Hindawi
International Journal of Chemical Engineering
Volume 2022, Article ID 9200438, 8 pages
https://doi.org/10.1155/2022/9200438

Research Article

Spatial Differentiation of Ecological Stoichiometry of Nitrogen and Phosphorus in Mollic Epipedon of China

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Received 7 June 2022; Revised 11 August 2022; Accepted 14 September 2022; Published 30 September 2022

Academic Editor: Jeevan Kumar Reddy Modigunta

Nitrogen (N) and phosphorus (P) are essential elements for crop growth. The study on the spatial differentiation characteristics of soil N and P can provide a theoretical basis for regional fertilization as well as prevention and control of agricultural surface pollution. Taking the typical mollic epipedon area in Northeast China as study area, using the geostatistical model and 3S technology (Remote Sensing, RS; Geography information systems, GIS; and Global positioning systems, GPS), the spatial variation and influencing factors of N and P ecological stoichiometry in the surface soil (0-20 cm) were studied with 1,057 samples by five-point soil sampling method. The outcomes of the study showed that the average total nitrogen (TN), total phosphorus (TP), and N/P ratio were 1.88 g/kg, 0.276 g/kg, and 6.81, respectively. The degree of spatial variation is moderate, and structural factors such as topography and soil parent material are the main factors affecting the spatial variation of soil TN, TP content, and N/P ratio. Vegetation primarily affects the soil TN, TP contents, and N/P specific spatial variation. Soil TN and TP contents showed a downward trend from the northeast to the southwest region of the study. Different approaches of balanced fertilization, soil and water conservation, and reasonable spatial allocation are beneficial to improving the balance of soil N and P in the typical mollic epipedon area of Northeast China.

1. Introduction

N and P are essential elements in the soil that play key roles in plant growth and development in terrestrial ecosystems. These elements can affect the physical energy cycle and terrestrial ecosystem balance [1]. Over the past few years, numerous studies have reported spatial variations and influencing factors for soil N/P chemometric characteristics in terrestrial ecosystems [2, 3]. A typical study is Cambardella et al. [4]. Based on the data of 41 soil element content parameters measured in two places, the spatial distribution of soil parameters such as total carbon, total nitrogen, pH, and other soil parameters in the central Iowa watershed was carried out by means of the semivariance function and the ratio of nugget to total semivariance. Analysis and research results show that soil organic carbon and total carbon in the experimental area have strong spatial dependence, while biomass C and NO^{-}_{3} N and other elements have relatively weak spatial dependence. Ma et al. [5] applied classical statistics and geostatistical methods to analyze the spatial differentiation characteristics of soil N and P ecological stoichiometry in a small watershed in the mollic epipedon region of China and then analyzed the main influencing factors. This study showed that the geostatistical analysis model has a high degree of fit ($R^2 > 0.833$) and effectively reflects the spatial variation characteristics of TN, TP contents, and N/P ratio in the study area. Liu et al. [6] explored vertical distribution characteristics and driving mechanism of soil carbon, nitrogen, phosphorus, and other elements along the altitude gradient in the karst dry-hot valley area of southwest China. The trend of the results is opposite to that of the carbon-nitrogen ratio. The recent studies on soil N and P have primarily focused on the characteristics of N and P variation in the soil; however, the correlation between soil N and P coupling equilibrium was not considered in these studies. Related research has shown that N and P can comprehensively describe soil N and P variations than individual variations of N and P in the soil [7, 8].

Studies on soil nutrients were primarily focused on the single or multiple elements within a certain administrative division [9]. However, the spatial distribution of soil nutrient elements and the analysis of influencing factors of the administrative division have ignored the natural process of soil nutrient formation and cyclic accumulation to a certain extent [7]. The characteristic mechanism of the natural evolution of natural elements has not been validated. At the same time, the research on mollic epipedon areas is scarce. While the typical mollic epipedon area in northeast of China is a fertile soil area for the plantation of important commodities in China, and it plays a vital role in the sustainable development of regional agriculture and national food security [10]. However, there is no research on the spatial differentiation law of soil N and P in the whole region based on the black soil region of China as a whole.

