Soil physical and hydraulic properties under different land uses in the black soil region of Northeast China

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Title page

Title: Soil physical and hydraulic properties under different land uses in the black soil region of Northeast China

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Abstract

Black soil is inherently productive and fertile but is subject to soil erosion. Understanding the distribution of soil physical and hydraulic properties of the soil profile under various land uses would help reveal the mechanism behind the degradation of black soil. In this study, we investigated the variation in soil physical and hydraulic properties with land uses and soil depths in the black soil area of Northeast China. Disturbed samples and undisturbed soil cores were collected from 0-100 cm soil depths under agricultural land, forestland and shrub land. Our results showed that the land use and soil depth significantly affected the soil bulk density (BD), field capacity (FC), capillary moisture capacity (CMC), saturated hydraulic conductivity (Ks), and soil water retention curve ($\theta_s$ and $\alpha$). Small macroaggregates accounted for most of the soil mass and were significantly higher in forest land but lower in agricultural land for the 0-50 cm of the soil samples. The FC, CMC and Ks decreased, but the BD increased with the soil depth across the three land use types. In addition, the soil in agricultural land had a higher BD but lower CMC and Ks than the soil in forestland and shrub land for most soil depths. These results indicated that land use can influence the variation in soil physical and hydraulic properties within the 0-100 cm soil depth, and agricultural use is a major reason for soil degradation in this black soil region.

Key words: forestland; shrub land; agricultural land; soil structure; soil hydraulic properties
Introduction

Black soil (Mollisol) is of global importance for its relevance to food security and climate change (FAO, 1988). On the one hand, black soil is inherently productive and fertile because of its higher soil organic matter content (Duan et al., 2011; Liu et al., 2010). On the other hand, black soil is vulnerable to soil erosion (Huffman et al., 2000) which can influence soil CO$_2$ emission (Gao et al., 2018). For example, the black soil region of Northeast China accounts for 25% of the global black soil area (Soviet Centre Statistics Department, 1992; Fan et al., 2005) and supplies more than half of China's total grain market (Duan et al., 2011; Liu et al., 2010). However, it has experienced severe erosion, and the mean soil depth has reduced from 60-70 cm in the 1950s to 20-30 cm presently (Fan et al., 2005). Herein, it is essential to elucidate the mechanisms underlying soil erosion in black soil region of Northeast China.

Soil physical and hydraulic properties are interrelated and have important effects on hydrology and soil erosion (Wang and Shao, 2013; Perkins et al., 2007). For example, soil bulk density and aggregate distribution have been widely observed to affect hydraulic conductivity (Perkins et al., 2007; Strudley et al., 2008). The structure of micro- and macroaggregates helps maintain the size, stability, and continuity of pores within and between aggregates, which can further decide soil pore-size distribution and bulk density (Kutilek, 2004). Furthermore, different sizes of soil aggregate shows different ability to resist degradation when exposed to external forces such as water erosion and wind erosion, shrinking and swelling processes, and tillage (Tatarko, 2001). Soil hydraulic properties such as saturated hydraulic conductivity and soil water retention curve affect water infiltration and accordingly
runoff generation, and they are usually coupled to the erosion models (Liu and Shen, 2018; Ouyang et al., 2018). Thus, it is important and necessary to understand the soil physical and hydraulic properties of black soil, which would provide essential information about how to protect black soil from degradation.

Land-use change usually has long-lasting effects on soil physical and hydraulic properties (Haghighi et al., 2010; Giertz et al., 2005; Celik, 2005) and further increases soil erosion by altering plant species composition and soil management (Christianl et al., 2008). For instance, the conversion of natural pasture to dryland farming decreased total porosity (Li et al., 2016), available water content, saturated hydraulic conductivity (Ks) (Celik, 2005) and the proportions of large aggregates but increased the soil bulk density (Giertz et al., 2005), negatively affecting soil productivity and erodibility (Haghighi et al., 2010). Due to long-term and large-scale intensive reclamation in Ukraine and USA, a black blizzard resulted in the loss of the top 5-12 cm of black soil in 1928 (Soviet Centre Statistics Department, 1992) and 5 cm of surface black soil in 1933 (Schubert et al., 2004), respectively. Therefore, knowledge on the soil physical and hydraulic properties under different land uses is imperative for assessing the soil erosion risk after land-use change under long-term intensive large-scale reclamation in black soil areas.

Most previous studies about the effects of land use on soil properties have been focused on the top soils (<40 cm) which reflected the human disturbances and the effects of shallow roots (Celik, 2005; Marzaïoli et al., 2010; Mainuri et al., 2013). The properties of deep soils, however, might be more important in influencing the
response of the land surface process to management practices due to the effects of deep roots or tillage activities in agricultural areas (Wang et al., 2015; Nasri et al., 2015). For example, the average maximum rooting depth of arable crops on a global scale can reach to 2.1 m below the soil surface (Canadell et al., 1996) and the deep root growth would affect the nutrient and water distribution in the soil as well as soil compaction in deep soil (Masle, 2002). Osman and Towhid (2013) reported that tillage could stimulate soil compaction and then destroyed soil structure, increased bulk density, reduced soil porosity, and limited movement of water and air within the soil. Additionally, depending on local climate, e.g. rain- or snow-fed precipitation, soil aggregation and erosion across depth can be very different due to the differences in infiltration depth and wetting-drying cycles (An et al., 2013; Zhong et al., 2019).

Moreover, the response of soil properties to land use in black soil was less examined compared with that of other soils, and whether the established mechanism could be applied in black soil was unknown. These knowledge gaps hinder the establishment of the relationships of land-use change and the degradation of black soil.

Given that soil physical properties determine the land surface hydrological processes and soil erosion (Perkins et al., 2007; Nasri et al., 2015), understanding how black soil responds to changes in land use would be important for mitigating soil erosion and land degradation. In this study, we investigated soil physical and hydraulic properties under three land uses (i.e., forestland, shrub land and agricultural land) along 0-100 cm soil depths in the black soil area of Northeast China, with the aim to characterize their spatial variations and to determine how land use affected
these properties of black soil.

