Soil Particle Size Distribution Characteristics of Scots Pine Plantations in Nur-Sultan: Postprint

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Abstract

To reveal the effects of Mongolian pine plantations of different stand ages on soil particle size composition in Nur-Sultan, this study analyzed the soil particle size and fractal dimension characteristics of Mongolian pine plantations of different stand ages in the vicinity of Nur-Sultan through a combination of field sampling and laboratory analysis, and investigated the relationship between fractal dimension and soil properties. The results showed that: (1) The soil particle size composition in the study area was dominated by silt, followed by sand, with clay being the least abundant; the planting of Mongolian pine plantations could significantly increase the content of fine particles in the soil surface layer. The difference in soil particle content in deep layers among plantations of different stand ages was not significant. The effect of planting Mongolian pine plantations on soil particle size was mainly confined to the surface layer. (2) The soil fractal dimension varied between 2.059 and 2.569, showing a trend of first increasing and then decreasing during the growth of the plantation, and reaching its maximum at a planting age of 15 years. The soil fractal dimension was positively correlated with clay and silt, and the 20 m particle size was the critical particle size reflecting the fractal dimension of plantation soils in the study area. (3) The soil fractal dimension in the study area was extremely significantly positively correlated with soil organic matter and total nitrogen content, and the soil fractal dimension could be used to evaluate soil nutrient status. The research results can provide a theoretical basis for plantation construction and ecological restoration in Nur-Sultan.

Full Text

Preamble

Soil provides the essential material foundation for vegetation development and growth, while soil texture directly influences soil structure, water regime, and fertility status. Soil particle size composition is a key indicator characterizing differences in soil physicochemical properties, with variations in particle coarseness directly affecting changes in soil nutrients and moisture. As a porous medium composed of different particles, soil exhibits fractal characteristics. Wang Guoliang et al. [11] proposed the concept of soil particle volume fractal dimension, providing a detailed and reasonable explanation of the relationship between fractal dimension and soil particle size composition. Fractal dimension can serve as a comprehensive index for evaluating soil conditions, quantitatively describing variations in soil particle size parameters and reflecting soil fertility, structural properties, and degradation degree.

Currently, numerous studies have investigated the effects of plantations on soil particle size composition. Su Min et al. [12] demonstrated that planting *Pinus sylvestris* var. *mongolica* plantations in the Hulunbuir Sandy Land can effectively increase fine particle content in soil. Huang Gang et al. [13] found that the increase in fine particles in *Pinus sylvestris* var. *mongolica* plantation soil in the Horqin Sandy Land originates from the dust interception effect of the pine forest. Applying fractal dimension is a reasonable method for evaluating soil particle size composition characteristics. Reyila Mumin et al. [14] noted that soil fractal dimension is significantly correlated with total nitrogen, organic matter, and available phosphorus, and that fractal dimension can characterize soil fertility status. Wang Xian et al. [15] discovered that fractal dimension characteristics of forest soil in mountainous areas of Chongqing can be used for forest soil quality evaluation.

Kazakhstan is located in the hinterland of the Eurasian continent. Its capital, Nur-Sultan, situated in the desert-steppe zone of north-central Kazakhstan, experiences a typical continental climate with dry, hot summers with little precipitation and cold, long winters with frequent strong winds. This harsh climate creates significant challenges for residents' production, living conditions, and ecological construction, troubling the development of the local living environment. Since 1996, the Kazakh government launched the Green Belt project, and through years of effort, has established 70,000 hectares of artificial forest around the capital, playing an important role in improving the ecological environment. However, research on soil physicochemical properties in the Nur-Sultan region remains limited. Insufficient understanding of soil particle size changes during plantation construction is not conducive to subsequent plantation development and scientific management. Therefore, systematically and comprehensively obtaining soil physicochemical characteristics of this region and clarifying soil particle size features of plantations in Nur-Sultan are of great significance for further studying plantation effects on soil and exploring plantation stability and sustainable development.

This study selected soils from *Pinus sylvestris* plantations of different ages in Nur-Sultan as research objects, analyzed their soil particle size characteristics, and explored the relationship between soil particle size composition, fractal dimension characteristics, and soil physicochemical properties. The results can provide references for land protection and ecological restoration in this region and data support for sustainable plantation utilization.