The scientific problem to be solved in this paper is the spatial differentiation characteristics of TN and TP contents and their ecological stoichiometry in typical mollic epipedon regions of China. Geostatistical model and 3S technology are used to analyze the spatial variation characteristics of ecological stoichiometry of soil elements in the mollic epipedon region of Northeast China, one of the three major mollic epipedon belts in the world [11]. This may improve the cognition of the evolution process of the balance of supply and demand and pattern of soil nutrients, provide a theoretical and technical basis for the sustainable development of agricultural production in the typical mollic epipedon area of Northeast China, and promote the coordinated development of grain production capacity improvement and farmland environmental protection in the mollic epipedon area.

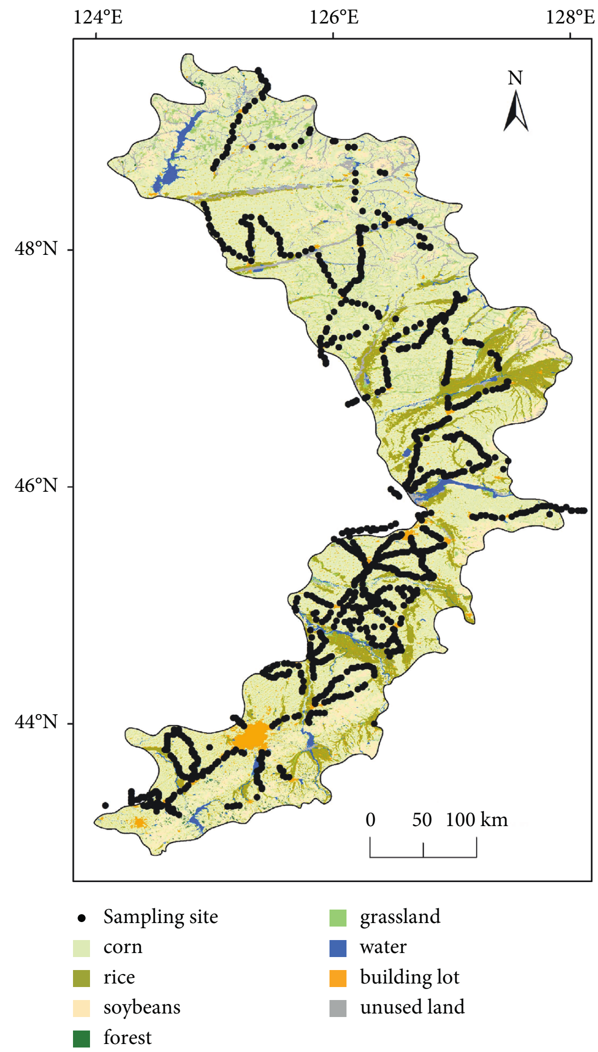

Figure 1: Distribution of sampling points in the study area.

2. Materials and Methods

2.1. Study Area. The typical mollic epipedon area in Northeast China was located at the southwest of Heilongjiang Province, central Jilin Province, northern Liaoning Province, and the Morin Dawa Daur Autonomous Banner of Inner Mongolia Autonomous Region (42°53′12″-49°39′44″N, 123°59′04″-128°01′03″E) (Figure 1). It is one of the "three mollic epipedon areas" in the world. The study area shows strip distribution from north to south, mainly with plains with rolling and low hills. The experimental area has a temperate continental monsoon climate. It is rainy and humid in summer and dry and cold in winter, with an average annual temperature of 2.9°C. The precipitation is mainly concentrated in June and September, accounting for 60% to 70% of the annual precipitation. The soil type is affected by temperature, precipitation, soil parent, and so on. The zonal soil type in the experimental area was mainly black and black calcium soil (Figure 2), with high organic matter content [12]. This type of soil is suitable for food production, and the staggered distribution of nonzonal soil types is mainly meadow and sandstorm. Natural vegetation in the experimental area was primarily deciduous broad-leaved forests, deciduous broad-leaved and mixed coniferous forests, coniferous forests, and grasslands [13, 14]. The agriculture in this area is dominated by corn, rice, and soybeans, which are ripe once a year (Figure 1).

