Spatial Heterogeneity of Soil Physicochemical Properties in Degraded Grasslands and Its Effects on Soil Moisture: Postprint

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Abstract

This study measured and analyzed the soil physicochemical properties (mass water content, bulk density, saturated water content, electrical conductivity, pH, and organic matter) of the 0–120 cm soil layer in a degraded grassland ecosystem at Elitu Pasture, Zhengxiangbai Banner, Xilingol League, and investigated their spatial heterogeneity and the influence of various physicochemical properties on soil moisture using classical statistical and geostatistical methods. The results showed that the degraded grassland soil was weakly alkaline; electrical conductivity, bulk density, and pH increased with soil depth, whereas saturated water content and organic matter content decreased with depth, thus demonstrating opposite trends for soil pH and organic matter content with increasing depth. Except for bulk density and pH, which exhibited weak variation, all other soil property indicators showed moderate variation. Except for the 80–120 cm soil layer, the coefficient of variation for soil water content in other layers decreased with increasing soil water content. Soil water content, organic matter, and pH in each soil layer of the study area exhibited strong spatial correlation; bulk density had the smallest degree of variation caused by random factors; saturated water content was subject to spatial variation caused by both structural and random factors; the factors influencing soil physicochemical properties in this study area were relatively complex. The range of spatial correlation for saturated water content in each soil layer was generally large, at 13.94–52.77 km, indicating good spatial continuity over longer distances. The pH in the 0–10 cm soil layer had the largest range, while organic matter had the smallest, whereas the opposite was true for the 80–120 cm soil layer. Mass water content in both the 0–10 cm and 80–120 cm soil layers showed significant positive correlation with saturated water content. Soil water content in the 10–20 cm and 80–120 cm layers was relatively high, indicating strong water-holding capacity. In the middle soil layer (20–80 cm), soil water content showed significant correlation with organic matter and pH.

Full Text

Preamble

Spatial Heterogeneity of Soil Physical and Chemical Properties and Their Effects on Soil Moisture in Degraded Grassland

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Abstract: The effects of spatial heterogeneity and physical and chemical properties on soil moisture were examined by measuring and analyzing physical and chemical properties, including mass water content, bulk density, saturated water content, electrical conductivity, pH, and organic matter content, of a 0–120 cm soil layer of the degraded grassland ecosystem in Zhenglan Banner, Xilin Gol League, using classical statistics and geostatistical methods. The results showed that the soil in the degraded grassland of Zhenglan Banner is weakly alkaline. The electrical conductivity, bulk density, and pH values increased with the deepening of the soil layer, while the saturated water content and organic matter content decreased with the deepening of the soil layer. The content of organic matter was inversely regular with the deepening of the soil layer. Except for the bulk density and pH value, the other soil characteristics were moderately variable. Except for the 80–120 cm soil layer, the coefficient of variation of the soil water content of the other soil layers increased with the soil water content. The soil water content, organic matter, and pH of each soil layer in this study area showed a strong spatial correlation, the bulk density caused the least degree of variation caused by random factors, and the saturated moisture content was caused by both structural and random factors. The factors affecting the physical and chemical properties of the soil in this study area were more complex: the soil water content of each soil layer was generally larger, ranging from 13.94–52.77 km, the spatial continuity was better at longer distances, and the pH range of the 0–10 cm soil layer was the largest, with the smallest organic matter range, and the opposite of the 80–120 cm soil layer. The soil mass water content of the 0–10 cm and 80–120 cm soil layers was positively correlated with the saturated moisture content of the 10–20 cm and 80–120 cm soil layers. Soil moisture was relatively large, with strong water retention in the soil, at the intermediate soil layer of 20–80 cm, the soil water content and organic matter

and pH were significantly correlated.

Keywords: degraded grassland; soil physical and chemical properties; geostatistics; spatial heterogeneity; soil moisture; Inner Mongolia

1 Introduction

1.1 Study Area

The study area is located in Zhenglan Banner, Xilin Gol League, Inner Mongolia Autonomous Region, with geographical coordinates of 114°05 -115°37 E, 42°05 -43°02 N. The region has a temperate continental monsoon climate, with an average annual temperature of 1.9°C, average annual precipitation of 314 mm, and average annual evaporation of 2126 mm. The frost-free period lasts approximately 106 days. The study area is situated in typical steppe grassland, which is one of the key areas for grassland degradation in China.