Materials and Methods

Study area

This study was conducted in a small watershed of Heshan farm (48°59′-49°03′N, 125°16′-125°21′E) of Heilongjiang Province in Northeast China (Fig. 1). The altitude of the area is 310-390 m above sea level. The topography of the watershed is characterized by gentle (1-4°) but long slopes (up to 800-1500 m). The study site is characterized by a continental monsoon climate of the cold temperate zone, with a windy spring; short, hot summer; cool autumn; and long cold winter. The temperature ranges from a minimum of -43.7°C in January to a maximum of 37°C in July, with a mean annual temperature of approximately 0.4°C. The frost-free period is 115-120 days, and the mean annual precipitation is 500 mm. The rainfall is unevenly distributed, with most of the rainfall occurring in June to August, which accounts for 66.6% of the annual precipitation.

The soil in the selected small watershed is typical black soil, classified as Mollisols according to the United States system of soil taxonomy (Liu et al., 2012). The soil clay content ranges from 30% to 40%, and the soil organic matter content ranges from 22 g kg⁻¹ to 45 g kg⁻¹ (China Soil Database, 2013). The land use types in the study site are agricultural land (AL), forestland (FL) and shrub land (SL) (Fig. 1). The AL and SL were converted from forests more than 50 years ago due to agricultural production and deforestation. The crops in the AL are annual corn (Zea
mays L.) and annual soybean (Glycine max (Linn.) Merr.). The dominate species are perennial Pinus sylvestris var. Mongolica Litv. in FL and perennial Hippophae rhamnoides Linn. in SL. For different root influencing depth of annual and perennial plants, fine roots (≤3 mm) and coarse roots (>3 mm) based on root diameter in FL and SL and total roots in AL are collected and measured to observe distribution of roots, respectively. For fine and coarse roots analyse, eight soil cores for tree roots were conducted at each soil depth around a tree (random three trees) with a 8.0 cm diameter soil auger, giving a total of 120 samples in FL and SL, respectively. Three corn roots were directly sampled by excavating whole corn root in AL and then separated into different samples according to soil depth. In the laboratory, each soil cores was submerged in a container with water and stirred, and then the tree root suspension was sieved with a 3 mm sieve but corn root samples were washed and directly collected. This routine was repeated at least three times. The roots were then oven-dried at 80°C for 48 h and weighed (Imada et al., 2008). The proportion of different plant roots at each soil depth to total roots dry weight across 0-100 cm soil profile were calculated in AL, FL and SL, respectively (Table A1 in Appendix).

Soil sampling

Soil samplings were conducted in early October 2017. Due to smaller heterogeneity of sampling sites in agricultural land (AL) than that in forest land (FL) and shrub land (SL), three, five, and five sampling sites were established in AL, FL and SL, respectively. In each sampling site, a 1.0 × 1.0 × 1.0 m pit was dug for the
collection of undisturbed soil cores. According to the natural depth of black soil (50-70 cm) and the tillage depth (30-50 cm) (Li et al., 2006), the soils below this depth could be affected by the mechanical pressure in AL and by roots in FL and SL, so we collected undisturbed soil cores from 0-100 cm depth to investigate the effects of land use types in this study. Undisturbed soil cores were collected with 100 cm³ stainless steel cylinders (5.05 cm diameter and 5.0 cm height) from 0-15, 15-30, 30-50, 50-70 and 70-100 cm soil depths. The soil cores were collected for the measurement of saturated hydraulic conductivity (Ks, cm d⁻¹), the bulk density (BD, g cm⁻³), the field capacity (FC, %), the capillary moisture capacity (CMC, %), and the soil water retention curve (SWRC).

Three sampling plots (3 m × 3 m) were randomly established in each sampling site with a distance of more than 10 m between each plot for the collection of disturbed soil samples. In each plot, soil samples from 0-15 cm, 15-30 cm, 30-50 cm, 50-70 cm and 70-100 cm were collected with a 5.0 cm diameter soil auger. The samples from the three plots at the same site were combined as a composite sample for the measurement of soil particle size distribution (i.e., clay, silt and sand) and water-stable aggregates.

**Determination of soil particle size and water-stable aggregate**

The disturbed soil samples were air-dried and separated into two portions. One portion of samples was ground to pass through a 2-mm sieve for analysis of the particle size distribution with laser diffraction methods using a Mastersizer 2000.
(Malvern Instruments, Malvern, England). The other portion was passed through an 8-mm mesh for aggregate analysis and aggregate separation, which were performed by the wet sieving method adopted from Six, (1998). Specifically, a 200-g air-dried soil sample on top of the 2-mm sieve was submerged into deionized water at room temperature for 5 min. The sieve was manually moved up and down 3 cm with 50 repetitions for 2 min. After that, the aggregates that remained on the 2-mm sieve were gently backwashed off the sieve into an iron bowl. Water plus soil that went through the sieve was poured onto the 0.25-mm sieve, and the sieving was repeated. The same procedure was conducted for the 0.053 mm sieve. After completing the whole wet sieving procedure, different fractions of aggregates were oven dried (40°C), weighed, and stored in a zip-lock bag at room temperature. The four aggregate groups were large macroaggregate (> 2 mm), small macroaggregate (0.25-2 mm), microaggregate (0.25-0.053 mm), and clay+silt fraction (< 0.053 mm).