2.2. Sample Collection and Analysis. The sampling points were uniformly distributed in space, and the total area of sample collection is 92 004.71 km^2. The sampler (1 m × 1 m) was set as per the five-point method. The central position of the sampling point was typed and recorded using a handheld Global Positioning System (GPS). Soil samples from the typical mollic epipedon area in Northeast China were collected in October 2014. The data source is from the Institute of Applied Ecology, Chinese Academy of Sciences. In addition, some sampling points were adjusted as per the conditions of land use type, accessibility of transportation, and slope based on Landsat satellite image features. After natural air drying, the soil samples were grounded and screened in the laboratory. The content of TN was determined by automatic Kjeldahl apparatus, and the content of

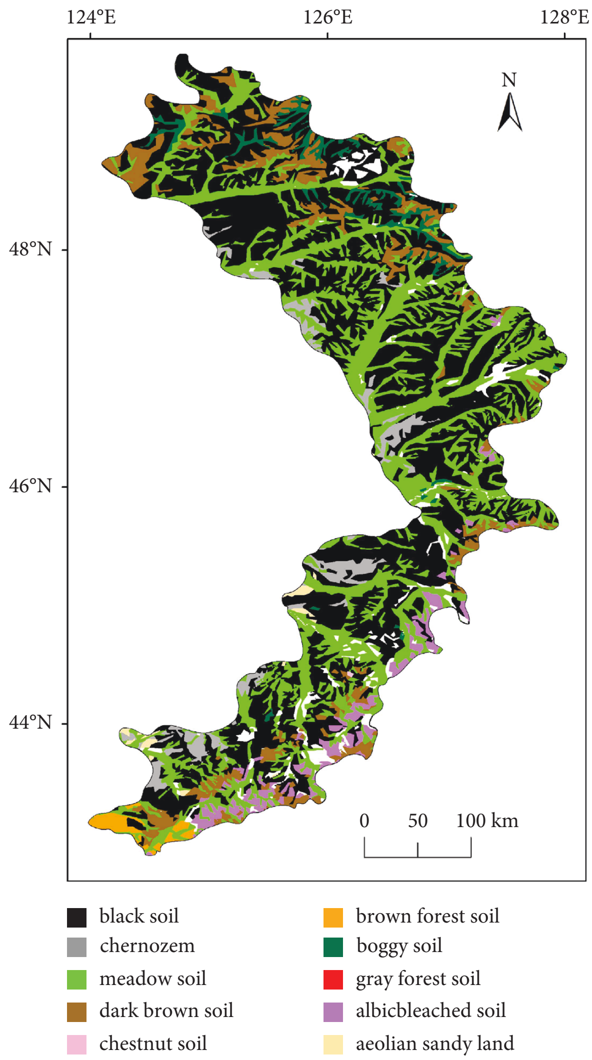

FIGURE 2: Soil types in the study area.

TP was determined by molybdenum-antimony resistance colorimetry [15].

2.3. Research Methods. The half-variance function model in the geostatistical analysis is an effective method to study the spatial differentiation characteristics of soil nutrient elements [16]. The semivariation function was used to obtain three important parameters: nugget, sill, and variation range, and these values were expressed as C0, C0 + C, and α, respectively. The nugget value (C0) can effectively explain the extent to which regional variables vary at smaller than the sampling scale. The base value (C0 + C) is generally used to represent the total variation in the system, and the nugget effect [C/(C0 + C)] is used to represent the proportion of the variation caused by the nonrandom part in the system to the total variation of the system. The nugget/sill ratio value [4], that is, C0/(C0 + C), was used to evaluate the nugget effect, which reflects the spatial self-correlation of parameters and the contribution of random factors to total variation. The study primarily analyzed the spatial variation characteristics of soil TN, TP content, and N/P ratio through the semivariance function model using the following formula [16]:

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

where $\gamma(h)$ is a variation function, $N(h)$ is the total number of sample points when the partition distance was h, and $Z(x)$ at x_i space position represents $Z(x_i)$ value. The measured value of $Z(x_i) + h$ is $Z(x)$ at h distance at x_i places.

