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Climate Factors Dominate the Spatial Distribution of Soil Nutrients in Desert Grassland

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Abstract: Soil nutrient distribution in desert grasslands is predominantly influenced by climatic factors, particularly precipitation and temperature. Siziwang Banner, situated within the desert grassland belt of Inner Mongolia, represents a typical arid zone where soil nutrient dynamics are shaped by the interplay of precipitation, temperature, and topography. This study aims to investigate the spatial distribution of soil nutrients and assess the dominant role of climatic factors in this region, using geostatistical analyses and GIS techniques. The results reveal that soil nutrients exhibit higher concentrations in surface layers, gradually decreasing with depth. Horizontally, a pronounced gradient can be observed, with nutrient levels being higher in the southern regions and lower in the northern regions. Precipitation and temperature emerge as decisive factors driving these patterns; increased precipitation enhances the accumulation of soil organic matter and nitrogen, whereas elevated temperatures accelerate decomposition of organic matter, leading to nutrient losses. These findings underscore the critical role of climatic factors in governing soil nutrient distribution, offering valuable insights for soil management and ecological restoration efforts in arid ecosystems.

Keywords: soil nutrient spatial distribution; desert grassland; climatic factors; geostatistical analysis; ecosystem restoration; nutrient cycling

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1. Introduction

Desert grasslands lie in the transitional zone between grassland and desert ecosystems, representing one of the world's vital ecosystem types. These regions are characterized by fragile ecological environments, nutrient-poor soils, low vegetation cover, and high sensitivity to climate change and human activities [1]. Siziwang Banner, situated in the desert grassland belt of Inner Mongolia, serves as a core area for the Beijing–Tianjin Sand Source Control Project and a pilot demonstration zone for the grassland grazing ban compensation policy. The ecological protection of Siziwang Banner holds significant implications for the ecological security of both the region and the nation [2]. Located in the temperate arid zone, Siziwang Banner's ecosystem is particularly vulnerable to the combined impacts of climate change and anthropogenic activities. In recent years, under the dual pressures of these factors, the region has experienced grassland desertification, degradation, and salinization, severely undermining ecological stability, soil health, and carbon cycling processes [3,4]. Therefore, a detailed investigation into the spatial distribution characteristics of soil nutrients and their influencing factors is essential. Such research not only provides a scientific basis for regional ecological management but also offers valuable insights for soil conservation and ecological restoration efforts in global arid zones. Climate change significantly affects soil physicochemical properties. Rising temperatures accelerate the decomposition of soil organic matter, resulting in reduced soil carbon storage. Conversely, decreasing precipitation exacerbates loss of water and nutrients [5,6]. Soil microbial communities, which are highly sensitive to climatic variations, play a critical role in regulating biogeochemical cycles, particularly for key elements like carbon and nitrogen [7]. Variations in precipitation and temperature influence soil nutrient availability and stability by modulating microbial activity and associated nutrient-cycling processes [8]. Increased precipitation enhances microbial activity, which accelerates the decomposition of organic matter and increases the availability of essential soil nutrients, such as nitrogen (N) and phosphorus (P). This process facilitates nutrient cycling and supports plant growth. Conversely, under drought conditions, plants adapt to water scarcity by accumulating higher concentrations of nutrients, including N and P, to sustain physiological processes. This adaptive mechanism highlights the complex interactions between soil, vegetation, and climatic conditions [9]. The interplay between climatic factors and soil physical properties significantly affects nutrient retention capacity across different soil types. For example, clay soils, with their larger specific surface area and higher adsorption capacity, immobilize nutrients effectively, thereby minimizing losses. In contrast, sandy soils, characterized by high water permeability, are prone to leaching and loss of nutrients, particularly potassium (K) and N. These contrasting behaviors emphasize the importance of soil texture in regulating nutrient availability and its sensitivity to environmental changes [10]. In the Siziwang Banner region, soil nutrient levels, including N, P, and K, are closely associated with vegetation type, coverage, and ecosystem functionality. Vegetation not only reflects but also actively influences soil nutrient dynamics by mediating nutrient uptake and cycling processes. Studies have shown that the spatial distribution of soil nutrients exhibits significant variability both temporally and spatially. This variability is primarily driven by precipitation patterns, topography, and vegetation heterogeneity [11]. Precipitation and topography influence nutrient distribution through mechanisms such as runoff, leaching, and sediment deposition. For instance, sloping terrain is more susceptible to water and wind erosion, leading to localized enrichment or depletion of nutrients. Erosion processes often remove surface soil layers rich in organic matter, thereby redistributing nutrients within the landscape. Vegetation type and density further modulate these effects by influencing nutrient uptake through root systems and promoting biological activity in the soil, such as microbial processes and decomposition of organic matter. Dense vegetation can reduce erosion, enhance soil stability, and contribute to nutrient accumulation, while sparse vegetation may exacerbate nutrient loss and soil degradation [12,13]. In areas with pronounced topographical variations, the redistribution of nutrients is particularly evident, as erosion and deposition processes disproportionately affect sloping and flat terrains. Despite the ecological and agricultural importance of understanding these dynamics, research on soil nutrient distribution and its driving factors in desert grasslands remains limited. Most existing studies have focused on agricultural lands, orchards, and forest ecosystems, neglecting the unique characteristics and challenges of arid and semi-arid grasslands [14]. Addressing this gap is critical for advancing soil management strategies and ecological restoration in these fragile ecosystems.

The spatial distribution of soil nutrients is influenced by multiple factors, including climate, soil properties, vegetation types, and human activities. Zhao et al. (2023) pointed out that in arid regions, variations in soil moisture can lead to changes in soil structure, which in turn affect the total carbon and nitrogen content [15]. Climate change, particularly fluctuations in precipitation and temperature, directly impacts soil moisture, plant growth, and microbial activity, thereby influencing the solubility and availability of nutrients. Soil texture and organic matter content are key factors affecting soil nutrient distribution. Rudgers et al. (2018) found that increased precipitation typically promotes the accumulation of soil organic matter, while drought leads to its reduction, thereby affecting the availability of nutrients such as nitrogen, phosphorus, and potassium. Climatic variability makes the response of soil organic matter more complex [16]. Vegetation types and coverage also regulate the cycling of soil nutrients, through root absorption and the decomposition of plant residues. An Ning et al. (2024) noted a strong correlation between precipitation and herbaceous plant biomass, while shrub biomass increased with precipitation within a certain range [17]. Regarding human activities, Zhao Jun et al. (2005) pointed out that excessive cultivation and improper fertilization can lead to soil nutrient loss, affecting its spatial distribution [18]. In conclusion, climate, soil properties, vegetation, and human activities collectively determine the spatial distribution of soil nutrients. Li Xuejie et al. (2023) emphasized that the spatial heterogeneity of soil nutrients is the result of the combined effects of these factors [19].