1.2 Sample Collection and Measurement

In June 2018, soil samples were collected from 9 plots (6 m × 6 m each) established in the study area. Using GPS positioning, soil samples were taken at 5 cm intervals from 0–120 cm depth (at depths of 0–10, 10–20, 20–40, 40–80, and 80–120 cm), with 3 replicates per layer. A 100 cm^3 ring knife was used to collect undisturbed soil samples for determining saturated water content and bulk density. Soil water content was measured by oven drying at 105°C. Soil pH was measured using a pH meter (soil:water ratio of 1:2.5), electrical conductivity using a conductivity meter (soil:water ratio of 1:5), and organic matter content using the potassium dichromate volumetric method.

1.3 Data Processing

Descriptive statistical analysis was performed using SPSS 25.0 and Excel 2013. The coefficient of variation (Cv) was classified as: Cv < 0.1 for weak variability, 0.1 < Cv < 1.0 for moderate variability, and Cv > 1.0 for strong variability. Normality of data distribution was tested using the Shapiro-Wilk test. Geostatistical analysis was conducted using GS^{+}9.0 software.

The semi-variance function was calculated as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

where h is the lag distance, $\gamma(h)$ is the semi-variance, $N(h)$ is the number of sample pairs at lag distance h, and $Z(x_i)$ and $Z(x_i + h)$ are measured values at spatial positions x_i and $x_i + h$.

The semi-variance function model includes four parameters: nugget (C_0), sill ($C_0 + C$), range (A_0), and nugget-to-sill ratio ($C_0/(C_0 + C)$). The spatial correlation is classified as: $C_0/(C_0 + C) \geq 75\%$ for weak spatial correlation, $25\% < C_0/(C_0 + C) < 75\%$ for moderate spatial correlation, and $C_0/(C_0 + C) \leq 25\%$ for strong spatial correlation.

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2 Results and Analysis

2.1 Descriptive Statistics of Soil Physical and Chemical Properties

The descriptive statistical analysis results for soil physical and chemical properties are shown in Table 1. Soil water content ranged from 10.94% to 27.79%, with a coefficient of variation of 0.16–0.32, indicating moderate variability. The average water content was highest in the 0–10 cm layer (27.79%) and lowest in the 80–120 cm layer (10.94%). Bulk density ranged from 1.17 to 1.57 $g \cdot cm^{-3}$, with a coefficient of variation of 0.06–0.09, showing weak variability. Saturated water content ranged from 38.13% to 24.37%, with a coefficient of variation of 0.11–0.27, indicating moderate variability. Electrical conductivity ranged from 165.94 to 233.07 $S \cdot cm^{-1}$, with a coefficient of variation of 0.19–0.44, showing moderate variability. Organic matter content ranged from 12.13 to 2.51 $g \cdot kg^{-1}$, with a coefficient of variation of 0.14–0.44, indicating moderate variability. pH values ranged from 7.74 to 8.73, showing weak variability.

**** Descriptive statistics of soil physical and chemical properties in each soil layer

2.2 Semi-Variance Function Analysis of Soil Physical and Chemical Properties

The semi-variance function analysis results (Table 2) show that the nugget-to-sill ratio for soil water content ranged from 13.53% to 22.52% across different layers, indicating strong spatial correlation. The range varied from 10.24 to 61.00 km, with the 0–10 cm layer showing the largest range (61.00 km). Bulk density exhibited strong spatial correlation in all layers, with a range of 13.83–13.94 km. Saturated water content showed moderate to strong spatial correlation, with ranges of 49.44–53.52 km. Electrical conductivity displayed moderate spatial correlation in the 0–10 cm layer (52.77% nugget-to-sill ratio) and strong correlation in deeper layers. Organic matter showed strong spatial correlation in the 0–10 cm layer (25.30% nugget-to-sill ratio) and moderate correlation in deeper layers. pH exhibited weak spatial correlation in the 0–10 cm layer (73.28% nugget-to-sill ratio) and moderate correlation in deeper layers.

**** Theoretical model of semi-variance function of soil water physical and chemical properties and related statistical parameters

The spatial distribution patterns of soil physical and chemical properties (Figure 1) show that soil water content, saturated water content, and organic matter content decreased with soil depth, while bulk density and electrical conductivity increased with depth. The pH values showed minimal variation with depth.

