Postprint: Soil Ecological Stoichiometric Characteristics of Different Tree Species Plantations in Subarctic Desert Steppe

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Abstract

To elucidate the differences in soil nutrient content and ecological stoichiometric characteristics among different tree species plantations in subarctic desert steppe, we analyzed plantations of three tree species (Betula platyphylla, Pinus sylvestris var. mongolica, and Acer negundo) with an 11-year stand age in Nur-Sultan, Kazakhstan, using a combination of field investigation and laboratory analysis, with bare land as the control. The results showed that: (1) Soil nutrient content was affected by tree species, but the differences in ecological stoichiometric characteristics among different tree species were not significant. (2) After plantation establishment, soil organic carbon and total nitrogen contents in plantations of different tree species increased significantly, and there were significant differences in surface soil organic C and total N contents between coniferous and broadleaf forests. (3) Soil C, N, and P contents showed highly significant positive correlations; C content was the controlling factor for C:N and C:P, while N content was the controlling factor for N:P. Although soil nutrient content increased significantly after plantation establishment in the study area, the overall content was still lower than the global average, and local soil nutrients remained in a state of deficiency. N is the limiting factor for nutrient cycling and plant growth in this region; appropriate application of nitrogen fertilizer during plantation growth can accelerate plantation growth and ecological restoration processes. This study can provide a scientific basis for the construction and sustainable management of plantations in Nur-Sultan, the capital of Kazakhstan.

Full Text

Abstract

To elucidate the differences in soil nutrient content and ecological stoichiometric characteristics among different tree species plantations in sub-frigid desert steppe, we analyzed soil nutrients and their ecological stoichiometry in three different tree species plantations in Nur Sultan, the capital of Kazakhstan. White birch (*Betula platyphylla*), Mongolian pine (*Pinus sylvestris* var. *mongolica*), and boxelder maple (*Acer negundo*) plantations with consistent stand age were selected as study objects, with bare land as the control. The results showed that: (1) After plantation establishment, soil organic carbon and total nitrogen contents increased significantly across all tree species, with significant differences in surface soil organic carbon and total nitrogen between coniferous and broad-leaved forests. (2) Soil nutrient content was affected by tree species, but ecological stoichiometric characteristics did not differ significantly among species. (3) Soil C, N, and P contents showed extremely significant positive correlations, with C content being the controlling factor for C:N and C:P ratios, and N content controlling the N:P ratio. Although soil nutrient content increased significantly after plantation establishment, the overall levels remained below global averages, indicating that local soil nutrients are still deficient. Nitrogen is the limiting factor for nutrient cycling and plant growth in this region, and appropriate nitrogen fertilization during plantation growth could accelerate forest growth and ecological restoration. This study provides a scientific basis for the construction and sustainable management of plantations in Nur Sultan, Kazakhstan.

Keywords: soil; desert steppe; ecological stoichiometry; soil nutrients; Kazakhstan

Introduction

Soil is a crucial component of ecosystems and the primary source of nutrients required for plant growth. Carbon (C), nitrogen (N), and phosphorus (P), as major elements needed for plant development, are important indicators in soil quality assessment. Their contents and dynamic equilibrium are primarily influenced by climate, topography, vegetation, soil parent material, soil fauna, and microorganisms, directly affecting litter decomposition rates and plant growth, thereby influencing ecosystem productivity. Ecological stoichiometry is the science that studies the balance of energy and chemical elements in ecosystems. In recent years, this emerging discipline has developed rapidly in China, focusing mainly on regional C:N:P ecological stoichiometric characteristics and their driving factors in forest and grassland ecosystems. Investigating soil ecological stoichiometry in forest ecosystems is essential for understanding soil element cycling processes, nutrient limitation relationships, and achieving forest ecological service functions and sustainable management.

Different plant types exhibit varying absorption and utilization efficiencies of soil elements, leading to differences in soil ecological stoichiometric characteristics. For instance, research in southwest China karst peak-cluster depressions found significant differences in soil C:N:P ratios among different forest types. Studies in the Ziwuling Forest Area of Shaanxi Province showed that tree species primarily affected soil C and N contents, with pine forest soil C and N contents significantly lower than those of *Quercus liaotungensis*, while species had no significant effect on soil P content. Climate types alter soil ecological stoichiometric characteristics by changing regional hydrothermal conditions. At large scales, plant leaf C:N ratios increase significantly with increasing latitude, while N:P ratios decrease. Soil C:N:P ratios in Guangxi karst ecosystems under different vegetation types are significantly higher than those in the Loess Plateau. Research indicates that soil N and P contents are higher in hot and humid regions, but soil P is lost due to leaching. Thus, different plantation ecosystems in different regions and climate types show significant differences in soil element contents and ecological stoichiometric characteristics, arising from regional climate, vegetation biological characteristics, and plantation management practices. Studying ecological stoichiometric characteristics can reveal nutrient limitation and cycling processes during plantation growth, making it crucial to conduct soil ecological stoichiometric research in specific regions and ecosystems.