**Determination of the hydraulic properties**

The cylinder cores were linked to a Mariotte’s bottle to measure the Ks using the constant-head method based on Darcy’s law (Klute and Dirksen, 1986). Subsequently, the BD, FC, and CMC could be determined from the same soil core samples (Zhang et al., 1999). Briefly, the weights of 100 cm³ stainless steel cylinders (m₀) and soil cores with fresh soil samples (m₁) were recorded. The soil cores were placed in a large plastic container, and water was added to the plastic container until the water surface was just at the top of the soil cores. The soil cores were kept saturated for 24 h.
After that, the soil core was placed on dry sand for 2 h at room temperature, and the resulting weight was recorded \((m_2)\). In that way, only the capillary water remained in the soil core. Then, the soil core was moved back onto the dry sands for 48 h, and the soil core \((m_3)\) was weighed. In the end, the soil cores were moved into the oven to dry at 105°C until constant weight \((m_4)\). The BD \((g \text{ cm}^{-3})\), FC \(\%\), and CMC \(\%\) were calculated as follows:

\[
BD = \frac{(m_4 - m_0)}{100}
\]

(1)

\[
CMC = \frac{(m_2 - m_4)}{(m_4 - m_0)} \times 100\%
\]

(2)

\[
FC = \frac{(m_3 - m_4)}{(m_4 - m_0)} \times 100\%
\]

(3)

The soil water retention curves (SWRCs) for soil core samples were determined by the centrifugation method that was adopted by Reatto et al. (2008). Specifically, we used a Hitachi CR21G centrifuge with an outer radius of 15 cm, which was specially designed to hold four soil samples. The inside temperature was maintained at approximately 20°C. Care was taken to keep the samples under constant rotation for particular time to reach the soil water potential equilibrium corresponding to a given centrifugal force (Table 2). After each centrifugation step, the samples were weighed and returned to the centrifuge to undergo a higher rotation speed. The samples were then oven-dried at 105°C for 24 h to obtain the soil dry mass and to calculate the soil water contents.

The van Genuchten model (van Genuchten 1984, Equation 4) was used to fit the water contents that were recorded with the centrifuge method to the suction pressures
(-1 to -800 KPa) and to derive the VG equation parameters ($\theta_s$, $\alpha$, and $n$) for each sample. The VG equation is represented as follows:

$$
\theta(h) = \theta_r + (\theta_s - \theta_r) / (1 + |\alpha h|^n)^{1/n}
$$

where $\theta(h)$ is the measured volumetric water content (cm$^3$ cm$^{-3}$), $\theta_r$ is the residual soil water content (cm$^3$ cm$^{-3}$), $\theta_s$ the saturated soil water content (cm$^3$ cm$^{-3}$), $\alpha$ is the scaling parameter related to the inverse of the air entry pressure (cm$^{-1}$), $n$ is the curve-shape parameters that are related to the pore size distribution, and $h$ is the metric potential (kpa).

**Statistical analysis**

We calculated the basic statistical parameters, such as the minimum, mean, maximum, and standard deviation (SD), for the three SWRC parameters ($\theta_s$, $\alpha$ and $n$). Two-way analysis of variance was used to test the effect of land use, soil depth, and their interaction effects on the soil physical and hydraulic properties. Shapiro-Wilk test was used to test for normality, and data were log transformed when necessary. Pearson’s correlation analysis was conducted to investigate the relationship among soil properties. All of the statistical analyses were conducted using SPSS13.0.

**Results**

The land use and soil depth had significant effects on the BD, CMC, FC, Ks and SWRC parameters ($\theta_s$ and $\alpha$) ($P < 0.05$) but did not affect the most soil aggregates ($P > 0.05$). Moreover, the interaction of land use and soil depth generally did not have
any effects on the soil physical and hydraulic properties in this study (Table 1).

*Distribution of soil bulk density and water-stable aggregates as affected by land uses and soil depths*

In this study, the BD increased with the increasing soil depths, with a value of 1.3 g cm\(^{-3}\) at 0-15 cm soil depth to 1.7 g cm\(^{-3}\) at 70-100 cm soil depth (Fig. 2). The soils collected from AL had significantly higher BD, while the soils from FL had significantly lower BD (Fig. 2). For example, when averaged across the 0-100 cm depth, the BDs were 1.46 g cm\(^{-3}\), 1.52 g cm\(^{-3}\) and 1.59 g cm\(^{-3}\) in FL, SL and AL, respectively.

The small macroaggregates (0.25-2 mm) dominated the soil mass, with proportions ranging from 50.5-78.0%. The large macroaggregates (> 2 mm) and clay+silt fraction (< 0.053 mm) accounted for a small fraction of the soil mass, with ranges of 2.1-14.4% and 4.1-12.8%, respectively. The microaggregates (0.053-0.25 mm) accounted for 6.6-26.9% of the soil mass.

There was no significant difference in the proportions of aggregates among soil depths (Table 1). For example, when averaged across the three land use types, the small macroaggregates varied between 56.9% and 66.8% across the 0-100 cm soil depth (\(P = 7.68\)), the large macroaggregates and clay+silt fraction varied between 3.4% to 7.5% (\(P = 2.63\)) and 6.1% to 11.3% (\(P = 2.19\)), while the microaggregates varied between 15.0% to 19.1% (\(P = 1.3\)), respectively.

The effect of land use types on soil aggregates varied with soil depth (Fig. 3).
The proportions of the large macroaggregates were significantly higher in SL (8.4-12.9%) than in AL (4.4-2.9%) and in FL (5.3-4.9%) for soils from the 0-50 cm soil depth, but were significantly higher in AL (8.2-14.4%) than in FL (3.3-4.3%) and SL (3.3-4.6%) for soils from 50-100 cm soil depth. The proportions of the small macroaggregates in FL were significantly higher at the 0-50 cm soil depth but were lower at the 50-100 cm soil depth, while the proportions in SL were lower at the 0-15 cm soil depth but higher at the 50-100 cm soil depth compared with AL. The proportions of microaggregates were significantly higher in AL (21.4-26.9%) than in SL (14.0-16.8%) and in FL (6.6-14.5%) for soils from the 0-30 cm soil depth, but there was no significant difference between different land uses for the 30-100 cm soil depth. The proportions of the clay+silt fraction were significantly higher in SL (11.6%) but lower in FL (4.1%) for the top 15 cm depth and were not affected by the land use types in the deep soils.