The objective of this study was to investigate the spatial distribution characteristics of soil nutrients across different topographical regions in the desert grassland of Siziwang Banner, including the northern plateau, central hills, and southern mountains. This research aimed to explore the influence of key factors such as climate, topography, and land use on the spatial distribution of soil nutrients. By employing geostatistical techniques combined with GIS methods, the spatial distribution of soil nutrients were analyzed using Kriging interpolation, a widely recognized approach for spatial prediction and estimation [20]. In addition, the relationships between soil nutrients and environmental factors including climate variables (e.g., precipitation and temperature) and topography were examined through Pearson correlation analysis. This method enables quantification of the strength and direction of associations, providing deeper insights into the mechanisms driving nutrient variability in different regions. The outcomes of this research offer a scientific basis for regional land management and ecosystem restoration strategies. Furthermore, the findings are expected to inform policy formulation aimed at enhancing soil conservation efforts in arid ecosystems. By identifying the key drivers of soil nutrient distribution, this study contributes to improving the precision of soil nutrient management in desert grasslands, ultimately promoting the ecological stability and sustainability of these fragile ecosystems. Such knowledge is crucial for addressing the dual challenges of climate change and human impact, ensuring the resilience of desert grassland ecosystems.

2. Materials and Methods

2.1. Overview of the Study Area

Siziwang Banner is located in the central part of Inner Mongolia Autonomous Region, northwest of Ulanqab City, at latitudes 41°10′ to 43°22′ N and longitudes 110°20′ to 113° E. It borders the Chahar Right Wing Middle Banner, Chahar Right Wing Rear Banner, and the Sonid Right Banner of Xilingol League to the east, Zhuozi County of Ulanqab City and Wuchuan County of Hohhot City to the south, Dalanmulun Joint Banner of Baotou City to the west, and the Mongolian border to the north, with a national boundary line extending 104 km. The dominant soil type in Siziwang Banner is calcareous soil, with typical soils including dark calcareous soil, black calcareous soil, chestnut calcareous soil, brown calcareous soil, and sandy soil [17]. The soil texture varies, encompassing clay, silt, and sandy soils, and these textural characteristics directly affect the soil's water retention capacity and the storage and availability of nutrients. However, the organic matter content in the soil is generally low, indicating limited soil fertility; this in turn restricts the spatial distribution of soil nutrients and plant growth.

From a climatic perspective, Siziwang Banner is located in the transitional zone between the Ulanqab Plateau and the desert grassland of Inner Mongolia, and the climate is typical of continental arid and semi-arid types. The average annual temperature in the region ranges from 1 °C to 6 °C, with limited rainfall and high evaporation. Annual precipitation varies from 110 to 350 mm, mostly concentrated in summer; the frost-free period lasts between 90 and 120 days, and the four seasons are distinct. In winter and spring, westerly winds prevail, while in summer and autumn, southerly winds dominate. The northern plateau area has a flat topography and a cold and dry climate, with an average annual temperature between 2 °C and 4 °C, and extremely low precipitation. The soil here is primarily brown calcareous soil, with poor nutrients [21]. The central hilly area has a relatively mild climate and slightly higher precipitation. The main soil type is calcareous soil, with land primarily used for pasture, and the organic matter content is relatively high, making it suitable for plant growth [22]. In the southern mountainous area, the terrain influences the precipitation, with an average annual rainfall ranging from 200 to 250 mm. The soil type is mountain meadow soil, which has a higher organic matter content and abundant nutrients, favoring the stable development of grassland ecosystems [23].

To further analyze the spatial distribution characteristics of soil nutrients in these three regions, this study collected soil samples from 38 sites across the northern plateau, central hills, and southern mountainous areas, covering different topographic and climatic conditions. Spatial analysis of the soil nutrient data from these sites revealed the trends and spatial heterogeneity in soil nutrient variation across the regions. The results show that the northern plateau area has relatively poor soil nutrients, the central hilly area has higher organic matter content, and the southern mountainous area has richer soil nutrients, demonstrating significant spatial differentiation. These differences reflect the influence of topography, climate, and land use on the spatial distribution of soil nutrients, and further reveal the ecological differences in the rates of wind erosion and water erosion as well as vegetation coverage across these regions. Therefore, understanding the spatial distribution characteristics of soil nutrients is of significant importance for ecological environmental protection and the prevention and precise control of wind and water erosion in the region. The study area is shown in Figure 1.

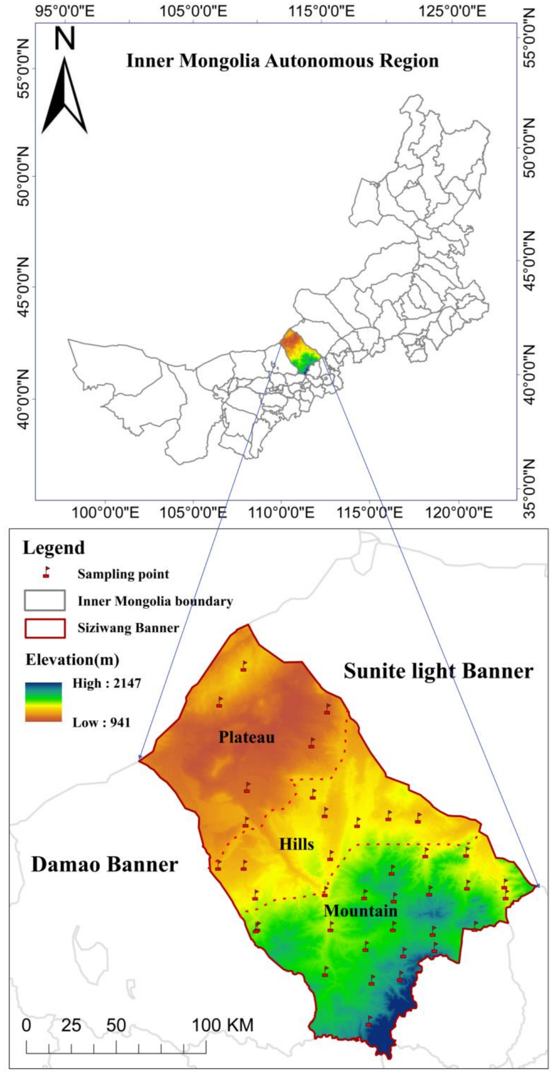

Figure 1. Overview of the study area and sampling sites.