[**Figure 1: see original paper**] Vertical distribution of soil physical and chemical properties at all sampling points in 0-120 cm soil layer

2.3 Correlation Analysis Between Soil Water Content and Physical and Chemical Properties

Correlation analysis results (Table 3) indicate that in the 0–10 cm layer, soil water content was significantly positively correlated with saturated water content ($r = 0.397$, $p < 0.05$) and significantly negatively correlated with bulk density ($r = -0.478$, $p < 0.05$). In the 40–80 cm layer, soil water content showed a highly significant positive correlation with saturated water content ($r = 0.631$, $p < 0.01$). In the 80–120 cm layer, soil water content was significantly positively correlated with saturated water content ($r = 0.416$, $p < 0.05$) and significantly negatively correlated with organic matter content ($r = -0.312$, $p < 0.05$). In the 20–40 cm layer, soil water content was significantly negatively correlated with organic matter content ($r = -0.629$, $p < 0.01$).

**** Pearson correlation coefficient between soil water content and soil physical and chemical properties

The relationship between soil physical and chemical properties and soil water content (Figure 2) demonstrates that saturated water content and bulk density are the main factors affecting soil water content. Soil water content increases with increasing saturated water content and decreases with increasing bulk density.

[**Figure 2: see original paper**] Relationship between soil physical and chemical properties and soil water content in 0-120 cm soil layers

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3 Discussion

The spatial heterogeneity of soil properties in degraded grassland is influenced by both structural factors (topography, soil parent material, climate) and random factors (human activities, grazing). The strong spatial correlation of soil water content, organic matter, and pH indicates that these properties are primarily controlled by structural factors. The moderate spatial correlation of saturated water content suggests it is influenced by both structural and random factors.

The range of spatial autocorrelation for soil water content (13.94–52.77 km) indicates that soil moisture has good spatial continuity at the landscape scale. The larger range in the surface layer (0–10 cm) may be due to the influence of surface vegetation and microtopography, while the smaller range in deeper layers reflects the influence of soil texture and root distribution.

The significant positive correlation between soil water content and saturated water content confirms that soil water retention capacity is a key factor controlling soil moisture. The negative correlation between soil water content and bulk density indicates that compacted soils have reduced water infiltration and storage capacity. The complex relationships between soil moisture and organic matter/pH reflect the integrated effects of soil formation processes and degradation status.

The intermediate soil layer (20–80 cm) showed relatively high water content and strong water retention capacity, suggesting that this layer plays an important role in plant water supply. The significant correlations between soil moisture, organic matter, and pH in this layer indicate that soil degradation has altered the vertical distribution of soil properties.

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4 Conclusions

(1) The soil in the degraded grassland of Zhenglan Banner is weakly alkaline, with electrical conductivity, bulk density, and pH increasing with soil depth, while saturated water content and organic matter content decrease with depth.

(2) Except for bulk density and pH, other soil properties show moderate variability. Soil water content, organic matter, and pH exhibit strong spatial correlation, while saturated water content shows moderate spatial correlation.

(3) Soil water content has a range of 13.94–52.77 km, with the 0–10 cm layer showing the largest range (61.00 km). The spatial continuity of soil moisture is better at longer distances.

(4) Soil water content is significantly positively correlated with saturated water content and negatively correlated with bulk density. In the intermediate layer (20–80 cm), soil water content shows significant correlations with organic matter and pH.

These findings provide a scientific basis for understanding water movement and nutrient cycling in degraded grassland ecosystems and can guide restoration efforts in the Xilin Gol region.

References

[1] Xu Zhu. Forward the 21st Century' s Chinese grassland resources [J]. Grassland of China, 1998(5): 1-8.

[2] White R, Rohweder M, Murray S. Grassland Ecosystems[M]. Pilot Analysis of Global Ecosystems, 2000.

[3] Shen Haihua, Zhu Yankun, Zhao Xia, et al. Analysis of the current situation of grassland resources in China[J]. Science Bulletin, 2016, 61(2): 139-154.

[4] Ministry of Environmental Protection of the People’ s Republic of China. 2012 China Environmental Status Bulletin[R]. 2013.

[5] State Council Bulletin. Several opinions of the State Council on strengthening grassland protection and construction[EB/OL]. http://www.gov.cn/gongbao/content/2002/content_{61781 2002/2017-03-07.

[6] Liu Yaling, Xing Qi, Wang Ruizhen, et al. Discussion on Xilin Gol grassland ecological restoration technology system[J]. Grassland and Prataculture, 2018, 30(4): 13-19.

[7] Brocca L. Spatial-temporal variability of soil moisture and its estimation across scales[J]. Water Resources Research, 2010, 46(2): W02516.

[8] Jeu RAM D, Wagner W, Holmes TRH, et al. Global soil moisture patterns observed by spaceborne microwave radiometers and scatterometers[J]. Surveys in Geophysics, 2008, 29(4-5): 399-420.