*Soil water and hydraulic properties, as affected by land uses and soil depths*

In general, FC, CMC and Ks decreased with increasing soil depths (Fig. 4). When averaged across the three land use types, FC, CMC and Ks decreased from 29.1%, 34.6% and 15.3 cm d⁻¹ at the 0-15 cm soil depth to 17.4%, 24.7% and 2.2 cm d⁻¹ at the 70-100 cm soil depth, respectively.

The CMC, FC, and Ks were significantly affected by the land use type (Table 1). The soils collected from AL had significantly lower CMC and Ks than those in FL and SL for most soil depths, while the soils from FL had significantly higher CMC
and Ks but lower FC for most soil depths (Fig. 4). When averaged across the 0-100 cm depth, CMC and Ks were higher in FL (32.8% and 8.6 cm d\(^{-1}\)) than in SL (29.1% and 6.1 cm d\(^{-1}\)) and in AL (27.4% and 4.7 cm d\(^{-1}\)), while FC were lower in FL (19.3%) than in AL (21%) and SL (23.4%). However, the ANOVA results showed that the effects of the land use types on these metrics were independent of soil depth (\(P > 0.05\) for the interaction between soil depth and land use type, Table 1).

The effects of soil depth on the \(\theta_s\) and \(\alpha\) of the SWRC varied by land use type (Fig. 5). The \(\theta_s\) decreased with soil depth in FL (from 56.04% at 0-15 cm to 40.96% at the 70-100 cm soil depth) and SL (from 45.63% to 35.73%) but was not affected in AL (with a range of 39.5% to 48.34%) for the 0-100 cm soil depth. The \(\alpha\) was significantly higher at 0-30 cm soil depth (0.157 cm\(^{-1}\) and 0.115 cm\(^{-1}\)) than at the 30-100 cm soil depth (0.045-0.058 cm\(^{-1}\)) in FL and was significantly lower in the top 50 cm of soils (0.021-0.039 cm\(^{-1}\)) than in the deep soils (0.067 cm\(^{-1}\) and 0.099 cm\(^{-1}\)) in SL, but it was significantly higher at the 0-15 and 50-70 cm depths (0.069 cm\(^{-1}\) and 0.067 cm\(^{-1}\)) than in the other soil depths (0.014-0.031 cm\(^{-1}\)) in AL. However, the parameter \(n\) of the SWRC was not affected by the soil depth in each land use type, with a range of 1.16 to 1.27, 1.11 to 1.24, and 1.11 to 1.21 for AL, FL and SL, respectively, for the 0-100 cm soil depth (Table 3).

The effects of land use on the parameters (\(\theta_s\), \(\alpha\), and \(n\)) of the SWRC depended on the soil depth (Fig. 5). The \(\theta_s\) was relatively lower in SL across the 0-100 cm soil depth but was higher in FL at the top 30 cm soil depth and in AL at the 50-100 cm soil depth. The \(\alpha\) at the 0-50 cm soil depth was significantly higher in FL than in SL.
and AL but was higher in SL than in the other land use types in deeper soils. The n was not affected by the land use type for each soil depth.

Discussion

Soil bulk density and water-stable aggregates along soil profiles under different land uses

Our results showed that land use significantly affected the soil BD, which was higher in AL than FL and SL at the 15-100 cm soil depth, and the BD in topsoils was smaller than that in deep soils in this black soil region, which agreed with previous observations in managed grasslands (Don et al., 2007), farmland (Unger and Jones, 1998) and forestland (Jalabert et al., 2010). In this study, the higher BD in deep soils from AL might be related to the compaction of long-term mechanical tillage. For example, Hill (1985) indicated that tillage treatments (i.e., no-tillage, reduced tillage, and conventional tillage) significantly affected the soil BD, which increased significantly with the depth in soils with conservation and conventional tillage for Mollisols. The higher BD in deep soils from FL and SL might be due to the compaction by root growth (Nizami et al., 1990; Edwards et al., 1964). Houlbrooke et al. (1997) indicated that the surface soils could be partially pushed up by more roots penetration, but the deep soils mainly formed soil compaction by roots growth. Although roots tend to be concentrated in the surface soil, higher proportions of aboveground biomass, litter, and leaves productivity stimulated microbial activity and accelerated humification in top soil in FL and SL, and thus decreased surface soil BD.
An alternative explanation for the greater BD in deep soils might be due to the higher clay content in deep soils than in topsoils (Table A2 in Appendix), because the soil BD was positively related with the clay content in this study (BD = 0.011 \times \text{Clay} + 1.128, n = 65, R^2 = 0.213, P < 0.001) and in other experiments (Kumar et al., 2009; Ruehlmann and Körschens, 2009). The higher clay content in deep soils might result from the transportation of fine soil particles from topsoils to deep soils through soil macropores, particularly in agricultural land (Hishe et al., 2017; Su et al., 2010).