2.2. Soil Sample Collection

Soil sampling for this study was conducted in July 2020, complemented by high-resolution satellite imagery, including 3 m resolution images from Mazar Technology (2019) and 15 m resolution Landsat imagery (1984). Sampling sites were systematically distributed across three distinct topographic zones in Siziwang Banner: the northern plateau, the central hills, and the southern mountains, representing varying climatic and topographic conditions. A total of 38 sampling points were established using a systematic 10 km × 10 km grid method to ensure uniform coverage. At each point, a 1 m × 1 m square sampling area was delineated, and soil samples were collected from five positions (four vertices and the center) and thoroughly mixed to form composite samples for each depth. To enhance representativeness and minimize sampling bias, two additional parallel samples were collected within a 100 m^2 area around each primary sampling point. Samples were taken from six standardized depth intervals (0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–25 cm, and 25–30 cm), with three parallel samples for each depth, resulting in 608 samples (38 sampling points × 3 parallel samples × 6 depths).

In arid and semi-arid regions such as desert grasslands, the 0–30 cm surface soil layer is typically rich in organic matter and nutrients, making it the primary zone for plant root growth and water absorption. Soil from this depth reflects the ecological function and health status of the region and holds significant research value. Selecting 30 cm as the standard sampling depth has become a common practice in many ecological and soil science studies because it encompasses the majority of plant root distribution and facilitates comparisons across different regions and time periods. This depth is particularly important in desertification and ecological restoration research, as understanding the changes in soil nutrients and structure within the surface layer is crucial for assessing the impacts of desertification and formulating effective restoration strategies. Therefore, sampling at a depth of 30 cm can accurately reflect the physical, chemical, and biological characteristics of the soil, making it an essential standard depth for studying the health of ecosystems in arid and semi-arid regions [24].

The selection of sampling sites considered the unique topographic features, climatic gradients, and variations in altitude within the region to ensure comprehensive environmental coverage. The collected soil samples were air-dried, ground, and sieved through a 2 mm mesh before laboratory analysis of key nutrient parameters, including soil organic matter (SOM), total nitrogen (TN), available phosphorus (AP), and available potassium (AK).

Soil organic matter (SOM) was determined using the potassium dichromate method. Dynamic changes in SOM are of significant importance for soil structure, physicochemical properties, and potential applications in precision agriculture. SOM plays a central role in soil nutrient supply, soil microbial activity, and plant growth, and it has a substantial impact on soil quality improvement and crop yield enhancement [25,26].

Total nitrogen (TN) was measured using the Kjeldahl method. Total nitrogen is a core indicator of soil nitrogen supply, directly influencing plant growth and yield. Nitrogen is an essential nutrient for plant growth, particularly in grassland and agricultural ecosystems, where nitrogen cycling and availability are critical for ecological health [27].

Available phosphorus (AP) was determined using the molybdenum–antimony anti-spectrophotometric method, following the standards "HJ 704-2014" and "NY/T 1121.7-2014", to assess the phosphorus supply level in the soil. Phosphorus is an indispensable element for plant growth, involved in energy transfer and multiple physiological processes. Understanding the availability of phosphorus in the soil is a crucial approach to improving soil fertility in nutrient management and precision agriculture [28].

Available potassium (AK) was measured using the flame photometric method. Potassium is equally essential for plant growth, especially in arid and semi-arid regions, where it helps plants maintain water balance and enhances stress resistance. By measuring available potassium in the soil, the soil's potassium supply capacity to plants can be evaluated, thereby optimizing fertilization management [29].

2.3. Other Data Sources

The multi-year average temperature and multi-year average precipitation data were downloaded from the Resource and Environmental Science Data Center, Chinese Academy of Sciences (https://www.resdc.cn/data, accessed on 2 December 2021) DEM data were downloaded from the Geospatial Data Cloud (https://www.gscloud.cn, accessed on 2 December 2021) and aspect and slope data were extracted using the ArcGIS 10.7 3D Analyst tool [30–33].

2.4. Data Processing and Analysis

The physicochemical properties of soil in the study area and the soil erosion data were analyzed using Kriging spatial interpolation in ArcGIS 10.8. This technique is widely used in geospatial analysis to estimate continuous spatial distributions from discrete observational data, based on the principle that points closer in space exhibit greater similarity, while similarity decreases with increasing distance [34–36]. Soil nutrient data, a critical determinant of soil fertility and ecosystem health, were interpolated to generate detailed spatial distribution maps using Kriging in ArcGIS. This approach enabled the visualization and assessment of both vertical and horizontal variability in soil nutrients, revealing patterns influenced by environmental gradients and anthropogenic activities.

To evaluate the spatial variability of soil characteristics, one-way analysis of variance (one-way ANOVA, San Francisco, CA, USA) was performed with significance levels set at $p = 0.05$ and $p = 0.01$, providing statistical evidence for differences in soil properties across spatial locations. This analysis helped to identify significant variations in soil nutrient concentrations across different topographic zones and depth intervals. Pearson correlation analysis was employed to examine the relationships between soil nutrients and environmental factors, including climate (precipitation and temperature), topography (elevation, slope, and aspect), and land use. These correlations provided insights into the driving forces behind nutrient distribution and the interdependence of soil properties.

To quantitatively describe the spatial variability and structural characteristics of soil organic matter (SOM), geostatistical models were used to compute parameters such as range, nugget-to-sill ratio, and spatial autocorrelation. Semivariograms were employed to evaluate the degree of spatial dependence and variability of SOM, offering a robust methodological framework for analyzing soil heterogeneity [37]. By integrating geostatistics with spatial interpolation, the study captured nuanced patterns of nutrient distribution and their associations with environmental variables.