Kazakhstan is located in the hinterland of the Eurasian continent. Its capital, Nur Sultan, lies in the desert steppe zone of north-central Kazakhstan and serves as the national railway transportation hub and major industrial and agricultural production base. The area has a typical continental climate with dry, hot summers and long, cold winters with frequent strong winds. This harsh climate creates significant challenges for residents' production, life, and ecological construction, affecting not only Nur Sultan' s economic and social development but also severely reducing its attractiveness as a capital city. Since 2005, the Kazakh government launched the Green Belt Project, and through 15 years of effort, established 66,700 hectares of plantations around the capital, playing an important role in improving the ecological environment. However, afforestation in high-altitude cold regions faces challenges such as harsh natural environments, slow plant growth, and low ecological stability. Currently, research on soil C, N, P pools and ecological stoichiometric characteristics of local plantations is limited, and understanding of soil quality changes during plantation construction is insufficient, hindering subsequent plantation development and scientific management. Therefore, this study selected plantations in the outskirts of Nur Sultan as research objects, using non-afforested bare land as a control, to analyze soil C:N:P ecological stoichiometric characteristics under different forest types. The aim is to reveal the effects of different forest types on soil quality evolution and ecological stoichiometric characteristics, providing a scientific basis for plantation construction and sustainable management in Nur Sultan, Kazakhstan.

1.1 Study Area Overview

The study area is located in Nur Sultan, Kazakhstan (51.1°N, 71.5°E), in the sub-frigid desert steppe of northern Kazakhstan. The terrain is flat with an elevation of 349–442 m. The area experiences an extreme continental climate with cold winters and hot summers. Summer maximum temperatures reach 36 °C, while winter temperatures drop to -52 °C, with uneven annual distribution (spring and summer account for 60% of precipitation, autumn and winter account for 40%). Annual precipitation is approximately 300 mm. Strong southwest winds prevail year-round with frequent high-wind events, and sandstorms occur 20–30 days annually. The soil type is primarily chestnut soil, with some poor-quality soils containing gravel, alkalization, and calcareous properties. A hard, compact calcium carbonate horizon exists in the subsoil. The original vegetation consists mainly of grassland with sparse natural forests.

1.2 Soil Sample Collection

In July 2019, three plantations with consistent soil type and stand age were selected in the study area: white birch (*Betula platyphylla*) pure stand, Mongolian pine (*Pinus sylvestris* var. *mongolica*) pure stand, and boxelder maple (*Acer negundo*) pure stand, with typical bare land outside the forest as the control (Table 1). Within each plantation, five 20 m × 20 m sample plots were randomly established. Five points were selected in each plot to dig soil profiles. After removing surface litter, soil samples were collected by depth layers (0–20 cm, 20–40 cm, and 40–60 cm). Soils from the same depth at different points within a plot were mixed, and the quartering method was used to obtain approximately 1 kg of soil, which was placed in ziplock bags. Ring knife samples were also collected to determine soil bulk density. A total of 60 soil samples were collected and brought back to the laboratory, with plot locations, topography, and vegetation growth conditions recorded. Soil samples were air-dried under natural conditions, then litter, plant roots, gravel, and other debris were removed before grinding and passing through a 0.149 mm sieve for laboratory analysis of soil organic carbon, total nitrogen, total phosphorus, and total potassium contents.

1.3 Measurement Items and Methods

Soil organic carbon (SOC) was measured using the potassium dichromate volumetric method with external heating. Total nitrogen (TN) was determined using the Kjeldahl method with a Foss Kjeltec 8400 automatic nitrogen analyzer. Total phosphorus (TP) was measured using perchloric acid-sulfuric acid digestion, followed by molybdenum-antimony anti-colorimetry with an Agilent CARY60 UV-Vis spectrophotometer. Total potassium (TK) was determined using acid dissolution and atomic absorption spectrometry with a Thermo Fisher atomic absorption spectrometer.