The small macroaggregates accounted for most of the soil mass across the three land use types (Fig. 3). This result was consistent with observations in native vegetation, no-tillage and conventional tillage (Six et al., 2000; Xu et al., 2007). Averaged across the 0-50 cm soils, the quantity of large and small macroaggregates was higher in SL and FL than AL, respectively, but opposite in 50-100 cm soils (Fig. 3), which was related to the differences in soil management. Tillage in AL resulted in the destruction of macroaggregates and, thus, a decrease in the quantity of large and small macroaggregates in 0-50 cm soils (Six et al., 2000; Su et al., 2010). Moreover, the tillage could also result in more soil aerobic condition, exposing soil organic matter (SOM) to the air and increasing soil decomposition and mineralization (Bronick and Lal, 2005; Gale et al., 2000). The harvest of aboveground biomass also reduced the input of organic materials into soils of AL. Both led to the lower content of SOM and thus accelerated the breakdown of large and small macroaggregates in
0-50 cm soils, as SOM is an important binding agent for aggregation (Wei et al., 2009; Six et al., 2000). On the contrary, the exclusion of tillage in FL and SL and the input of above- and belowground biomass (litters and roots) from trees and shrubs favored the accumulation of organic matter in 0-50 cm soils (Compton and Boone, 2002; Wang and Wang, 2007; Singh and Singh, 1996). The high SOM in these two lands resulted in the relatively higher proportion of large and small macroaggregates (Six et al., 2000; Su et al., 2010). Previous studies also confirmed that fungi may preferentially colonize small macroaggregates because of the higher C:N ratios associated with these fractions, while large macroaggregates were dominated by bacterial communities (Harris et al., 2003; Smith et al., 2014; Waring et al., 2013). Therefore, the proportions of large and small macroaggregates for soils from the 0-50 cm soil depth was higher in SL and FL than AL, respectively. However, long-term intense tillage in AL was prone to causing soil compaction and promoting formation of large and small macroaggregates in 50-100 cm soils with substantially higher clay content. Additionally, the mechanism that mechanical compaction by tillage in AL formed macroaggregates in 50-100 cm soils was greater compared with mechanical compaction by root penetration in SL and FL. Thus, the proportions of large and small macroaggregates for soils from the 50-100 cm soil depth was higher in AL than SL and FL. Our results showed that the effects of land use on small macroaggregates was greater in topsoils than in deep soils, which indicated that land management mainly affects the top 50 cm soils in this study region. However, we did not observe significant effects of land use on large macroaggregates, microaggregates and
silt+clay fractions, possibly due to their proportion was lower than 26.9% across soil depths and land uses (Fig. 3).

Soil water and hydraulic properties along soil profiles under different land uses

The differences in the FC and CMC among AL, FL and SL could be ascribed to the variations of evaporation (Jackson et al., 1973), root distributions and the amounts of water uptake by roots (Qiu et al., 2001; Wang et al., 2013), the total porosity and capillary porosity (Li et al., 2016) and soil water retention capacity (Mcbeath et al., 2012) among land use types. Generally, the large aboveground biomass and deep roots in FL and SL resulted in higher the SOM content, the total porosity and capillary porosity, and higher soil water retention capacity, causing relatively higher FC and CMC in FL and SL than these in AL (Fig. 4). Our results showed that CMC was higher in FL but FC in SL, respectively. This was related to the existed discrepancy of the response of the SOM content, BD, the total porosity and capillary porosity to FL and SL (Chen et al., 2007; Hernández et al., 2005). The findings were partly consistent with the current understanding that the conversion of cropland to forest land could ameliorate total porosity and capillary porosity and improve soil fertility, and positively affect CMC and FC (Wang et al., 2012). The general decrease in the FC and CMC with the soil depth was consistent with observations by Wang et al. (2012 and 2013), in that the FC and CMC decreased with the increasing soil depth in forestland, and the vertical distribution and quantity of the SOM content, BD, the total porosity and capillary porosity were significantly influenced by land use type in the
In this study, the $K_s$ decreased with the increasing soil depth, which was attributed to higher soil BD and clay contents in deep soils than in topsoils (Fig. 1 and Table A2 in Appendix), as $K_s$ significantly decreased with increasing soil BD ($K_s = -43.438 \times BD + 72.916, n = 65, R^2 = 0.746, P < 0.001$) and clay contents ($K_s = -0.587 \times Clay + 28.284, n = 65, R^2 = 0.251, P < 0.001$). These results were consistent with previous observations about the vertical distribution of $K_s$ (Bormann and Klaassen, 2008) and the negative relationships of $K_s$ to BD (Nasri et al., 2015; Qiao et al., 2017) and clay content (Stolte, 2003). Our results showed that $K_s$ was higher in SL than in FL and AL at the 0-15 cm soil depth but was higher in FL than in SL and AL at 15-100 cm soil depth (Fig. 4). This was primarily due to the variation in the BD and clay content among the land uses and soil depths (Fig. 2 and Table A2 in Appendix).

Our explanation about the effect variation in clay content among the land uses on $K_s$ was supported by our observation that the mean clay content of soil in AL across soil profile was highest (39.6%), followed by SL (36.7) and FL (33.0%) in the same soil texture, which was mainly related to that land use change could affect clay content in soil. Rezapour et al. (2014) indicated that some changes in clay content by the X-ray diffraction of illite and smectite were observed in the cultivated soils compared to those of the adjoining grassland soils. Furthermore, Rezaie et al. (2018) reported that after changing forest to tea cultivation, clay content was decreased at $P < 0.01$ significance level under natural forest. An alternative explanation for difference in $K_s$ among land use types could be the intensive agricultural use, which resulted in soil root zone.
compaction and a reduction in soil porosity and thus a lower $K_s$ in AL compared with that in FL and in SL (Bormann and Klasseen, 2008).

We found that the effects of land use on the parameters of the SWRC varied with soil depth (Fig. 5). The $\theta_s$ and $\alpha$ were significantly higher in FL than in SL and AL for topsoils (0-50 cm), mainly due to the lower BD in FL compared with that of the other two land use types. This is because $\theta_s$ and $\alpha$ are determined by the soil porosity. Our explanation about the soil porosity response to $\theta_s$ and $\alpha$ was supported by our observation that FL had a lower BD than AL and SL (Fig. 2), and $\theta_s$ and $\alpha$ were negatively correlated with BD (Table 4). Karlen et al. (1994) indicated that the conversion of cropland to forest land increased earthworm population but decreased bulk density, and Somaratne and Smettem (1993) showed greater total porosity under conventional tillage than for no-tillage on a sandy loam decreased in conventional tillage from 0.56 at pre-seeding to 0.48 after harvest, which equaled the porosity under no-tillage, indicating more input of organic material and roots disturbance could decrease BD and increase soil porosity. Therefore, the soil porosity is higher in FL than in SL and AL (Alaoui et al., 2011; Hartmann et al., 2009). This explanation was supported by results from Qiao et al. (2017), in that BD was an important soil metric for explaining the variation in $\theta_s$ in the Loess Plateau. This result further indicated that the effects of land use on SWRC parameters mainly resulted from changes in the soil structure and, thus, the soil porosity at the small watershed scale (Wang et al., 2015; Qiao et al., 2017). In addition, based on Pearson’s correlation analysis, CMC and silt content also made significant contribution to $\theta_s$ variation ($P < 0.05$), and $\theta_s$ was
significantly positive correlation with $\alpha$ ($P < 0.01$). $\alpha$ was positive correlation with clay and silt content. However, $n$ only had correlation with clay ($P < 0.05$).