Data processing and analysis utilized an array of advanced software tools, including ArcGIS 10.8 for geospatial analysis, SPSS for statistical evaluations, and Origin 9.0 for data visualization. This multifaceted approach ensured rigorous analysis and comprehensive insights into the spatial heterogeneity of soil nutrients. Furthermore, the geographic detector method was employed to quantify the contributions of various environmental factors, such as climate, topography, and land use, to the observed spatial variability in soil nutrients. This method provided a more nuanced understanding of the interactions among driving factors and their collective impact on soil properties. The integration of these methodologies enabled a holistic assessment of soil nutrient dynamics in the Siziwang Banner region. The findings offer critical insights into the complex interplay between natural and anthropogenic factors shaping soil properties, providing a scientific foundation for informed soil management and ecological restoration strategies in arid and semi-arid regions. By uncovering the spatial patterns and underlying drivers of nutrient variability, this study contributes to advancing precision agriculture, sustainable land use planning, and climate-adaptive soil management practices. Although soil erosion is not the primary focus of our study, the impact of processes such as wind erosion and other forms of soil degradation are indirectly reflected in the spatial distribution of sampling points, changes in soil depth, and variations in nutrient concentrations. We specifically focus on the dominant role of climatic factors (such as precipitation and temperature) in soil nutrient distribution, as climate change in desert grassland areas significantly influences soil moisture, nutrient cycling, and soil erosion processes. Through systematic sampling and laboratory analysis, we identified the spatial variation patterns of soil nutrients, further revealing how climate change drives the occurrence of these processes.

In conclusion, although we did not directly measure soil erosion rates, the analysis of nutrient spatial distribution and the interpretation of sampling data allow us to infer trends in soil degradation through the interactions between climate and soil. This provides foundational data for future, more in-depth studies on soil erosion [24].

3. Results

3.1. Spatial Distribution of Soil Organic Matter (SOM)

The spatial distribution of soil organic matter (SOM) in the desert grassland region of Siziwang banner demonstrates significant heterogeneity, highlighting the complex interplay between topography, vegetation, and climatic conditions. In the low-altitude plains, soil organic carbon (SOC) content is notably lower compared to the hilly and mountainous areas. Analysis of the Kriging interpolation maps (Figures 1 and 2) combined with elevation data reveals that SOC content is generally lower in the eastern lowlands compared with the western highlands. This finding underscores the critical role of elevation and topographic characteristics in influencing SOM distribution, as higher altitudes tend to support greater vegetation cover and reduced erosion, both of which contribute to SOC accumulation.

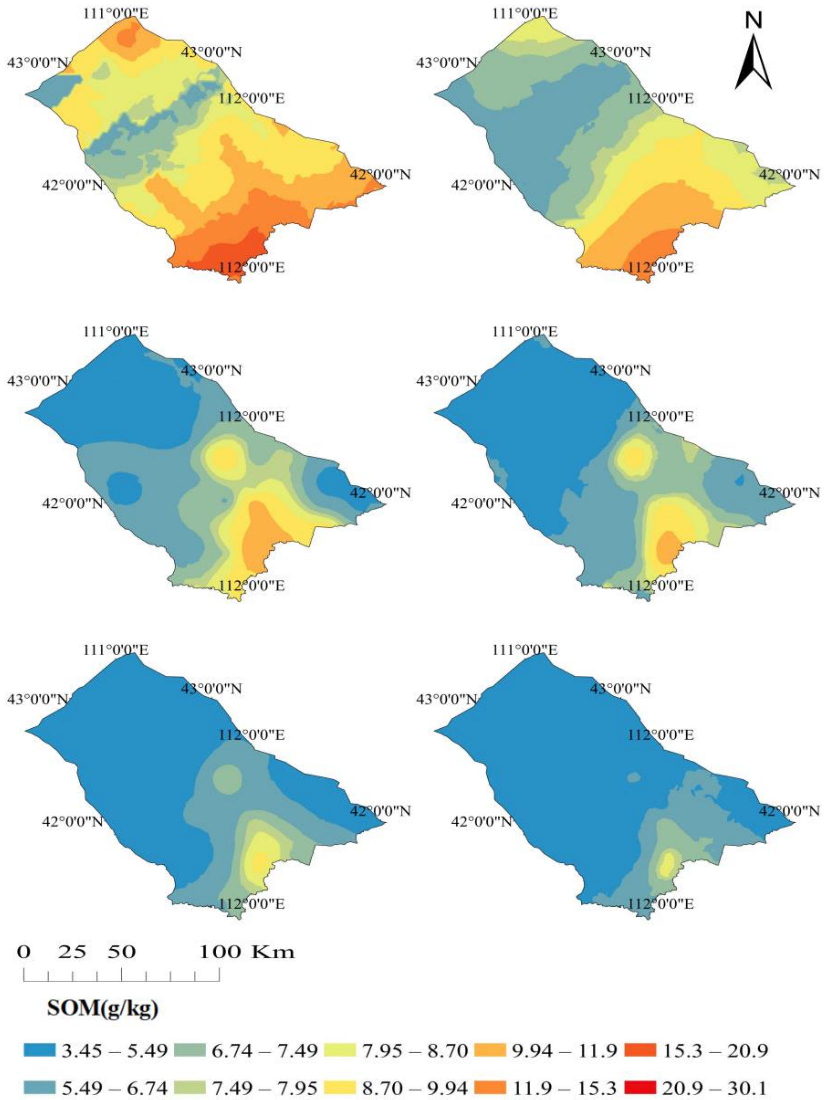

Figure 2. Kriging interpolation map of soil organic matter.

As shown in Figure 2 and Table 1, substantial horizontal variability in SOM content exists across the southern mountainous region, central hills, and northern plateau. The differences are particularly pronounced in the 0–10 cm soil depth, where SOM content varies significantly. Specifically, SOM content in the mountainous region is approximately 1.5 times higher than in the hilly areas and 2.5 times higher than in the plateau regions, with concentrations predominantly ranging from 11 to 16.5 kg^{-1}. These values align closely with those reported by Zhang Xiaona from the Xilamuren desert grasslands, where SOM ranged between 10.21 and 14.09 g kg^{-1}, indicating similar ecological processes across these arid regions.

Table 1. Descriptive statistics of soil nutrients in different soil horizons of the study area.