Kriging interpolation is one of the most widely used methods in the field of spatial interpolation of natural geographical elements. Using ArcGIS (10.2) software platform, the operation is completed by Geostatistical Analyst tool. Based on existing research, spatial distribution interpolation of soil TN, TP content, and N/P ratio in the study area was performed as per the descriptive statistical analysis, normal distribution test by Kolmogorov–Smirnov (k-s) test, and variance analysis of sample data [17].

3. Results

3.1. Soil TN, TP Content, and N/P Spatial Variation Characteristics

Classical statistical analysis of TN, TP content, and N/P ratio of soil samples in typical black soil areas in Northeast China. The soil TN, TP content, and N/P ratio in the typical black soil area of Northeast China ranged from 0.89 to 5.93 g/kg, 0.54 to 3.77 g/kg, and 0.47 to 3.21, with an average value of 1.91 g/kg, 1.28 g/kg, and 1.51 g/kg, respectively (Table 1). The coefficients of variation are [0, 0.1), [0.1, 1), and [1, +∞), which indicate weak variation, medium variation, and strong variation. The coefficients of soil TN, TP content, and N/P in the study area were 34.01%, 34.28%, and 21.19%, respectively. The spatial distribution was moderately variable, indicating that random factors such as human activities, farming measures, and land use had certain effects on the spatial variation of soil TN, TP, and N/P ratio.

The semivariant model was employed to obtain soil N, P content, and ecological stoichiometry ratio in the typical mollic epipedon area in Northeast China. K–S test revealed that TN, TP content, and N/P were in line with the log-normal distribution. The model-fitting results showed that the theoretical model of soil TP content and N/P ratio in the study area were exponential, and TN content was Gaussian (Table 2). Thus, it was highly fitting and effectively represented the spatial variation characteristics of TN, TP content, and N/P ratio in the study area. The nugget of soil TN, TP content, and N/P were 0.319, 0.423, and 0.468, respectively. The massive gold effect of soil TN, TP content, and N/P ratio in the study area were 0.152, 0.262, and 0.462, respectively. This indicated that the spatial variation of soil TN, TP content, and N/P ratio were not affected by random factors, such as human activity, agricultural production, and structural factors. The TN, TP content, and N/P ratio variations in the study area were 5.417, 4.400, and 2.075,

Table 1: Descriptive statistical characteristics of soil TN, TP content, and N/P.

Index	Number of samples	Average values	Minimum	Maximum	Standard deviation	Deflection	Peak degree	Coefficient of variation (%)
TN	1056	1.91	0.89	5.93	0.65	1.53	4.55	34.01
TP	1056	1.28	0.54	3.77	0.44	1.96	5.45	34.28
N/P ratio	1056	1.51	0.47	3.21	0.32	0.75	1.62	21.19

Table 2: Parameters of the semivariogram models for soil TN, TP contents, and N/P ratio.

Index	Theoretical model	Nugget	Massive gold effect	Variation	Fitting residual error	R^2
TN	Gaussian	0.319	0.152	5.417	4.520×10^{-2}	0.899
TP	Exponential	0.423	0.262	4.400	3.480×10^{-2}	0.863
N/P	Gaussian	0.468	0.462	2.075	2.214×10^{-2}	0.874

respectively, indicating a strong continuity in the TN, TP content, and N/P ratio.

3.2. Soil TN, TP Content, and N/P Spatial Distribution Characteristics. The soil TN and TP contents showed a downward trend from northeast to southwest of the typical mollic epipedon area in Northeast China, and the spatial change characteristics were apparent (Figure 3). High-value areas of soil TN and TP contents were distributed in the north region of the typical mollic epipedon area in Northeast China, that is, southeast of Nenjiang County, Wudalianchi City, and the Midwest of Bei'an City in Heilongjiang Province (Figure 3(a)). This area entails a transitional zone from Xiaoxing'anling Mountains to Songnen Plain, which formed as a result of soil erosion and sedimentation. Low-value areas of soil TN and TP contents were mainly distributed in the central and southern regions of the study area, that is, Changtu County and the northern part of Xifeng County, Jilin Changchun City, Siping City, Jiutai City, Dehui City, the northern part of Dongliao County, Gongzhuling City, and Lishu County, central and eastern Lishu County, central and western Yitong Manchu Autonomous County, western Yongji County, Nong'an County, Fuyu County, southern part of Yushu City, western part of Jilin City, and Jiaohe City (Figure 3(b)). The primary reason for the insufficient soil N and P content in these areas might be explained by the different crop plantations in this area, such as corn and soybeans, as these crops have low soil erosion resistance and are prone to soil erosion. Under the influence of soil TN and TP contents, the maximum soil N/P ratio appeared in the central region of the research area with a low and intermediate-high spatial variation on both sides (Figure 3(c)). The region's ecological environment was relatively fragile, unstable with environmental problems, such as agricultural production and agricultural nonpoint source pollution.

