers. AK at 40–50 cm was significantly correlated to that in the 20–30 and 30–40 cm layers, and AK at 50–60 cm was significantly correlated to that at 30–40 and 40–50 cm.

Discussion

The proportion of the spatial structure ($C_0/(C_0 + C)$) of <0.25, 0.25–0.75, and 0.75< can be used to describe strong, moderate, and weak spatial autocorrelation, respectively (Zhang et al. 2007a, b). Geo-statistical results indicate that spatial autocorrelations as influenced by human activities were weak for AK in layers 0–20, 20–30, 40–50 and 50–60 cm ($C_0/(C_0 + C) < 0.25$) and was moderate for 30–40 cm ($0.25 < C_0/(C_0 + C) < 0.75$) (Table 2). Due primarily to the long history of intensive management on these farmlands and a plow pan was formed in the 30–40 cm layer where considerable Potassium (K) from K fertilizer and K mineral weathering could be deposited and fixed between adjacent phylosilicate layers as non-exchangeable forms, and thus the K variance was stronger influenced by random factors (Soil survey service of Hailun 1985; Zhang et al. 2006a, b, 2007a, b). The uniform autocorrelation distance ($A_0 = 3{,}110$ m) and models (Gaussian model) can guide people in the collection of soil samples in a local watershed, and higher r^2 and lower RSS showed the models were fit to predict AK spatial distribution in the study area (Robertson 2000).

In the study, the spatial pattern of AK typically decreased from forest to surrounding farmland at the

Table 3 AK and TN in soil depths of Farmland and forest areas

Landuse (N)	Depth (cm)	AK		TN	AK/TN
		Mean (mg kg^{-1})	CV^b (mg kg^{-1})	Mean (g kg^{-1})	%
Farmland (113)	0–20	198.0 (± 57.8) ad^a	0.29	1.7 (± 0.5)	11.7
	20–30	181.8 (± 44.6) b	0.24	1.4 (± 0.6)	13.1
	30–40	188.6 (± 40.9) ab	0.22	1.2 (± 0.7)	15.5
	40–50	194.7 (± 42.9)acd	0.22	1.0 (± 0.7)	19.7
	50–60	205.7 (± 43.9) d	0.21	0.9 (± 0.7)	22.6
Forest (9)	0–20	234.5 (± 77.9) A	0.49	1.5 (± 0.6)	15.4
	20–30	188.1 (± 43.7) A	0.24	1.3 (± 0.6)	14.3
	30–40	229.3 (± 82.3) A	0.37	1.3 (± 0.8)	17.4
	40–50	226.8 (± 76.9) A	0.36	1.5 (± 1.1)	15.3
	50–60	216.0 (± 57.1) A	0.28	1.5 (± 1.5)	14.0

[b] *CV* variable coefficient

[a] Values followed by the same letter within the same columns are not significantly different by LSD's multiple range test ($P \leq 0.05$)

Table 4 Correlation of AK with main driving factors in various soil depths

Landuse (N)	0–20 cm	20–30 cm	30–40 cm	40–50 cm	50–60 cm
Farmland (113)					
0–20 cm	1				
20–30 cm	0.680**	1			
30–40 cm	0.473**	0.629**	1		
40–50 cm	0.376**	0.470**	0.480**	1	
50–60 cm	0.330**	0.358**	0.482**	0.470**	1
GSL[a]	−0.229*	−0.077	−0.201*	−0.047	−0.157
NSL[b]	−0.166	−0.005	−0.130	−0.014	−0.096
Steepness	−0.225*	−0.123	−0.169	−0.016	0.040
DEM	0.263**	0.234*	0.219*	0.054	0.223*
Forest (9)					
0–20 cm	1				
20–30 cm	0.617	1			
30–40 cm	0.136	0.324	1		
40–50 cm	0.509	0.667*	0.716*	1	
50–60 cm	0.221	0.516	0.851**	0.929**	1
GSL	0.021	−0.111	0.225	0.060	0.208
NSL	0.269	0.045	0.372	0.365	0.386
Steepness	0.083	−0.137	−0.204	−0.091	−0.058
DEM	−0.232	−0.428	0.111	0.200	0.234

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

[a] GSL mean Gross Soil Loss that was calculated by USLE based GIS, and this result published (Zhang et al. 2013)