	ST (cm)	Max	Min	Average	SD	VC
SOM (g/kg)	0–10	23.1	3.16	9.520	4.2717	0.45
	10–20	13.9	2	6.312	2.6900	0.43
	20–30	11.13	1.292	5.342	2.4360	0.46
TN (g/kg)	0–10	2.55	0.61	1.425	0.4584	0.32
	10–20	1.74	0.48	1.014	0.3406	0.34
	20–30	1.64	0.31	0.813	0.3177	0.39
AK (mg/kg)	0–10	163.55	48.08	86.265	27.8960	0.32
	10–20	132.55	23.59	53.743	25.3350	0.47
	20–30	101.32	14.54	38.070	18.7545	0.49
AP (mg/kg)	0–10	25.53	4.98	8.581	4.2419	0.49
	10–20	17.02	3.21	6.729	2.4820	0.37
	20–30	13.32	3.5	6.267	2.3807	0.38

In deeper soil layers, SOM content follows a declining trend from south to north, with lower values observed on the plateau compared with the mountainous and hilly regions. This gradient reflects the combined effects of climatic factors, such as precipitation and temperature, and vegetation cover. Higher precipitation levels in the southern regions enhance vegetation growth and the input of organic matter, while lower precipitation and increased wind erosion on the northern plateau contribute to nutrient depletion. Additionally, the protective role of vegetation in reducing erosion and promoting the accumulation of organic matter is more pronounced in the hilly and mountainous areas. Vertically, the average SOM content decreases progressively with increasing soil depth, a pattern consistent with the general trend observed in arid and semi-arid regions. Organic matter is predominantly concentrated in surface layers, due to the deposition of plant residues, limited leaching, and active microbial decomposition. Deeper layers receive less organic input and experience slower decomposition rates due to reduced microbial activity and limited oxygen availability. These findings highlight the vertical "surface accumulation effect", a common phenomenon in dryland ecosystems, where surface layers act as a critical zone for nutrient cycling and retention.

3.2. Distribution Characteristics of Total Nitrogen (TN)

The total nitrogen (TN) content in the desert grassland region of Siziwang Banner demonstrated a gradual decrease with increasing soil depth, while maintaining a consistent trend across other soil layers. This vertical pattern is similar to findings by Zhang Xiaona from the Xilamuren desert grasslands of Inner Mongolia, which reported significant differences in TN content between various geomorphic units. Such differences were particularly notable in sparsely vegetated areas, where soil nitrogen content was markedly lower due to limited organic input and reduced vegetation-mediated nitrogen cycling. Sparse vegetation not only limits nitrogen fixation through root exudates but also reduces the organic matter contributions necessary for nitrogen accumulation in the soil.

As illustrated in Figure 3 and Table 1, TN distribution varied distinctly across different topographic types (plateau, hills, and mountains) and soil depths (0–10 cm, 10–20 cm, and 20–30 cm). Topography and soil depth significantly influence the spatial variability of soil nitrogen. In the plateau and hill regions, TN content was significantly higher in the surface layer (0–10 cm) compared with the middle (10–20 cm) and deep layers (20–30 cm), suggesting a pronounced "surface enrichment effect". This accumulation is primarily attributable to vegetation cover, organic matter deposition, and microbial activity that concentrates nitrogen near the surface. Vegetation acts as both a nitrogen source and a regulator, with plant residues contributing to organic nitrogen pools and root activity enhancing microbial nitrogen cycling. Conversely, in mountainous regions, TN content showed minimal variation across the soil depths, reflecting a more uniform vertical distribution. This uniformity can be attributed to the complex topography and higher precipitation levels in these areas, which facilitate the redistribution of nitrogen through leaching and sedimentation processes.

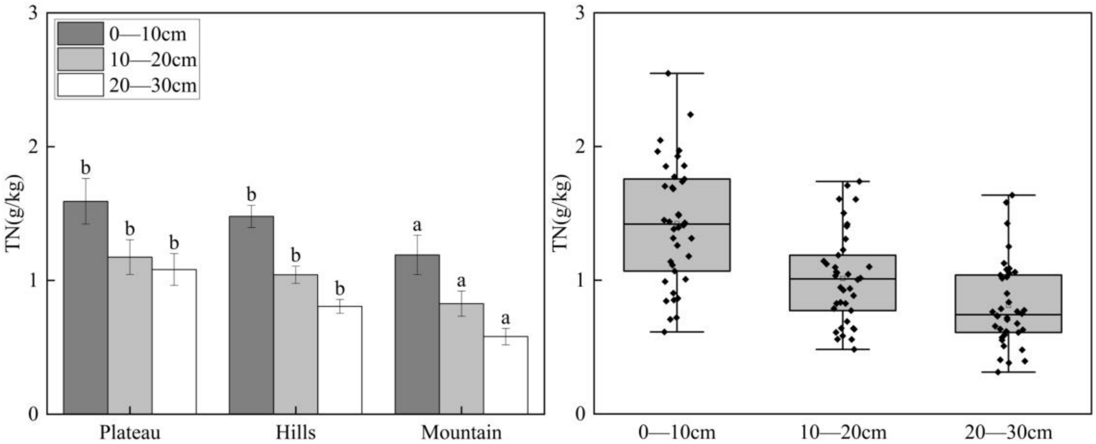

Figure 3. TN analysis of variance (ANOVA) plot.

3.3. Spatial Distribution of Available Potassium (AK) and Available Phosphorus (AP)

The spatial distribution of available potassium (AK) and available phosphorus (AP) across the desert grassland region of Siziwang Banner demonstrated relatively uniform horizontal patterns, with noticeable aggregation similar to the distribution of soil organic matter (SOM) (Figure 4 and Table 1). However, with increasing soil depth, the average contents of AK and AP gradually decreased. In the marginal grassland areas, both AK and AP contents were significantly lower.

AK predominantly originates from the weathering of mineral potassium in the soil's parent material. In the cold and arid climatic conditions characteristic of the study region, where precipitation levels are low, soil leaching processes are relatively weak. This limited leaching environment ensures that potassium remains concentrated near the soil surface, primarily in the form of exchangeable potassium adsorbed onto soil colloids and released from clay minerals. These conditions contribute to the relatively uniform horizontal distribution of AK and its enrichment in surface soil layers. Furthermore, the adsorption capacity of clay particles and the low mobility of potassium in weakly leached soils play crucial roles in its retention, highlighting the influence of soil texture and mineralogy under specific climatic conditions.