[9] Lakhankar T, Jones AS, Combs CL, et al. Analysis of large-scale spatial variability of soil moisture using a geostatistical method[J]. Sensors, 2010, 10(1): 913-932.

[10] Abbott MB, Refsgaard JC. Distributed Hydrological Modelling[M]. Distributed Hydrological Modelling, 1996.

[11] Entin JK, Robock A, Vinnikov KY, et al. Temporal and spatial scales of observed soil moisture variations in the extratropics[J]. Journal of Geophysical Research, 2000, 105(D9): 11865.

[12] Wang Lixia, Chen Lixin, Du Shan, et al. Effects of gap size on spatial heterogeneity of soil moisture in mixed Pinus koraiensis and broad-leaved forest[J]. Chinese Journal of Applied Ecology, 2013, 24(1): 17-24.

[13] Li Yuanshou, Wang Genxu, Ding Yongjian, et al. Spatial heterogeneity of soil moisture in alpine meadow area of the Qinghai-Tibet Plateau[J]. Advances in Water Science, 2008, 19(1): 61-67.

[14] Zhang Chuan, Chen Hongsong, Zhang Wei, et al. Spatial variability of surface soil water content, bulk density and saturated hydraulic conductivity on karst slope[J]. Chinese Journal of Applied Ecology, 2014, 25(6): 1585-1591.

[15] Schneider K, Huisman JA, Breuer L, et al. Temporal stability of soil moisture in various semi-arid steppe ecosystems and its application in remote sensing[J]. Journal of Hydrology (Amsterdam), 2008, 359(1-2): 16-29.

[16] Ma Mei, Zhang Shengwei, Wei Baocheng. Variation characteristics and driving factors of grassland degradation in the Xilinguole grassland in the past 30 years[J]. Chinese Journal of Grassland, 2017, 39(4): 86-93.

[17] Ma Lingyun, Xu Xiaocheng, Cheng Yi, et al. Desertification control measures and their effects in Zhengzhongbai Banner[J]. Inner Mongolia Agricultural Science and Technology, 2007(7): 85-88.

[18] Yao Yuefeng, He Chengxin, Zeng Danjuan, et al. Spatial heterogeneity of surface soil water physical properties in Lijiang River Basin[J]. Advances in Water Science, 2016, 27(5): 696-704.

[19] Zhang Chuan, Chen Hongsong, Zhang Wei, et al. Spatial variability of surface soil water content, bulk density and saturated hydraulic conductivity on karst slope[J]. Chinese Journal of Applied Ecology, 2014, 25(6): 1585-1591.

[20] Zhao Yanan, Zhou Yurong, Wang Hongmei. Spatial heterogeneity of soil moisture under the introduction of desert grassland shrubs in eastern Ningxia[J]. Chinese Journal of Applied Ecology, 2018, 29(11): 78-87.

[21] Pei Yanwu, Huang Laiming, Jia Xiaoxu, et al. Soil moisture availability and influencing factors of two typical shrublands on the Loess Plateau[J]. Acta Pedologica Sinica, 2019, 56(3): 627-637.

[22] Liu Xiaodong, Qiao Yuna, Zhou Guoyi. Controlling action of soil organic matter on soil moisture retention and its availability[J]. Chinese Journal of Plant Ecology, 2011, 35(12): 1209-1218.

[23] Wu Junhu, Zhang Tiegang, Zhao Wei, et al. Effect of bulk density on soil moisture infiltration characteristics of different organic matter contents[J]. Journal of Soil and Water Conservation, 2013, 27(3): 63-67.

[24] Su Wei, Nie Yimin, Hu Xiaojie, et al. Using kriging interpolation to study spatial variability of farmland soil nutrients in Beima Town, Longkou, Shandong[J]. Journal of Anhui Agricultural University, 2004(1): 76-81.

[25] Wang Yunguo, Huang Laiming, Jia Xiaoxu, et al. Spatial heterogeneity of soil moisture in Xilinguole grassland and Hulunbuier grassland as research areas[J]. Journal of Dalian Nationalities University, 2015, 17(1): 1-5.

[26] Li Meng, Liu Yang, Duan Wenbiao. Heterogeneity of shallow soil temperature in gaps of Pinus koraiensis and broad-leaved mixed forest[J]. Chinese Journal of Ecology, 2013, 32(2): 319-324.

[27] Owe M, Jones EB, Schmugge TJ. Soil moisture variation patterns observed in Hand County, South Dakota[J]. Journal of the American Water Resources Association, 1982, 18(6): 949-954.