3.3. Soil TN, TP Content, and N/P under Different Land Use Patterns. TN and TP contents and N/P ratio were significantly different under different land use patterns (Figure 4). The average soil TN and TP contents were in the following order: forest land > maize land > rice land and rice land > maize land > forest land, which was affected by the soil TN and TP contents. The soil N/P ratio average in the basin was in the following order: forest land > cornfield > rice land. The TN content of woodland soil was significantly higher than that in maize land and rice land. It was correlated to the relatively closed environment and less interference from human activities at forest land sampling sites and the long-term effects of forest vegetation containing deciduous leaves and microorganisms. The TP content of rice land soil was significantly higher than that of cornfield and forest land, which was correlated to the application of phosphate fertilizer in rice land. Rice land was relatively flat, with higher TP content. In addition, rice land was flooded for a long time with a high environmental pH, conducive to P adsorption and fixation.

4. Discussion

4.1. Chemical Metrological Characteristics of Soil Nitrogen and Phosphorus. The soil TN, TP content, and N/P ratio in the study area showed a step-like change trend from south to north in space. The changes of soil TN, TP content, and N/P ratio were small in the east-west direction, which was closely related to the gentle topographic changes in the east-west direction. The high-value areas of soil TN content were distributed in the transition zone from the higher altitude forest land to the plain farming area. The high-value area of soil TP content mainly occurs in the eastern mountainous area and the western river confluence area, which is mainly caused by soil erosion and sedimentation, which is similar to the research results in the typical black soil area and the Dadong River Basin of Dianchi Lake [5, 18, 19]. Previous studies have shown that the primary source of soil N is through biological N fixation, rainfall, irrigation, and the application of their fertilizers, and the forms of soil N are affected by the processes such as mineralization and fixation, nitrification, and denitrification [5]. Soil P is primarily derived from soil parent, fertilization, and surface crops. Besides, the accumulation and transformation of P are identical under microbial decomposition [20, 21]. The overall average TN and TP contents in typical mollic