[b] NSL mean net soil loss equal to GSL minus soil deposition, and this result published (Zhang et al. 2013)

0–20, 20–30, 30–40, 40–50 and 50–60 cm depths due to the forest absorbing much water and competing for more sunshine at the farmland edges (Miller and Pallardy 2001), leading to decreased crop growth, thus absorbing limited AK nearer to the forest than farther from the forest. Zhang et al. (2006a) reported that soil water content was positively correlated to both DEM and soybean yield in black soils of northeast China, and intensive crop production or relatively more vigorous plant growth on the lower slope with more water content resulted in considerably higher K absorption (Jalali and Zarabi 2006; Zhang et al. 2012). Thus, in our study area, AK deceased from west to east along the water flow direction in farmland areas for all depth and became lowest at the intersection of the HRs, especially at the watershed outlet. Also most of the AK significantly positively correlated to elevation, similar to a study in an Indian forest (Gairola et al. 2012).

In the study, AK was significantly different between layers in farmland, but was not significantly different in the forest because cultivation and fertilization application in farmland can cause the AK variance in the soil profile, while farmland returned to forest reduces interruption from human beings. At the same time, after long-term spontaneous recovery by mineralization processes, microbiology activities, tree roots and so on in the soil, AK variance in the forest was moderate (Brady and Weil 2000). Coefficient of variation (CV) discovered that AK variance in space decreased from 0–20 to 50–60 cm, and especially decreased quickly from 0–20 to 30–40 cm deeper in the profile because the closer to surface the soil layer was, the more easily AK was affected by environmental factors. At the same time, crop roots were predominant at 0–45 cm, and the root density decreased as the soil depth increased, thus AK absorbed by crops was decreasing as the soil depth increased (Jin et al. 2007). However, AK in the forest did not follow this trend, possibly due to accumulation of leaf litter on the soil surface, and tree roots rotting at deeper levels of the soil profile, which would influence the dynamics of AK content.

In the study area, K fertilizer was seldom used because AK is usually rich in the mollisols of northeast China (Han et al. 2002). AK was highest at 50–60 cm and then followed 0–20, 40–50, 30–40 and 20–30 cm in the farmland due to the crop absorbing AK easily from the upper soil. Soil mineral weathering and much crop litter falling to the surface of the soil during the growing season was helpful to increase AK (Brady and Weil 2000). At the same time, in the soil profiles, mean AK/TN increased from 0–20 to 50–60 cm (Table 3), and mean AK was more difficult use at increasing soil depth because nitrogen scarcity deeper in the profile is a limiting factor to crop absorbtion of AK (Askegaard and Eriksen 2002). The leaching of K^+ is not considered a problem in Mollisols with high clay content (Jalali and Rowell 2003; Heilongjiang bureau of land management 1992), but harvesting crops without returning crop residues to the farmland is adverse to nutrient conservation. Generally, AK was higher in the forest than in the farmland for all layers, and was larger by 3–22 %, which means that reforestation is helpful to increase soil AK A similar result was reached by Peng et al. (2005) who reported that AK increased when farmland returned to forest for 10 years.

It is obviously that the steepness of a slope influences the intensity of soil erosion and runoff thus affects soil nutrient distribution, especially in the surface layer of the farmland (Agassi et al. 1990; Walson and Laflen 1986; Liu et al. 2006; Morgan 2005). So, AK was negatively correlated to gross soil loss (GSL) and steepness in all layers, and became significant at 0–20 cm. However, net soil loss (NSL) was negatively but not significantly correlated to AK in all layers, which may be due to AK movement being mainly influenced by runoff rather than NSL. In the forest, the negative or positive correlation was not consistent between AK and GSL, AK and NSL, AK and steepness, or AK and elevation in the profile, possibly due to the lower soil loss and improved natural processes after the farmland returned to forest.

Slope aspect can also be important in affecting nutrient distribution, as equatorial-facing slopes tend to be dryer than polar-facing ones because they have greater evapotranspiration rates (Rundel 1981; Zhang et al. 2011), while the amount of rainfall, and thus runoff, tends to be greater on a windward slope than on the leeward side (Agassi et al. 1990). Therefore, AK spatial distribution was different, and increased from up slope to down slope on southern aspects, while it decreased from up slope to down slope in northern aspect except in the 40–50 and 50–60 cm layers. However, AK differed between the two banks of the HRs mainly because of slope aspect, steepness, elevation, land use and so on.