Vertically, AP content within the 0–30 cm soil layer ranged from a peak of 13.28 mg/kg to a minimum of 5.48 mg/kg. This range aligns closely with AP values reported by Zhang Xiaona from Xilamuren desert grasslands (12.59–17.92 mg/kg). The highest average AP content (9.65 mg/kg) was observed in the 0–5 cm surface layer, while deeper layers exhibited relatively consistent average AP contents of approximately 6–7 mg/kg. This distribution reflects the combined effects of organic matter decomposition, microbial activity, and limited downward phosphorus transport in arid soils.

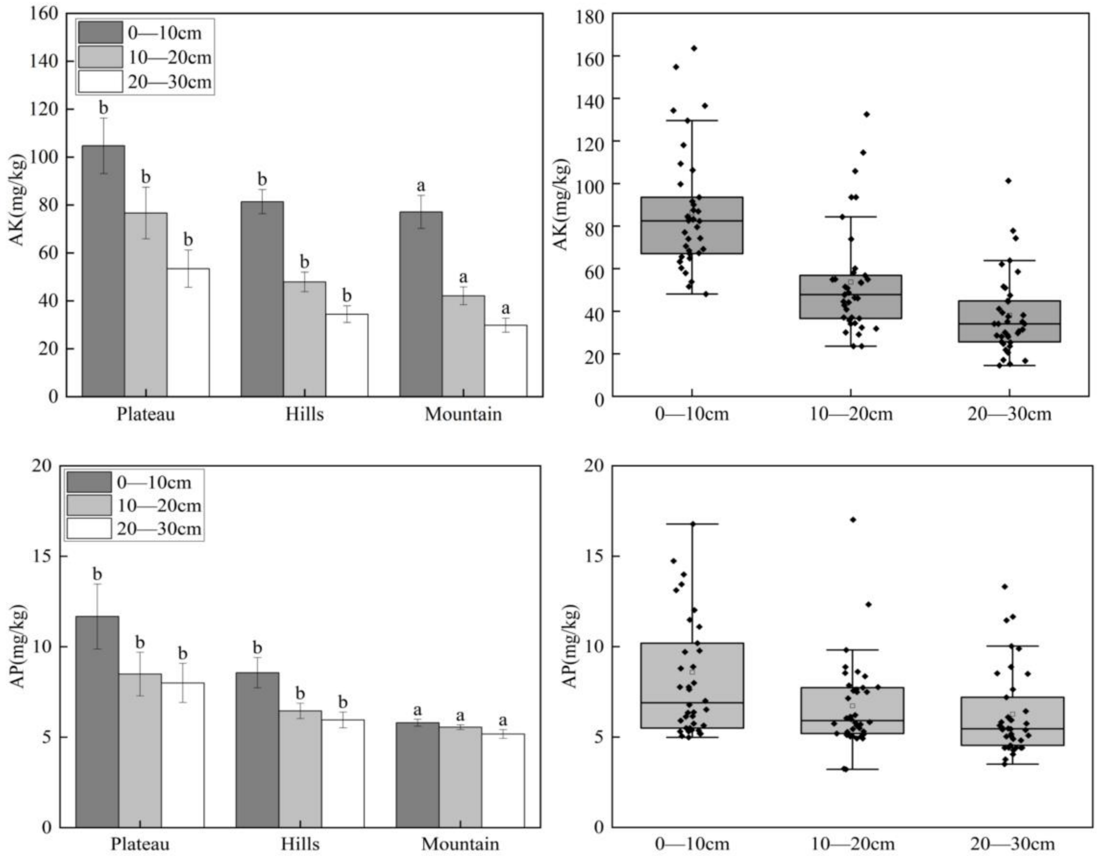

Figure 4. AK and AP analysis of variance (ANOVA) plot.

Horizontally, within the 0–15 cm soil depth, AP content in the southern mountainous region was found to be significantly higher than in the northern plateau and central hilly regions ($p < 0.05$). Specifically, at the 0–5 cm depth, AP content in the southern mountains was 1.86 times and 1.5 times that of the northern plateau and central hills, respectively. Within the 5–15 cm depth range, the southern mountains displayed AP levels 1.7 times higher than those of the northern plateau and central hills. This substantial difference can be attributed to higher precipitation levels on shaded mountain slopes promoting the accumulation of organic matter. Through microbial decomposition, this organic matter transforms into plant-available forms of AP. Moreover, the increased surface organic matter enriches the soil's phosphorus reserves by preventing its rapid fixation into insoluble forms, commonly observed in drier areas with lower biological activity.

3.4. Main Environmental Variables Affecting the Spatial Distribution of Soil Nutrients

The spatial distribution of soil organic matter (SOM) is significantly influenced by climatic factors, as indicated by the Pearson correlation analysis in Figure 5. Precipitation was positively correlated with SOM ($r = 0.72$, $p < 0.01$), suggesting that precipitation promotes vegetation growth and enhances microbial activity, which play critical roles in the accumulation of organic matter. In contrast, temperature exhibited a significant negative correlation with SOM ($r = -0.76$, $p < 0.01$). Elevated temperatures accelerate the decomposition rate of organic matter, leading to a decrease in SOM content. These findings indicate that variations in precipitation and temperature exert significant and mutually constraining effects on the processes of SOM input and decomposition.

The spatial distribution of total nitrogen (TN) is also closely related to precipitation and temperature. Precipitation significantly enhances TN accumulation ($r = 0.66$, $p < 0.01$). Conversely, temperature variations have dual effects on nitrogen dynamics; while moderate temperatures promote nitrogen mineralization and availability, elevated temperatures may increase nitrogen volatilization, resulting in nitrogen loss. Furthermore, the synergistic effects of precipitation and temperature across different topographic gradients exacerbate the spatial heterogeneity of TN, with higher TN reserves observed in regions with abundant precipitation.