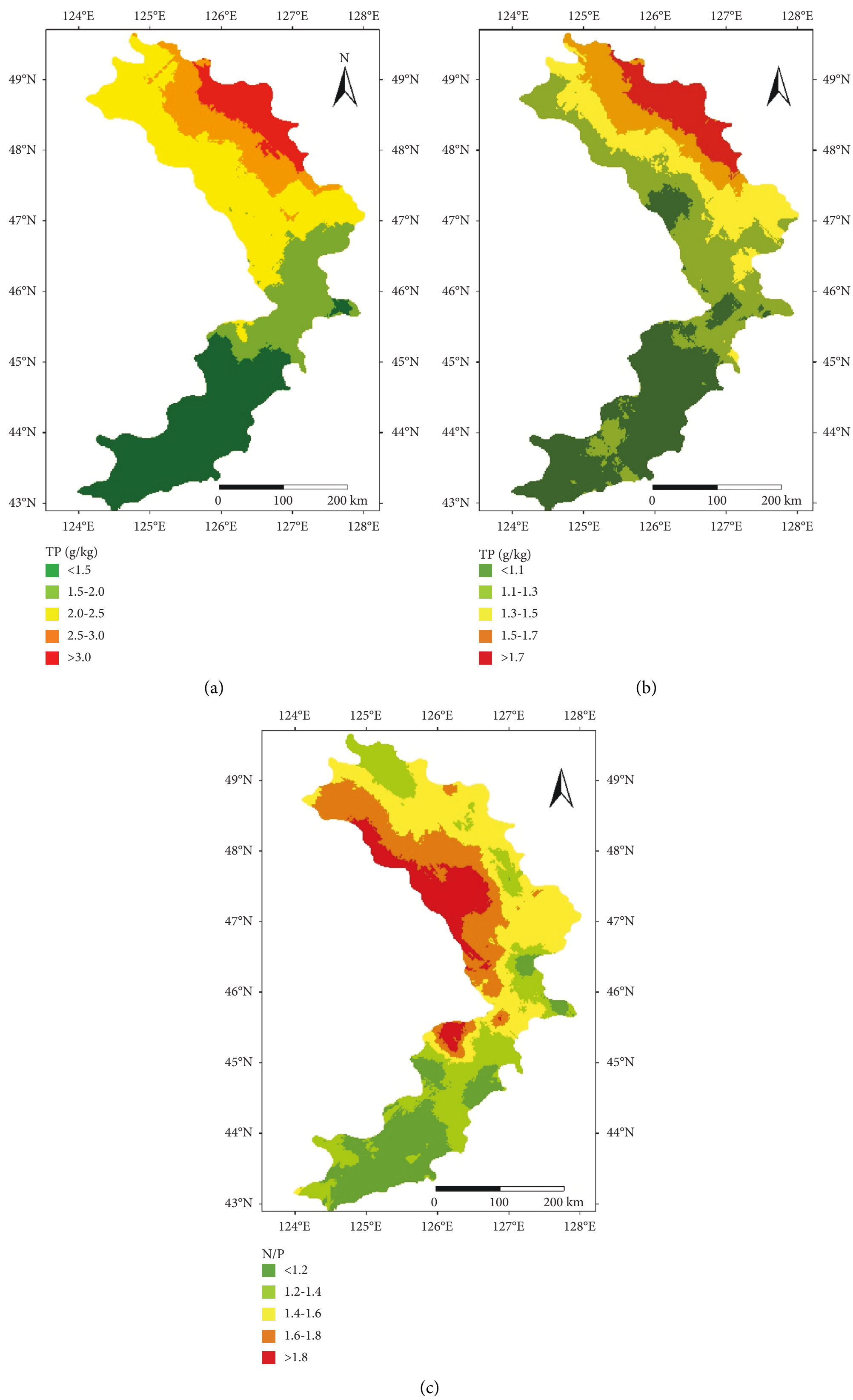

Figure 3: Soil TN, TP content, and spatial distribution of N/P (a). TN content; (b). TP content; and (c). N/P ratio.

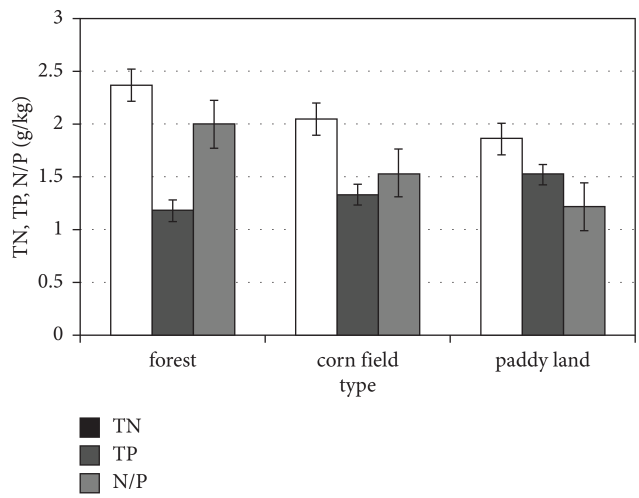

Figure 4: Comparative analysis of soil TN, TP content, and N/P in different land-use types.