1. Materials and Methods

1.1 Study Area Overview

The study area is located in the protective forest belt around Nur-Sultan, the capital of Kazakhstan, in the hinterland of the Eurasian continent (50°55'-51°36' N, 71°01' -71°57' E). The region has a temperate continental semi-arid climate, belonging to the sub-boreal zone. Winters are cold and long, summers are dry with little rain, and annual precipitation is 200-300 mm. The area experiences frequent strong winds and snowstorms, earning it the nickname "City of Winds." The plantation species are rich, with main afforestation species including *Pinus sylvestris*, *Betula platyphylla*, *Acer negundo*, etc. Before afforestation, the area was desert steppe, and the local soil is mainly chestnut soil with a hard, compact calcium accumulation layer in the lower soil profile.

1.2 Soil Sample Collection

In July 2019, *Pinus sylvestris* plantations with similar habitat conditions and stand ages of 8, 15, 25, and 40 years were selected in the study area, with bare land in the same location used as a control (Table 1). During sampling, five sample plots were randomly selected within each forest stand, and profiles were excavated. After removing litter from the soil surface, soil samples were collected by depth layers of 0-20 cm, 20-40 cm, and 40-60 cm. Soil samples from the same depth at similar sampling points were mixed and reduced by quartering, then placed in ziplock bags. The latitude, longitude, and topography of each sample plot were recorded.

The collected samples were brought back to the laboratory, air-dried naturally, and debris such as litter, plant roots, and gravel was removed. Part of each sample was passed through a 2 mm sieve for soil particle size composition determination, and another part was passed through a 0.149 mm sieve for determination of soil organic carbon, total nitrogen, total phosphorus, and total potassium content.

1.3 Determination of Soil Particle Size Composition and Physicochemical Indices

Soil particle size composition was analyzed using a Malvern laser particle size analyzer with a measurement range of 0.2-2000 m. Following the international soil particle size classification system, soil was divided into sand (0.02-2 mm), silt (0.002-0.02 mm), and clay (<0.002 mm). The specific measurement method was: weigh 0.5 g of soil sample, add 10 mL of 30% H_2O_2, and digest at constant temperature to remove organic matter; after cooling, add 10 mL of 1 mol $\cdot$ L^{-1} HCl, stir well and boil to remove carbonate impurities from the sample; add

10 mL of 0.5 mol $\cdot$ L^{-1} $(NaPO_3)_6$, stir evenly, and set aside for later measurement. When measuring with the laser particle size analyzer, the sample solution was fully shaken and quickly added to the instrument [16], with each sample measured three times, and the soil particle size corresponding to a cumulative percentage content of 50% was output for subsequent data calculation.

Soil bulk density was determined using the ring knife method; organic carbon (SOC) was measured by the potassium dichromate external heating method; total nitrogen (TN) was determined using a FOSS Kjeltec 8400 automatic nitrogen analyzer; total phosphorus (TP) was measured by acid dissolution molybdenum antimony anti-colorimetry using an Agilent CARY60 UV-Vis spectrophotometer; and total potassium (TK) was determined by atomic absorption using a Thermo Scientific iCE 3500 atomic absorption spectrometer.

1.4 Data Analysis and Processing

Soil volume fractal dimension was calculated using the formula proposed by Wang Guoliang et al. [11]. The calculation formula is as follows:

$$\frac{V(r<R)}{V} = \left(\frac{R}{\lambda_V}\right)^{3-D}$$

where $V(r < R)$ is the cumulative volume of particles with diameter r smaller than R; R is the maximum particle diameter in the soil particle size classification; V is the total volume of soil particles; λ_V is the upper limit value for all particle size fractions; and D is the soil particle volume fractal dimension.

During calculation, logarithms were first taken on both sides of the formula, i.e., $\log(V(r<R)/V) = (3-D)\log(R/\lambda_V)$. Using $\log(V(r<R)/V)$ and $\log(R/\lambda_V)$ as vertical and horizontal coordinates respectively, a double logarithmic curve was plotted. According to the principle of least squares, regression analysis was used to obtain the slope of the straight line, i.e., $3-D$, and then the fractal dimension D value was calculated [11].

Excel software was used for statistical analysis of the data. One-way ANOVA was applied to test significant differences in soil particle size parameters and fractal dimensions among different stand ages. Duncan’ s method was used for multiple comparisons. Pearson correlation analysis was employed to test the correlation between soil fractal dimension and soil physicochemical properties. Origin software was used for graphing.