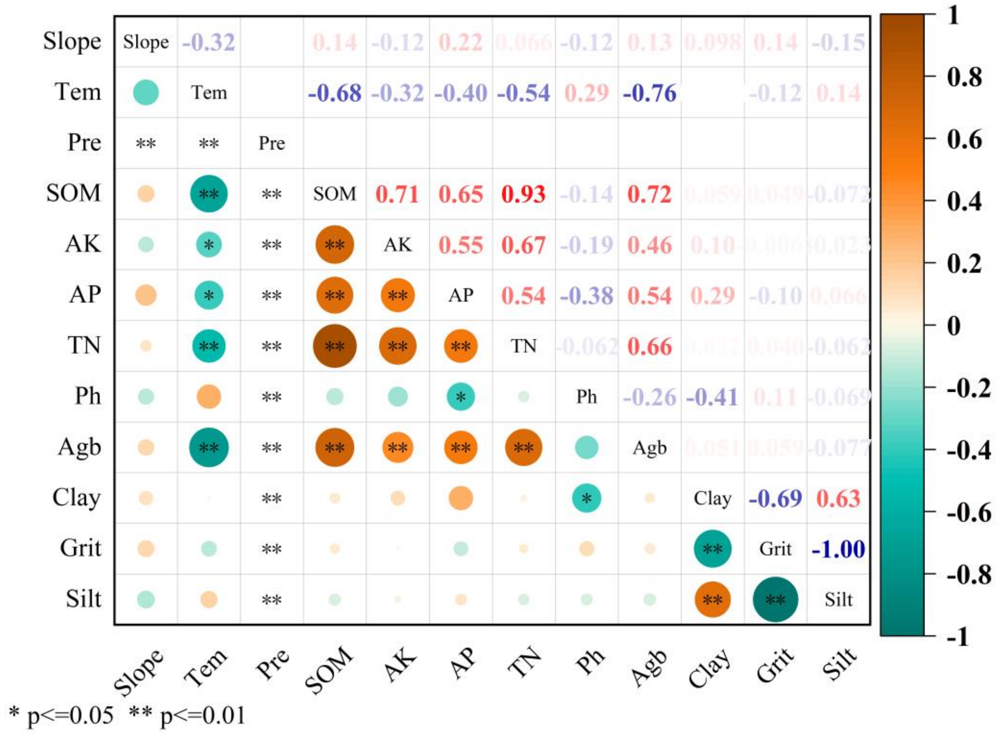

Figure 5. Pearson correlation analysis: soil nutrients.

The distribution patterns of available potassium (AK) and available phosphorus (AP) are similarly controlled by climatic factors. Precipitation was found to be positively correlated with AK ($r = 0.55$, $p < 0.01$) and AP ($r = 0.54$, $p < 0.01$), which is likely to have been due to its role in enhancing vegetation growth and microbial activity. However, excessive precipitation can cause nutrient leaching, significantly affecting the mobility and redistribution of potassium and phosphorus. Temperature further influences the spatial distribution of AK and AP by accelerating mineral weathering and organic matter decomposition. However, in arid regions, elevated temperatures combined with limited water availability suppress microbial activity, reducing the transformation of nutrients into plant-available forms.

Climatic factors, through their complex interactions with topography and vegetation, significantly affect the spatial distribution of SOM, TN, AK, and AP. The correlation analysis highlights the dominant role of climatic factors in driving the spatial variability of soil nutrients. Soil nutrient distribution is not only influenced by the direct effects of individual factors but also by interactions among multiple factors. The synergistic effects of climatic and vegetation factors are particularly important for nutrient accumulation. For example, the significant positive correlation between precipitation and aboveground biomass (AGB) ($r = 0.67$, $p < 0.01$) indicates that precipitation enhances vegetation growth, which increases litter input and organic matter accumulation, thereby improving SOM and TN content. However, topographic factors, such as slope, play a regulatory role in this accumulation process. Increased slope intensifies nutrient loss caused by precipitation and alters runoff paths and sedimentation patterns, as evidenced by the weak negative correlation between slope and SOM ($r = -0.32$). This underscores the constraining effects of erosion on nutrient distribution. Additionally, soil particle composition plays a critical role in nutrient retention. The significant positive correlation between clay content and SOM ($r = 0.63$, $p < 0.01$)

suggests that clay particles have a strong adsorption capacity for organic matter, enhancing its stability and long-term storage potential. In contrast, areas with higher sand content, due to their loose structure, are more prone to wind and water erosion, leading to greater nutrient loss.

It is important to highlight that human activities, through alterations in vegetation cover and soil management practices, indirectly modulate the relationship between climatic factors and soil nutrients. Increased intensity of land use—such as overgrazing, agricultural expansion, or vegetation degradation—exacerbates the risk of nutrient loss. Consequently, examining the interactions among climatic factors, vegetation, topography, and anthropogenic activities is essential for a comprehensive understanding of the underlying mechanisms driving nutrient distribution.

4. Discussion

4.1. The Synergistic Effects of Climatic Conditions and Soil Physical Properties on the Spatial Distribution of Nutrients

This study reveals that soil nutrients exhibit significant spatial variability at both macro and micro scales, a fundamental property of soil. This variability is primarily driven by multiple environmental variables, including soil texture, topography, and climate. The results indicate that SOC, TN, AP, and AK concentrations are significantly higher in the 0–10 cm soil layer compared with the 10–30 cm layer, with nutrient levels decreasing with depth. This "surface accumulation" distribution pattern is consistent with findings from Zhang Xiaona's study in the Xilamuren desert grasslands, where shallow soils were enriched with organic matter and nitrogen due to active decomposition and abundant biological inputs [38]. Horizontally, soil nutrients in Siziwang Banner show a distinct spatial gradient, with the highest concentrations in the southern mountainous regions, followed by the central hills, and the lowest in the northern plateau. This pattern is likely to be associated with higher precipitation levels and depositional processes in the southern regions. Similarly, research by Xi Qiaomei in the desert grasslands of Ningxia highlights that regions with lower terrain and higher precipitation tend to concentrate soil organic matter and nutrients [39].