[28] Wu Mousong, Huang Jiesheng, Tan Xiao, et al. Freezing test and simulation of unsaturated sandy loam under different groundwater recharge conditions[J]. Advances in Water Science, 2014, 25(1): 60-68.

[29] Chai Hua, He Nianpeng. Characteristics of soil bulk density in China and its significance for regional carbon storage estimation[J]. Acta Ecologica Sinica, 2016, 36(13): 3903-3910.

[30] Wan Dan, Liang Bo, Nie Xiaogang, et al. Soil physical properties of Sejila Mountain in Tibet, vertical zonation[J]. Acta Ecologica Sinica, 2018, 38(3): 1065-1074.

[31] Guo Xudong, Fu Bojie, Ma Keming, et al. Study on the spatial variability of soil nutrients based on GIS and geostatistics: Taking Zunhua City, Hebei Province as an example[J]. Chinese Journal of Applied Ecology, 2000, 1(4): 557-563.

[32] Xu Shuqin, Lang Yabin, Meng Shuyu. Anomalous climatic characteristics in the winter of 2009 in Zhengzhongbaiqi area[J]. Modern Agricultural Science and Technology, 2011(17): 15-16.

[33] Xue Shuqin, Lang Yabin, Meng Shuyu. Anomalous climatic characteristics in the winter of 2009 in Zhengzhongbaiqi area[J]. Modern Agricultural Science and Technology, 2011(17): 15-16.

[34] Li Meng, Liu Yang, Duan Wenbiao. Heterogeneity of shallow soil temperature in gaps of Pinus koraiensis and broad-leaved mixed forest[J]. Chinese Journal of Ecology, 2013, 32(2): 319-324.

[35] Scharrenbroc BC, Bockheim JG. Impacts of forest gaps on soil properties and processes in old growth northern hardwood-hemlock forests[J]. Plant and Soil, 2007, 294(1-2): 219-233.

[36] Liu Shaochong, Duan Wenbiao. Spatial heterogeneity of soil nutrients in the gap of Pinus koraiensis and broad-leaved mixed forest[J]. Journal of Soil and Water Conservation, 2011, 25(3): 142-146.

[37] Chen Sanxiong, Shen Yi. Soil infiltration characteristics and simulation analysis of main vegetation types in the source area of the Huangpu River[J]. Research of Soil and Water Conservation, 2016, 23(6): 59-63.

[38] Yang Y, Dou Y, Liu D, et al. Spatial pattern and heterogeneity of soil moisture along a transect in a small catchment on the Loess Plateau[J]. Journal of Hydrology, 2017, 550: 466-477.

[39] Zhang Shuyuan, Qin Shengjin, Zong Guo, et al. Spatial heterogeneity of the main chemical properties of soils in secondary forests in the eastern mountainous region of Liaoning[J]. Chinese Journal of Ecology, 2018, 37(7): 2076-2082.

[40] Dai Wanhong, Huang Yao, Wu Li, et al. Relationship between zonal soil organic matter content and pH in China[J]. Acta Pedologica Sinica, 2009, 46(5): 851-860.

[41] Gao Haifeng, Bai Junhong, Wang Qinggai, et al. Distribution characteristics of soil pH and soil water content of wetlands in typical floodplains in the lower Huolin River[J]. Research of Soil and Water Conservation, 2011, 18(1): 268-271.

[42] Li J, Zhao CY, Zhu H, et al. Multi-scale heterogeneity of soil moisture following snow thawing in Haloxylon ammodendron shrubland[J]. Science in China Series D: Earth Sciences, 2007, 50(Suppl. 1): 49-55.

[43] Li Congjuan, Lei Jiaqiang, Xu Xinwen, et al. Spatial distribution of soil moisture and chemical properties in the Gurbantunggut Desert[J]. Acta Ecologica Sinica, 2014, 34(15): 4380-4389.

[44] Li Xiangfu, Liu Muxing, Yi Jun, et al. Hydrological function and its influencing factors of soil layers in different vertical belts of the Three Gorges mountainous region[J]. Resources and Environment in the Yangtze River Basin, 2018, 27(8): 158-167.

[45] Li Xiaofu, Liu Muxing, Yi Jun, et al. Hydrological function and its influencing factors of soil layers in different vertical belts of the Three Gorges mountainous region[J]. Resources and Environment in the Yangtze River Basin, 2018, 27(8): 158-167.

[46] Yang Siwei, Zhang Degang, Niu Yujie, et al. Effects of short-term grazing on surface soil infiltration and water retention capacity of alpine meadows[J]. Journal of Soil and Water Conservation, 2016, 30(4): 96-101.

Note: Figure translations are in progress. See original paper for figures.