In the study, AK was between 80–430 mg kg^{-1}, and was above the sufficiency level in most area. According to Han et al. (2005) AK in Chinese mollisols can be classified into very insufficient(<30 mg kg^{-1}), insufficient(30–50 mg kg^{-1}), sufficient(50–150 mg kg^{-1}), rich(150–200 mg kg^{-1}) and very rich(>200 mg kg^{-1}) levels respectively. Han et al. (2002) and Wu et al. (1998) indicated that generally potassium fertilizer was not the limitation factor affecting soybean and corn yield, but it was useful when drought condition or continuous cropping or other special conditions were faced. In this study area, AK was above the rich level over most of the farmland area (Table 5), and so farmland will not be lacking in AK, although the soil surface depth (in 0–50 cm) was eroded. Liu et al. (2008) reported that 1–3 mm per year of surface soil was removed by erosion including of water erosion, wind erosion, tillage erosion and so on. Crop roots were found over 70 cm underground, and were predominant in the 0–45 cm depth in black soils of northeast China (Jin et al. 2007).Thus generally, AK is sufficient for crop production for at least 160 year with a little potassium fertilizer application during the growing season. However, in order to increase potassium storage and promote the efficiency of AK in soils, crop residue

Table 5 Area of AK in levels accounted for total area in soil depth

Soil depth (cm)	Proportion of AK in levels to total area (%)				
	<30 (mg kg^{-1}) Very insufficient	30–50 (mg kg^{-1}) Insufficient	50–150 (mg kg^{-1}) Sufficient	150–200 (mg kg^{-1}) Rich	>200 (mg kg^{-1}) Very rich
0–20	0	0	4.3	54.4	42.2
20–30	0	0	11.9	74.8	14.9
30–40	0	0	5.3	74.6	21.5
40–50	0	0	4.2	62.3	35.7
50–60	0	0	0.2	44.9	56.5

management and fertilizer application, especially manure and nitrogen application in special conditions (dry seasons, intensive cropping without residue return and so on) and in specific areas (such as Low elevation, closer forest and so on) is necessary (Wu et al. 2002; Askegaard and Eriksen 2002).

Conclusions

In the study area, Gaussian models were recognized as the best for predicting AK at 0–20, 20–30, 30–40, 40–50 and 50–60 cm depths. Spatial autocorrelations as influenced by human activities were weak for AK at 0–20, 20–30, 40–50 and 50–60 cm and was moderate in 30–40 cm, and autocorrelation distance ($A_0 = 3{,}110$ m) is uniform across the profile.

The content of AK was 21.1–428.4 mg kg^{-1} in farmland and 117.2–401.0 mg kg^{-1} in forest (farmland returned to forest over 10 years) in the 0–60 cm profile. Generally, AK was higher in the forest than that in farmland in same layer. AK variance in space decreased from 0–20 to 50–60 cm depth, with a large decrease from 0–20 to 30–40 cm.

The horizontal distribution of AK was similar at layers across the profile, and typically decreased from the western forest, southwestern forest and the middle eastern forest to the surround farmland. Generally, AK deceased from west to east along the water flow direction in all layers, and became the lowest at the watershed outlet. As well, AK increased from up slope to down slope in northern aspect, while decreased from up slope to down slope in southern aspect except at the 40–50 and 50–60 cm layers. Furthermore, there were big different between the two banks of the HRs.

In the farmland, AK was negatively correlated to GSL and steepness, and became significant in the 0–20 cm layer, while it was significantly positively correlated to DEM except at 40–50 cm. In the forest, the negative or positive correlation was not consistent between AK and soil loss, AK and NSL AK and steepness, or AK and elevation. Generally, AK is sufficient for crop production for at least 160 year with a little potassium fertilizer application needed during the growing season in the study area. However, crop residue management and fertilizer application, especially manure and nitrogen application in special conditions (dry seasons, intensive cropping without residue return and so on) and sensitive areas (such as Low elevation, closer forest and so on) is still necessary in order to increase potassium storage and promote the efficiency of AK for plants.

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