2. Results

2.1 Soil Particle Size Composition Characteristics of *Pinus sylvestris* Plantations of Different Ages

According to the soil particle size distribution of *Pinus sylvestris* plantations of different ages (Fig. 1), in the 0-20 cm soil layer, the study area soil was mainly composed of silt, followed by sand, with clay being the least. The clay and silt contents of *Pinus sylvestris* plantation soil were significantly higher than those of bare land, while sand content was significantly lower than that of bare land. The clay content was highest (5.49%) in the 15-year-old plantation and lowest (2.26%) in the bare land control. The silt content was highest (62.46%) in the 15-year-old plantation and lowest (35.64%) in the bare land control. The sand content was highest (61.54%) in the bare land control and lowest (35.05%) in the 15-year-old plantation.

In the 20–40 cm soil layer, there were no significant differences in clay, silt, and sand contents among plantations of different ages. In the 40–60 cm soil layer, there were also no significant differences in soil particle contents among plantations of different ages. The effect of planting *Pinus sylvestris* plantations on soil particle size was mainly observed in the surface area.

2.2 Fractal Dimension Characteristics of *Pinus sylvestris* Plantation Soil

The soil fractal dimension in the study area ranged from 2.059 to 2.569, overall at a relatively low level (Table 2). As a parameter reflecting soil structural morphology, soil fractal dimension decreases as soil texture becomes coarser and sand content increases [17]. In the 0–20 cm soil layer, the fractal dimension of bare land soil was significantly lower than that of the four different aged *Pinus sylvestris* plantations, indicating that plantation establishment significantly improved soil structure and particle size distribution. With increasing planting years, the surface soil fractal dimension showed a decreasing trend, with the 15-year-old plantation reaching the maximum value of 2.569. In the 20–40 cm soil layer, there were no significant differences in fractal dimension among plantations of different ages. In the 40–60 cm soil layer, the fractal dimension of *Pinus sylvestris* plantation soil was significantly higher than that of bare land, but differences among different stand ages were not significant.

The fractal dimension of *Pinus sylvestris* plantations of different ages varied differently along the vertical gradient. The bare land control showed no obvious change in fractal dimension values along the vertical gradient. The 8-year-old plantation soil fractal dimension increased with depth, the 15-year-old plantation soil fractal dimension showed no significant difference with depth, while the 25-year and 40-year-old plantation soil fractal dimensions decreased with depth, indicating that plantations of different planting years showed certain patterns in fractal dimension changes along the vertical gradient.

Correlation analysis between soil particle size composition and fractal dimension (Fig. 2) showed that soil clay and silt contents had positive correlations with soil fractal dimension, while soil sand content had a negative correlation with soil fractal dimension, consistent with the research results of Shi Zhanfei et al. [18]. As shown in the figure, the regression equation between soil silt content and fractal dimension had the largest determination coefficient (R^2 =

0.82), indicating that silt content had the greatest influence on soil fractal dimension in the study area. For every 1% increase in soil clay content, fractal dimension increased by 0.036; for every 1% increase in soil silt content, fractal dimension increased by 0.012; and for every 1% increase in soil sand content, fractal dimension decreased by 0.011. This demonstrates that the increase of soil particles <20 m and the decrease of particles >20 m jointly contribute to the increase in soil fractal dimension. The 20 m particle size is the critical particle size reflecting the fractal dimension of plantation soil in the study area.

2.3 Relationship Between Soil Fractal Dimension and Soil Physicochemical Properties

To further analyze the relationship between fractal dimension and soil physicochemical properties of *Pinus sylvestris* plantations, correlation analysis was conducted between fractal dimension and soil organic matter content, total nitrogen content, total phosphorus content, total potassium content, and soil bulk density (Table 3). The results showed that soil fractal dimension was extremely significantly positively correlated with soil organic matter and total nitrogen content ($P < 0.01$), and extremely significantly negatively correlated with soil bulk density, indicating that fractal dimension can characterize some physicochemical properties of plantation soil in the study area. Specifically, the larger the fractal dimension, the higher the soil organic matter and total nitrogen contents, and the lower the bulk density. No significant correlations were found between soil fractal dimension and total phosphorus or total potassium contents.