Furthermore, the SWRC describes the relationship between matric potential and soil water content in the unsaturated soil that exhibits a high degree of spatial heterogeneity due to the influence of geological and pedological factors on soil formation. The unsaturated soil hydraulic properties are key factors governing the partitioning of rainfall and irrigation into soil water storage, evapotranspiration, and deep drainage. As discussed above, the lower BD in FL resulted in higher the $\theta_s$ and $\alpha$ in FL than AL for 0-50 cm soils, indicating that soil water storage and infiltration could be higher for undisturbed soils in FL than AL. That was related to that the water content in undisturbed soil entered the most rapidly with increasing soil matric potential. Van Genuchten (1980) indicated that sufficiently accurate estimates of both $\theta_r$ and $\theta_s$ are available in different semiarid, arid and humid region, and Dexter and Bird (2001) resulted that higher infiltration has been found to increase the soil water content in FL with lower clay content, whereas infiltration was lower due to the application of energy to soil drier. According to the relationship between the parameters of SWRC and basic black soil physical properties, information about the spatial variations of the SWRC parameters under AL, FL and SL and related factors are essential when describing and estimating the flow of water and the transport and fate of solutes in soil within AL, FL and SL. Overall, an accurate prediction of the parameter (i.e. $\theta_s$, $\alpha$ and $n$) by the soil water retention curve could reflect the variation of soil water storage and infiltration and was important for assessing unsaturated
hydraulic conductivity under land use change in the unsaturated zone.

Conclusions

The results of this study indicated that land use and soil depth had significant effects on the BD, CMC, FC, Ks and SWRC parameters (\(\theta_s\) and \(\alpha\)) but did not affect the most soil aggregates. Moreover, the interaction of land use and soil depth generally did not have any effects on the soil physical and hydraulic properties. In addition, BD was higher in AL than FL and SL at the 15-100 cm soil depth, and the higher BD in deep soils from AL than from FL and SL might partially be related to the higher clay content of Mollisol in China and the effect land use change on clay content with soil depth. Furthermore, the differences in Ks, FC, CMC and the SWRC parameters (\(\theta_s\) and \(\alpha\)) among AL, FL and SL could partly be ascribed to the variation in the BD and clay content among the land uses and soil depths. Regardless of the weak effect of land use and soil depth on the most soil aggregates, the small macroaggregates accounted for most of the soil mass across the three land use types. Averaged across the 0-50 cm soils, lower large and small macroaggregates amounts of the soil in AL than in FL was attributed to that tillage in AL resulted in not only the destruction of macroaggregates but only the exposure of SOM to the air, while the exclusion of tillage in FL and SL and the input of above- and below-ground biomass (litters and roots) from trees and shrubs favored the accumulation of organic matter in soils. Overall, land uses change are needed for ameliorating soil BD, particle size distribution, aggregate and thus saturated and unsaturated soil hydraulic properties,
and improving the sustainable use of soil resources in regions with serious water and soil erosion, such as the Mollisol region in Northeast of China.

Acknowledgements

This study was supported by the National Key Research and Development Program (No. 2018YFC0507001), National Natural Science Foundation of China (41571296, 41622105 and 41571130082), the Programs from Chinese Academy of Sciences (QYZDB-SSW-DQC039), and Northwest A&F University (2452017028), and the Special-Funds of Scientific Research Programs of State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau (A314021403-Q5).

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Imada, S., Yamanaka, N., Tamai, S., 2008. Water table depth affects Populus alba fine root


Table 1. Analysis results of the effects of land use types and soil depths on soil properties

<table>
<thead>
<tr>
<th></th>
<th>BD</th>
<th>CMC</th>
<th>FC</th>
<th>$\theta_s$</th>
<th>$\alpha$</th>
<th>$\gamma$</th>
<th>Water stable aggregates</th>
<th>Ks</th>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;2 mm</td>
<td>0.25-2 mm</td>
<td>0.053-0.25 mm</td>
<td>&lt;0.053 mm</td>
<td></td>
</tr>
<tr>
<td>land use</td>
<td>7.68</td>
<td>4.39</td>
<td>3.01</td>
<td>2.83</td>
<td>4.36</td>
<td>1.22</td>
<td>2.63</td>
<td>7.68</td>
<td>1.30</td>
<td>2.19</td>
<td>3.24</td>
</tr>
<tr>
<td>soil depth</td>
<td>14.62</td>
<td>9.65</td>
<td>5.48</td>
<td>1.59</td>
<td>1.29</td>
<td>1.01</td>
<td>0.88</td>
<td>0.44</td>
<td>1.27</td>
<td>0.38</td>
<td>12.66</td>
</tr>
<tr>
<td>land use × soil depth</td>
<td>0.69</td>
<td>1.25</td>
<td>0.57</td>
<td>1.74</td>
<td>1.87</td>
<td>1.39</td>
<td>2.06</td>
<td>1.67</td>
<td>2.24</td>
<td>1.22</td>
<td>0.91</td>
</tr>
<tr>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>land use</td>
<td><strong>0.002</strong></td>
<td><strong>0.020</strong></td>
<td><strong>0.042</strong></td>
<td><strong>0.033</strong></td>
<td><strong>0.020</strong></td>
<td>0.306</td>
<td>0.086</td>
<td><strong>0.002</strong></td>
<td>0.284</td>
<td>0.127</td>
<td><strong>0.021</strong></td>
</tr>
<tr>
<td>soil depth</td>
<td>&lt; <strong>0.001</strong></td>
<td>&lt; <strong>0.001</strong></td>
<td><strong>0.002</strong></td>
<td><strong>0.027</strong></td>
<td><strong>0.023</strong></td>
<td><strong>0.04</strong></td>
<td>0.484</td>
<td>0.777</td>
<td>0.302</td>
<td>0.824</td>
<td>&lt; <strong>0.001</strong></td>
</tr>
<tr>
<td>land use × soil depth</td>
<td>0.699</td>
<td>0.301</td>
<td>0.792</td>
<td>0.123</td>
<td>0.096</td>
<td>0.236</td>
<td>0.067</td>
<td>0.142</td>
<td>0.048</td>
<td>0.316</td>
<td>0.517</td>
</tr>
</tbody>
</table>