1.4 Data Processing

Excel 2010 was used for data organization and statistical analysis. One-way ANOVA was used to test the effects of forest type on soil C, N, P, K contents and ecological stoichiometric characteristics. Differences among forest types were compared using Duncan' s multiple range test. Pearson correlation analysis was used to examine relationships between soil nutrient contents and their ecological stoichiometric characteristics. Origin 2018 was used for data visualization.

2 Results and Analysis

2.1 Soil C, N, P, K Contents

As shown in Figure 1, soil organic carbon and total nitrogen contents in the 0-20 cm layer of boxelder maple plantation were significantly higher than those in Mongolian pine plantation and the control (bare land). Compared with bare land, organic carbon and total nitrogen in white birch plantation increased by 78.6% and 59.3%, respectively; in Mongolian pine plantation by 52.8% and 38.4%; and in boxelder maple plantation by 97.3% and 88.4%. Except for the significantly higher total phosphorus content in white birch, differences in organic carbon and total nitrogen contents among tree species were not significant. Soil nutrient contents in the study area showed a decreasing trend with soil depth. Surface soil total phosphorus contents did not differ significantly among the three tree species, while white birch total phosphorus was significantly higher than Mongolian pine and boxelder maple. Total potassium content did not change significantly along the vertical gradient. In the 20-40 cm layer, differences in soil organic carbon and total nitrogen among tree species were not significant. In the 40-60 cm layer, except for significantly higher total phosphorus in white birch, differences in soil organic carbon, total nitrogen, and total phosphorus among tree species were not significant. Overall, plantation establishment significantly improved soil nutrient contents compared with bare land.

2.2 Soil Ecological Stoichiometry Characteristics

As shown in Table 2, surface soil C:N ratios among different tree species ranged from 10.22 to 13.5, with no significant differences among plantations but all significantly higher than bare land. In the 20-60 cm layer, C:N ratios ranged from 12.88 to 49.81, all higher than the control, with no significant differences among plantations. Surface soil C:P ratios ranged from 33.3 to 49.81, significantly higher than bare land, with white birch and boxelder maple significantly higher than Mongolian pine. In the 20-40 cm layer, C:P ratios ranged from 15.86 to 36.36, with no significant differences among species but all significantly higher than the control. In the 40-60 cm layer, C:P ratios ranged from 12.88 to 20.78, with no significant differences among species. Surface soil N:P ratios ranged from 2.75 to 3.72, with no significant differences among species but all significantly higher than bare land. In the 20-40 cm layer, N:P ratios ranged from 1.39

to 3.05, with no significant differences among species. In the 40-60 cm layer, N:P ratios ranged from 1.3 to 1.72, with no significant differences among species. Overall, soil C:N, C:P, and N:P ratios showed significant decreasing trends with soil depth ($P < 0.05$), while no significant differences existed among different depth layers within the same species.

Correlation analysis (Table 3) showed extremely significant positive correlations between organic carbon and total nitrogen contents and C:N:P stoichiometric characteristics ($P < 0.01$). Total nitrogen was extremely significantly positively correlated with organic carbon and C:N:P stoichiometric characteristics ($P < 0.01$). Total phosphorus was extremely significantly positively correlated with organic carbon and total nitrogen ($P < 0.01$). Total potassium was significantly correlated with organic carbon and total nitrogen ($P < 0.01$), and extremely significantly correlated with total phosphorus ($P < 0.01$).

3 Discussion

3.1 Effects of Different Tree Species on Soil C, N, P, K Contents

Soil organic carbon and total nitrogen contents are primary indicators of soil fertility. In the 0-20 cm layer, soil organic carbon and total nitrogen differed significantly among plantations, with broad-leaved forest (white birch) significantly higher than coniferous forest (Mongolian pine), consistent with previous research. This may result from differences in litter quantity and chemical composition. Different tree species produce varying amounts of above- and below-ground litter, affecting soil organic carbon and nitrogen accumulation. Soil organic carbon and nitrogen mainly originate from the transformation and accumulation of surface litter and animal residues, with most soil microbial biomass concentrated in the surface layer, resulting in highest organic matter and total nitrogen contents in surface soil. Deep soil nutrients mainly result from leaching and diffusion migration, showing large spatial variation along the vertical scale. Soil total phosphorus is derived from rock weathering and parent material through a long, stable process less affected by external factors. The lack of significant differences in total phosphorus among plantations suggests similar parent materials across sample plots.