3. Discussion

The surface soil of the ecological barrier *Pinus sylvestris* plantations in Nur-Sultan had significantly higher clay and silt contents than bare sandy land, which is due to the deposition effect of shelter forests [19]. Nur-Sultan experiences strong winds year-round; clay and silt particles, due to their small size and low threshold velocity, are more susceptible to wind transport. As stand age increases, herbaceous plants gradually begin to grow under the plantation canopy, plant diversity increases, and the ecosystem becomes more stable, which can influence soil particle size composition to some extent [20]. *Pinus sylvestris* forest belts have low porosity, and the tree canopy can effectively reduce wind speed and inhibit wind erosion [21]. Additionally, vegetation reduces raindrop impact on the surface through interception by branches and leaves, thereby decreasing the loss of fine soil particles. Forests exchange materials with soil through litterfall and change soil properties. Surface litter can increase surface roughness, raise the threshold wind speed for soil particle movement, and effectively increase soil organic matter content, promote the formation of soil aggregates, improve soil structure, and enhance soil ecosystem stability, thereby inhibiting wind-sand erosion. The surface sand fraction content of bare sandy land was significantly higher than that of forest land surface, while there was no significant difference in sand fraction content between middle and deep layers, be-cause the *Pinus sylvestris* plantation canopy can effectively intercept wind-sand movement, causing fine particles to settle and accumulate when encountering obstacles, resulting in higher fine particle content in surface soil than in lower layers [22].

In the 20-40 cm and 40-60 cm soil layers, there were no significant differences in soil particle size composition among plantations of different ages, indicating that planting *Pinus sylvestris* had no obvious effect on deep soil particle size composition. However, some scholars believe that *Pinus sylvestris* roots can increase soil nutrients and improve soil structure, thereby affecting particle size composition [23]. Due to wind-sand interception by the tree canopy and soil improvement by plant litter, the soil amelioration by *Pinus sylvestris* is top-down, and the refinement process of lower soil layers has certain hysteresis [24].

Previous studies have shown that soil fractal dimension can effectively reflect soil fertility characteristics [25]. In the study area, soil fractal dimension was extremely significantly positively correlated with soil organic matter and total nitrogen content. Planting plantations can effectively increase soil fractal dimension and improve local soil structure and fertility. Meanwhile, regression analysis showed that fractal dimension was positively correlated with soil clay and silt contents; the higher the fine particle content, the larger the fractal dimension and the higher the soil nutrient content. Soils with more fine particles have stronger adsorption and fixation capacity for nutrients and contain more nutrients [26]. Different soil particle size fractions have different nutrient adsorption capacities; fine particles have larger specific surface area and stronger adsorption capacity, making it easier to absorb and fix soil nutrients, resulting in larger fractal dimension [27]. The increase in fine particles in surface soil is caused by the combined effect of fine particle deposition and surface accumulation of soil nutrients [28]. As plantations are established and develop, tree litter returns nutrients to the soil, surface soil organic matter and nutrient content gradually increase, and soil fractal dimension also increases. Therefore, soil fractal dimension can be used to evaluate soil nutrient status.

4. Conclusion

This study analyzed the soil particle size composition of *Pinus sylvestris* plantations of different ages in Nur-Sultan and reached the following conclusions:

1. The surface soil of *Pinus sylvestris* plantations in the ecological barrier of Nur-Sultan was dominated by silt, followed by sand, with clay being the least. The clay and silt contents in plantation surface soil were significantly higher than those in bare sandy land. Deep soil (20-40 cm and 40-60 cm) was mainly dominated by sand, and there were no significant differences in deep soil particle content among plantations of different ages. The effect of planting *Pinus sylvestris* plantations on soil particle size was mainly observed in the surface layer.

2. The soil fractal dimension in the study area ranged from 2.059 to 2.569,

overall at a relatively low level. The fractal dimension of *Pinus sylvestris* plantation soil was significantly higher than that of bare land, indicating that plantation establishment improved soil particle size composition. Plantation establishment promoted surface soil refinement and significantly increased soil fractal dimension. The soil fractal dimension of *Pinus sylvestris* plantations showed a trend of first increasing and then decreasing with planting years; the fractal dimension of 40-year-old plantations was lower than that of 15-year-old plantations, possibly due to the single species composition of *Pinus sylvestris* plantations and excessive soil nutrient consumption from long-term planting, leading to soil degradation after a certain period. The fractal dimension of 15-year-old plantation soil in the study area showed a decreasing trend with increasing depth, as the vertical movement of fine soil particles occurs mainly through leaching by precipitation, slowly moving downward through large soil pores [29]. Plant root growth and development can also cause changes in soil particles along the vertical gradient, but the effect of plant roots on soil is mainly manifested in the surface layer.