This study also demonstrates that soil in the upper slopes is subject to significant nutrient loss, particularly nitrogen and organic matter, due to water erosion. In contrast, the foot slopes experience nutrient enrichment due to depositional effects. This observation aligns with findings by Li Xuebin in the Ningxia desert grasslands, where wind erosion contributed to the formation of "fertility islands", highlighting how both water and wind erosion amplify the heterogeneity of soil nutrients [40]. Climate factors (precipitation and temperature) are the dominant drivers of soil nutrient spatial distribution. Jobbagy and Jackson (2001) demonstrated that precipitation enhanced soil moisture conditions and microbial activity, thereby promoting the accumulation of soil organic matter (SOM) and total nitrogen (TN) [41]. Bogunovic et al. (2014) further noted that precipitation not only facilitates nutrient migration and accumulation but also enhances vegetation growth, increasing carbon and nitrogen reserves in soils [42]. In contrast, rising temperatures accelerate the decomposition of organic matter and nutrient volatilization, a phenomenon particularly pronounced in arid and semi-arid regions (Schlesinger et al., 1996; He et al., 2015) [43,44]. Together, precipitation and temperature shape the spatiotemporal patterns of soil nutrient distribution.

Topographic factors significantly influence nutrient distribution by regulating water flow, erosion, and sediment deposition. In the study area, steep slopes are subject to severe erosion, leading to losses of SOM and TN from the surface layer, while low-lying areas accumulate higher nutrient levels due to sediment deposition. Zhang et al. (2014) reported that slopes exhibited lower nutrient levels due to soil and water loss. Flat and low-lying areas concentrate nutrients more effectively [45]. Correlation analysis confirmed these findings, with a negative relationship between slope and SOM highlighting the critical role of topographic variation in driving nutrient heterogeneity [46].

Land use patterns have also significantly altered soil nutrient distribution. Na et al. (2019) revealed that long-term agricultural practices led to higher alkaline hydrolyzed nitrogen (AN) and available potassium (AK) concentrations in the surface soil while depleting nutrient reserves in deeper layers [47]. Song et al. (2023) emphasized that grasslands and shrublands with better vegetation cover exhibited stronger nutrient retention and spatial stability [48]. Furthermore, Schlesinger et al. (1996) the localized enrichment of nutrients beneath vegetation, especially in arid regions [43].

Soil texture plays a pivotal role in nutrient retention and loss. Soils with higher clay content exhibit strong adsorption capacity, effectively retaining SOM and nutrients, whereas sandy soils, with their loose structure, are prone to water and nutrient loss, especially in regions with higher precipitation, exacerbating nutrient spatial heterogeneity [49].

Biological factors also significantly influence nutrient accumulation and distribution through interactions between aboveground vegetation and belowground microorganisms. Xu et al. (2016) found that aboveground vegetation contributed to soil nutrients via litter and root exudates, while soil microorganisms accelerated nutrient cycling and availability through the decomposition and mineralization of organic matter [50]. He et al. (2015) demonstrated that in arid ecosystems, plants regulate soil nutrient dynamics through distinct allocation strategies among roots, stems, and leaves [44].

In conclusion, the spatial distribution of soil nutrients in the desert grasslands of Siziwang Banner is the result of complex interactions between climate, topography, land use, soil texture, and biological factors. Among these, climate factors predominantly influence soil moisture and microbial activity, playing a leading role in nutrient dynamics. Topography and soil texture further modify nutrient distribution by regulating erosion, deposition, and retention processes. Biological factors enhance nutrient cycling and redistribution, adding complexity and dynamism to nutrient patterns. These findings provide valuable insights for sustainable soil resource management and precision fertilization strategies in arid and semi-arid ecosystems.

4.2. Recommendations and Perspectives on Soil Nutrient Management

This study revealed the spatial distribution characteristics of soil nutrients in the desert grasslands of Siziwang Banner and the mechanisms through which they are influenced by various environmental factors, such as soil texture, climate, topography, and pH. The findings highlight the critical roles of climatic conditions and geographic factors in regulating soil fertility and nutrient distribution. Moreover, this study demonstrated significant heterogeneity in soil nutrient distribution both vertically and horizontally, providing a scientific basis for regional soil management.

However, there are certain limitations to this research. First, the spatial coverage of the sampling sites was limited, failing to comprehensively reflect the full picture of soil nutrient distribution. Second, this study does not account for the significant impact of human activities, such as fertilization, irrigation, and cultivation, on soil nutrient dynamics. Third, it lacks predictive analysis of soil nutrient distribution under climate change scenarios. Additionally, important indicators including soil physical properties, biological characteristics, and trace elements have not been thoroughly investigated.

Future research should aim to expand the sampling scope, integrate climate models and remote sensing technologies for multidimensional analysis, and incorporate human factors and diversity indicators to comprehensively elucidate the dynamic patterns of soil nutrients.

To address these gaps, future research should (1) expand sampling coverage to improve representativeness; (2) integrate climate models and remote sensing techniques for multidimensional spatial analyses and long-term predictions of climate impacts on soil nutrients; (3) incorporate anthropogenic factors and ecological processes to achieve a holistic understanding of soil nutrient dynamics; and (4) include indicators such as soil biodiversity, microbial composition, and micronutrient contents to deepen insights into soil system functioning [51,52]. Based on these findings, practical recommendations for soil management in Siziwang Banner are proposed to balance ecological and economic benefits, as follows: (1) promote the use of organic fertilizers to reduce reliance on chemical fertilizers, alleviate soil acidification, and improve nutrient use efficiency [53,54]; (2) optimize nitrogen and phosphorus fertilizer application to restore degraded grassland ecosystems and enhance soil fertility; (3) strengthen vegetation restoration and ground cover to mitigate the impacts of overgrazing on soil structure and nutrient distribution [55]; and (4) regulate soil pH to improve the availability of phosphorus and promote plant growth and nutrient cycling [56]. These strategies are essential for mitigating the challenges posed by climate change and ensuring sustainable agricultural productivity and ecosystem resilience.

5. Conclusions

This study reveals the spatial distribution characteristics of soil nutrients in a desert grassland ecosystem, highlighting the dominant role of climate factors in shaping soil nutrients. The results show that variations in precipitation and temperature play a key role in the changes in soil organic matter, nitrogen, phosphorus, and potassium levels. Through the integration of geospatial analysis and experimental data, this study demonstrates how climate factors in combination with soil texture and topographic features jointly influence the availability and distribution of soil nutrients.

Although direct measurement of soil erosion was not conducted, this study indirectly reveals the potential impact of processes such as wind erosion on soil nutrient dynamics. Through analysis of the spatial distribution of nutrients and correlating the results with climate data, trends in soil degradation and nutrient loss are inferred, providing valuable quantitative data for land management.

This study provides important insights into the soil–environment interactions in arid and semi-arid regions, with results that are significant for soil health and ecosystem stability.

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