Note: BD: bulk density; CMC: capillary moisture capacity; FC: field capacity; Ks: saturated hydraulic conductivity; $\theta_s$: saturated soil water content; $\alpha$: scaling parameter related to the inverse of the air entry pressure; $\gamma$: curve-shape parameters related to the pore size distribution. A bold value indicates statistical significance.
Table 2. The centrifugation time, centrifugation speeds and the corresponding the water potentials ($h$) in determining the soil water retention curves (SWRCs) by the centrifugation method

<table>
<thead>
<tr>
<th>Water potential (kpa)</th>
<th>-1</th>
<th>-10</th>
<th>-20</th>
<th>-40</th>
<th>-60</th>
<th>-80</th>
<th>-100</th>
<th>-200</th>
<th>-400</th>
<th>-600</th>
<th>-800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centrifugation speeds (rad min$^{-1}$)</td>
<td>310.1</td>
<td>980.6</td>
<td>1386.8</td>
<td>1961.2</td>
<td>2402.1</td>
<td>2773.6</td>
<td>3100.9</td>
<td>4385.4</td>
<td>6201.9</td>
<td>7595.7</td>
<td>8770.8</td>
</tr>
<tr>
<td>Centrifugation time (min)</td>
<td>10</td>
<td>26.2</td>
<td>35.8</td>
<td>45.4</td>
<td>51.1</td>
<td>55.1</td>
<td>58.2</td>
<td>67.8</td>
<td>77.4</td>
<td>83</td>
<td>87</td>
</tr>
</tbody>
</table>
Table 3. Parameters describing soil water retention curve in three land use types across soil depths in black soils region of the Northeast China

<table>
<thead>
<tr>
<th>Land uses</th>
<th>Parameters</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>SD</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL</td>
<td>θ&lt;sub&gt;s&lt;/sub&gt;</td>
<td>0.352</td>
<td>0.622</td>
<td>0.444</td>
<td>0.073</td>
<td>16.50</td>
</tr>
<tr>
<td></td>
<td>α</td>
<td>0.004</td>
<td>0.903</td>
<td>0.010</td>
<td>0.235</td>
<td>235.34</td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>1.077</td>
<td>1.379</td>
<td>1.2078</td>
<td>0.010</td>
<td>8.25</td>
</tr>
<tr>
<td>FL</td>
<td>θ&lt;sub&gt;s&lt;/sub&gt;</td>
<td>0.327</td>
<td>0.674</td>
<td>0.481</td>
<td>0.095</td>
<td>19.74</td>
</tr>
<tr>
<td></td>
<td>α</td>
<td>0.009</td>
<td>0.902</td>
<td>0.177</td>
<td>0.257</td>
<td>145.38</td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>1.019</td>
<td>1.304</td>
<td>1.292</td>
<td>0.523</td>
<td>40.46</td>
</tr>
<tr>
<td>SL</td>
<td>θ&lt;sub&gt;s&lt;/sub&gt;</td>
<td>0.328</td>
<td>0.482</td>
<td>0.407</td>
<td>0.045</td>
<td>11.13</td>
</tr>
<tr>
<td></td>
<td>α</td>
<td>0.004</td>
<td>0.337</td>
<td>0.051</td>
<td>0.072</td>
<td>141.19</td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>1.064</td>
<td>1.547</td>
<td>1.149</td>
<td>0.092</td>
<td>8.00</td>
</tr>
<tr>
<td>mean</td>
<td>θ&lt;sub&gt;s&lt;/sub&gt;</td>
<td>0.327</td>
<td>0.674</td>
<td>0.440</td>
<td>0.077</td>
<td>17.55</td>
</tr>
<tr>
<td></td>
<td>α</td>
<td>0.004</td>
<td>0.903</td>
<td>0.105</td>
<td>0.198</td>
<td>188.00</td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>1.019</td>
<td>1.547</td>
<td>1.174</td>
<td>0.091</td>
<td>7.74</td>
</tr>
</tbody>
</table>

Note: θ<sub>s</sub>: saturated soil water content; α: scaling parameter related to the inverse of the air entry pressure; n: curve-shape parameters related to pore size distribution; Min: minimum; Max: maximum; SD: standard deviation; CV: coefficient of variation; AL: agricultural land; FL: forestland; SL: shrub land.
Table 4. Pearson’s correlation coefficients among soil properties in the black soils region of Northeast China (n = 65)