3. Soil fractal dimension was positively correlated with clay and silt contents, and the 20 m particle size was the critical particle size reflecting the fractal dimension of plantation soil in the study area.

4. Soil fractal dimension was extremely significantly positively correlated with soil organic matter and total nitrogen content, and soil fractal dimension can be used to evaluate soil nutrient status. When planting *Pinus sylvestris* plantations in Nur-Sultan, attention should be paid to regulating the restoration period, and mixed planting with other species should be considered to increase community species diversity and prevent soil degradation.

References

[1] Liu Simian. Study on the effect of disturbance intensity on environmental characteristics of Chinese fir plantation in Huitong[D]. Changsha: Hunan University, 2016.

[2] Wang D, Fu B J, Zhao W W, et al. Multifractal characteristics of soil particle size distribution under different land use types on the Loess Plateau, China[J]. Catena, 2007, 72(1): 29-36.

[3] Hu Y F, Liu J Y, Zhuang D F, et al. Fractal dimension of soil particle size distribution under different land use/land coverage[J]. Acta Pedologica Sinica, 2005, 42(2): 336-339.

[4] Gui Dongwei, Lei Jiaqiang, Zeng Fanjiang, et al. Analysis on soil PSD and its affecting factors at different depths in oasis farmland: A case study in the Qira Oasis[J]. Arid Zone Research, 2011, 28(4): 622-629.

[5] Wang De, Fu Bojie, Chen Liding, et al. Fractal analysis of soil particle size

distribution under different land use types: A case study in the loess hilly areas of the Loess Plateau, China[J]. Acta Ecologica Sinica, 2007, 27(7): 3081-3089.

[6] Huang G, Zhang R. Evaluation of soil water retention curve with the pore solid fractal model[J]. Geoderma, 2005, 127(1-2): 52-61.

[7] Montero E. Rényi dimensions analysis of soil particle size distributions[J]. Ecological Modelling, 2005, 182(3-4): 305-315.

[8] Yuan Jie, Zeng Guangchao, E Chongyi, et al. Grain size distributions of the surface soil deposit around Qinghai Lake and its implications[J]. Research of Soil and Water Conservation, 2015, 22(3): 150-154.

[9] Sun Mei, Sun Nan, Huang Yunxiang, et al. Multifractal characterization of soil particle size distribution under long-term different fertilizations in upland red soil[J]. Scientia Agricultura Sinica, 2014, 47(11): 2173-2181.

[10] Bao Shidan. Study of analysis of soil and agrochemistry[M]. 3rd ed. Beijing: China Agriculture Press, 2008.

[11] Wang Guoliang, Zhou Shenglu, Zhao Qiguo. Volume fractal dimension of soil particles and its applications to land use[J]. Acta Pedologica Sinica, 2005, 42(4): 545-550.

[12] Su Min, Ding Guodong, Gao Guanglei, et al. Multi-fractal analysis of soil particle size distribution of *Pinus sylvestris* var. *mongolica* plantations in Hulunbeier Sandy Land[J]. Journal of Arid Land Resources and Environment, 2018, 32(11): 129-135.

[13] Huang Gang, Zhao Xueyong, Su Yangui, et al. Assessment on the effects of *Pinus sylvestris* var. *mongolica* plantation on microenvironment improvement in the Horqin Sandy Land[J]. Arid Zone Research, 2008, 25(2): 212-218.

[14] Reyila Mumin, Halik Umut, Aishan Tayierjiang, et al. Influence of different aged *Populus alba* on soil physicochemical properties based on fractal dimension[J]. Chinese Journal of Soil Science, 2018, 49(2): 313-319.

[15] Wang Xian, Zhang Hongjiang, Cheng Jinhua, et al. Fractal characteristics and related affecting factors of particle size distribution of different forest soil in Simian Mountains, Chongqing[J]. Journal of Soil and Water Conservation, 2011, 25(3): 154-159.