epipedon areas in Northeast China were found to be 1.91 g/kg and 1.28 g/kg, respectively, higher than the average TN and TP content in China [22]. This is mainly because farmers in this area have increased the amount of chemical fertilizers to increase production. However, it still varied between different regions. The soil TN and TP contents in the study area showed a decreasing trend in space from the northeast to the southwest region of the typical mollic epipedon area in Northeast China. We observed that the correlation between soil TN and TP was the primary reason for the consistency in the spatial distribution due to differences in different sampling points [23]. The soil TN and TP contents were localized, and the study area showed a strong variability. It should be pointed out that the parameters and accuracy of the models used in this study may also have a certain impact on the final results. However, geostatistical analysis is a method commonly used by scholars, and the calculation results of the model after accuracy evaluation have reference value [24]. The N/P ratio in the study area was lower than the average value of soil N/P in China (4.2), indicating that the soil in the study area was in a nitrogen-limited state. This study can provide a theoretical and technical basis for the improvement of arable land productivity, the management of fertilization process, and the sustainable development of agricultural production in mollic epipedon areas. It should be pointed out here that the data sampling point will also have a certain influence on the spatial analysis results; so in future work, the grid sampling method can be used to further improve the analysis accuracy.

4.2. Factors Influencing the Chemical Metrological Characteristics of Soil Nitrogen and Phosphorus. Soil ecological stoichiometry characteristics are comprehensively regulated by natural environmental factors, such as regional hydrothermal conditions, weathering of soil parent, farming, and fertilization. Different land use intensities significantly impact soil N and P reserves and circulation processes [25]. Land use alters soil nutrients near farmland and affects plants closely related to the soil [26, 27]. The soil TN and TP contents in the northeast dry-cropping area decreased with the increasing crop productivity, in line with the study by Zhang et al. [28] and others on the altered characteristics of TN and TP contents in farmland under different land-use methods. N fertilizer application is high, and organic matter accumulation is low in high N and high-yield fertilization strategies. The high degree of agricultural mechanization in high-yielding areas and high-intensity farming adversely affected the soil surface structures, making soil N and P vulnerable to lose and leakage with surface runoff [29]. As a result, regional soil TP content and N/P were found to be higher in low fertilization areas and low-yielding areas, which were primarily correlated to climatic conditions and soil mother-mass weathering. This sample survey showed that the dry farming area of Heilongjiang Province is mainly suitable for maize-soya bean rotation, while the dry farming area of Jilin Province and Liaoning Province is suitable for continuous maize cropping.

Long-term application of nitrogen fertilizer or nitrogen-phosphorus-potassium fertilizer can significantly increase the content of nitrate nitrogen and ammonium nitrogen in the soil, but the effect on soil organic nitrogen content is small. The application of organic fertilizer can directly increase the amount of soil organic nitrogen. In addition, the application of organic fertilizers to the soil can increase the organic matter content of the soil, and the organic matter can reduce the fixation of inorganic phosphorus and promote the dissolution of inorganic phosphorus. Therefore, this method can effectively improve soil productivity.

In this study, we observed that different land-use methods affected nutrient content; however, the upper soil layer significantly impacted the soil nutrient content. It varied with land use patterns and was related to regular farming activities and high organic fertilizer application or fertilizer inputs. This, in turn, was correlated to recurrent farming activities and a high amount of organic fertilizer or fertilizer inputs on the soil surface [30, 31]. Therefore, the difference in regional planting patterns also impacts the spatial distribution characteristics of soil N and P ecological stoichiometry, and it demands in-depth analysis.

5. Conclusion

The soil TN, TP content, and N/P ratio in the typical mollic epipedon area in Northeast China ranged from 0.89 to 5.93 g/kg, 0.54 to 3.77 g/kg, and 0.47 to 3.21 and a mean of 1.91 g/kg, 1.28 g/kg, and 1.51, respectively, with spatial variation. The degree of difference was medium. Structural factors, such as topography, climatic conditions, and parent soil formation, affected soil TN, TP content, and N/P ratio spatial variation in the basin.

Soil TN and TP contents showed a gradually decreasing trend in space from northeast to southwest, which was highly in line with the topographic changes in the research area. In the middle of the study area, we observed a high N/P value. The N/P value in the study area showed a low-edge and intermediate-high spatial variation. The study of poor ecological environment stability in the region is the key protection area for agricultural production fertilization management and nonpoint source pollution prevention and control. The soil TN, TP content, and N/P vary remarkably based on the land use method. The average value of soil TN and N/P forest land was higher than that of maize land and rice land. Besides, the average value of TN and TP contents in the soil of rice land was higher than that of maize land and forest land, and the total N/P of cultivated land was low.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interests.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (NO. 41871022).

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