<table>
<thead>
<tr>
<th></th>
<th>CMC</th>
<th>FC</th>
<th>$\theta_s$</th>
<th>$\alpha$</th>
<th>n</th>
<th>Water stable aggregates</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;2 mm</td>
<td>0.25-2 mm</td>
<td>0.053-0.25 mm</td>
<td>&lt;0.053 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.874**</td>
<td>-0.647**</td>
<td>-0.242*</td>
<td>0.105</td>
<td>0.029</td>
<td>0.192</td>
<td>0.212</td>
</tr>
<tr>
<td>CMC</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>0.785**</td>
<td>0.272*</td>
<td>0.139</td>
<td>-0.071</td>
<td>0.015</td>
<td>0.119</td>
<td>-0.15</td>
</tr>
<tr>
<td>FC</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>0.133</td>
<td>0.071</td>
<td>-0.151</td>
<td>0.132</td>
<td>-0.169</td>
<td>-0.035</td>
<td>0.151</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>-0.097</td>
<td>0.067</td>
<td>0.177</td>
<td>0.004</td>
<td>0.186</td>
<td>-0.195</td>
<td>-0.153</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>-0.034</td>
<td>0.042</td>
<td>0.109</td>
<td>-0.16</td>
<td>-0.095</td>
<td>0.275*</td>
<td>-0.156</td>
</tr>
<tr>
<td>n</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>-0.416**</td>
<td>-0.492**</td>
<td>-0.218</td>
<td>0.013</td>
<td>-0.054</td>
<td>0.156</td>
<td>-0.183</td>
</tr>
<tr>
<td>&gt;2 mm</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td>-0.509**</td>
<td>-0.715**</td>
<td>0.052</td>
<td>-0.116</td>
<td>0.052</td>
<td>0.078</td>
<td></td>
</tr>
<tr>
<td>0.25-2 mm</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td>0.648**</td>
<td>-0.112</td>
<td>0.238</td>
<td>-0.156</td>
<td>-0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.053-0.25 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.002</td>
<td>0.046</td>
<td>-0.172</td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;0.053 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ks</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>-0.501**</td>
<td>0.385**</td>
<td>0.081</td>
<td></td>
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</tr>
<tr>
<td>Clay</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>-0.799*</td>
<td>-0.113</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Silt</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: ** $p < 0.01$; * $p < 0.05$.

BD: bulk density; CMC: capillary moisture capacity; FC: field capacity; Ks: saturated hydraulic conductivity; $\theta_s$: saturated soil water content; $\alpha$: scaling parameter related to the inverse of the air entry pressure; n: curve-shape parameters related to the pore size distribution. A bold value indicates statistical significance.
Figure caption

Fig. 1. The location of the Heshan farm of Heilongjiang Province in the Northeast China and the general view of agricultural land, forestland and shrub land in the small watershed of Heshan farm. The maps were created using ArcGIS by Esri (Environmental Systems Resource Institute, ArcGIS 10.0; www.esri.com).

Fig. 2. The soil bulk density of soil profiles as affected by land use types. The error bars are two standard errors of the means.

Fig. 3. The distribution of water-stable aggregates of the soil profile as affected by land use types. The error bars are two standard errors of the means.

Fig. 4. Soil field capacity, capillary moisture capacity and saturated hydraulic conductivity (Ks) of soil profiles as affected by land use types. The error bars are two standard errors of the means.

Fig. 5. The parameters ($\theta_s$, $\alpha$ and $n$) describing the soil water retention curves (SWRCs) of soil profiles as affected by land use types. The error bars are two standard errors of the means.
Figures

**Fig. 1.** The location of the Heshan farm of Heilongjiang Province in the Northeast China and the general view of agricultural land, forestland and shrub land in the small watershed of Heshan farm. The maps were created using ArcGIS by Esri (Environmental Systems Resource Institute, ArcGIS 10.0; www.esri.com).
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Fig. 5. The parameters ($\theta_s$, $\alpha$ and $n$) describing the soil water retention curves (SWRCs) of soil profiles as affected by land use types. The error bars are two standard errors of the means.
**Table A1.** The proportion of all roots of annual *Zea mays* L. at each soil depth (i.e. 0-15, 15-30, 30-50, 50-70, 70-100 cm) to total roots dry weight across 0-100 cm soil profile in AL, and the proportion of fine and coarse roots of perennial *Pinus sylvestris* var. *Mongolica* Litv. and *Hippophae rhamnoides* Linn. at each soil depth to total roots dry weight across 0-100 cm soil profile in FL and SL.

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>FL</th>
<th>SL</th>
<th>AL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fine roots (%)</td>
<td>Coarse roots (%)</td>
<td>Fine roots (%)</td>
</tr>
<tr>
<td>0-15</td>
<td>32.29</td>
<td>45.59</td>
<td>35.75</td>
</tr>
<tr>
<td>15-30</td>
<td>29.35</td>
<td>43.95</td>
<td>40.75</td>
</tr>
<tr>
<td>30-50</td>
<td>28.77</td>
<td>4.6</td>
<td>12.14</td>
</tr>
<tr>
<td>50-70</td>
<td>5.75</td>
<td>2.75</td>
<td>8.97</td>
</tr>
<tr>
<td>70-100</td>
<td>3.84</td>
<td>1.17</td>
<td>3.58</td>
</tr>
</tbody>
</table>

**Note:** AL: agricultural land; FL: forestland; SL: shrub land. Fine and Coarse roots were the roots with diameter ≤3 mm and >3 mm, respectively.
Table A2. Particle size distribution in three land use types across soil depths in the black soil region of Northeast China

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>AL Clay (%)</th>
<th>AL Silt (%)</th>
<th>AL Sand (%)</th>
<th>FL Clay (%)</th>
<th>FL Silt (%)</th>
<th>FL Sand (%)</th>
<th>SL Clay (%)</th>
<th>SL Silt (%)</th>
<th>SL Sand (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>35.5</td>
<td>34.1</td>
<td>30.5</td>
<td>25.3</td>
<td>32.9</td>
<td>41.8</td>
<td>30.2</td>
<td>34.1</td>
<td>35.7</td>
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Note: AL: agricultural land; FL: forest land; SL: shrub land.