[16] Jia Mengmeng, Zhang Zhongliang, Lei Jiaqiang, et al. Fractal characteristics of soil particle size distribution in protection forest of Tarim Desert Highway[J]. Arid Zone Research, 2015, 32(4): 674-679.

[17] Shi Zhanfei, Wang Li, Wang Jianguo. Volume fractal characteristics and significance of soil particles in the Shenmu Colliery in north Shaanxi Province[J]. Arid Zone Research, 2011, 28(3): 394-400.

[18] Chen Yuxuan, Zhang Feiyue, Gao Guanglei, et al. Soil particle size distribution of *Pinus sylvestris* var. *mongolica* plantations in the Horqin Sandy Land[J].

Arid Land Geography, 2020, 43(4): 1051-1058.

[19] Jia Xiaohong, Li Xinrong, Li Yuanshou. Fractal dimension of soil particle size distribution during the process of vegetation restoration in arid sand dune area[J]. Geographical Research, 2007, 26(3): 518-525.

[20] Liu Yundong, Gao Guanglei, Ding Guodong, et al. Soil quality in wind erosion desertified regions: A review[J]. Journal of Nanjing Forestry University (Natural Science Edition), 2017, 41(5): 161-168.

[21] Hupy J P. Influence of vegetation cover and crust type on wind blown sediment in a semi-arid climate[J]. Journal of Arid Environments, 2004, 58(2): 167-179.

[22] Yu K Y, Yao X, Deng Y b, et al. Effects of stand age on soil respiration in *Pinus massoniana* plantations in the hilly red soil region of southern China[J]. Catena, 2019, 178(5): 313-321.

[23] Cao Chengyou, Jiang Deming, Quan Guijing, et al. Soil physical and chemical characters changes of *Caragana microphylla* plantation for sand fixation in Keerqin Sandy Land[J]. Journal of Soil and Water Conservation, 2004, 18(6): 108-111, 131.

[24] Liu Jinfu, Hong Wei, Wu Chengzhen. Fractal features of soil clusters under some precious hardwood stands in the central subtropical region, China[J]. Acta Ecologica Sinica, 2002, 22(2): 197-205.

[25] Li Yi, Li Min, Cao Wei, et al. Spatial variability of fractal dimension for soil particle size distribution and particle volume percentage in farmlands[J]. Transactions of the Chinese Society of Agricultural Engineering, 2010, 26(1): 94-102.

[26] Xiao Dongdong, Shi Zhengtao, Liu Xinyou, et al. Fractal dimension of soil particle volume in rubber forest of Xishuangbanna[J]. Chinese Journal of Tropical Crops, 2017, 38(5): 817-823.

[27] Lei Zeyong, Yu Dongwei, Zhou Fengyan, et al. Effects of *Pinus sylvestris* var. *mongolica* afforestation on change of soil particle size distribution in sandy land[J]. Acta Ecologica Sinica, 2020, 40(15): 5367-5376.

[28] Chen X, Zhou J. Volume-based soil particle fractal relation with soil erodibility in a small watershed of purple soil[J]. Environmental Earth Sciences, 2013, 70(4): 1735-1746.

[29] Tyler S W, Wheatcraft S W. Application of fractal mathematics to soil water retention estimation[J]. Soil Science Society of America Journal, 1989, 53(4): 987-996.

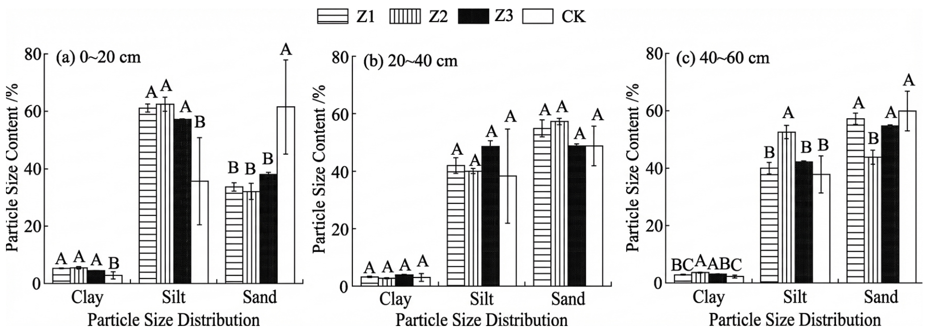

Figure 1: Figure 1

Figures

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