In this study, soil C:N ratios (10.22-13.5) were significantly lower than the global average of 14.3, indicating relatively deficient soil nutrients. Surface soil organic carbon and total nitrogen in different plantations were significantly higher than in bare land, demonstrating that plantations in Nur Sultan effectively improve local soil nutrient content. This occurs because plantations reduce wind erosion, improve water retention, and promote litter accumulation and decomposition while enhancing understory herbaceous diversity, thereby increasing soil organic carbon and total nitrogen contents.

3.2 The Role of Soil Ecological Stoichiometry in Characterizing Soil Quality and Nutrient Limitation

Ecological stoichiometric ratios serve as important indicators for evaluating soil organic matter composition, quality status, and nutrient supply capacity. The C:N ratio is a sensitive indicator of soil quality that measures soil carbon and nitrogen balance, affecting mineralization and immobilization processes. Except for white birch surface soil, C:N ratios in other plantations showed no significant differences but were all higher than bare land. After afforestation, vegetation growth and litter transformation increased organic carbon and total nitrogen contents, with organic carbon increasing more than total nitrogen, resulting in C:N ratios greater than the control. The relatively stable C:N ratios across different tree species and soil layers indicate that soil ecological stoichiometry is primarily controlled by organic carbon and total nitrogen contents, reflecting the intrinsic nutrient balance mechanism and dominating soil nutrient cycling.

The C:P ratio can reflect soil organic matter decomposition rates. Research shows that increased decomposition rates enhance nitrogen availability, while C:P ratios determine microbial decomposition rates. When soil C:P ratios exceed 300, organic matter decomposition is slow; when below 200, decomposition is faster. The study area' s soil C:P ratios (10.22–13.5) indicate rapid organic matter decomposition, favoring nitrogen availability improvement. The N:P ratio can measure soil phosphorus release potential and indicate phosphorus availability. Lower N:P ratios represent higher phosphorus availability. When N:P ratios are below 10, soil microbial carbon content increases and microbial phosphorus undergoes net mineralization. The study area' s soil N:P ratios (1.3-3.69) are not only lower than the global soil average of 5.9 but also lower than the global forest soil average of 12.5, indicating high phosphorus availability. However, as vegetation increases, soil organic carbon content continuously rises, gradually increasing N:P ratios and reducing phosphorus availability. Although phosphorus availability may be low, it may not become a limiting factor for plantation growth during vegetation restoration. Correlation analysis also shows that soil N:P ratios are extremely significantly positively correlated with soil organic carbon content ($P < 0.01$), indicating that N:P ratios are primarily controlled by organic carbon content.

3.3 Correlation Analysis Between Soil Nutrients and Ecological Stoichiometry Characteristics in Nur Sultan Plantations

Correlation analysis shows extremely significant positive correlations between soil organic carbon, total nitrogen, and total phosphorus contents ($P < 0.01$), indicating that nitrogen and phosphorus are the main limiting factors for plantation growth in Nur Sultan. Total potassium is not significantly correlated with organic carbon and total nitrogen but is extremely significantly correlated with total phosphorus ($P < 0.01$), suggesting that potassium deficiency is an important factor affecting nutrient cycling. The lack of significant correlation between total potassium and C:N:P stoichiometric characteristics occurs because potassium is not a structural component of organic matter, and its cycle differs from that of carbon, nitrogen, and phosphorus. These results indicate that nitrogen deficiency is the primary factor constraining local plantation growth, consistent with research results from the Loess Plateau.

4 Conclusion

By analyzing the physicochemical properties and ecological stoichiometric characteristics of soils in three different tree species plantations in Nur Sultan and their interrelationships, we conclude: (1) Surface soil nutrient contents are significantly affected by vegetation type, with significant differences in surface soil organic carbon and total nitrogen between coniferous and broad-leaved forests. (2) Ecological stoichiometric characteristics do not differ significantly among tree species. (3) Soil nutrient contents and ecological stoichiometric characteristics in Nur Sultan plantations are lower than global averages, indicating that local soil nutrients remain deficient. (4) Correlation analysis shows that nitrogen is the main limiting factor for plantation growth, and potassium deficiency is an important factor affecting nutrient cycling in Nur Sultan plantations. We recommend appropriate nitrogen fertilization during plantation growth to improve soil fertility and accelerate plantation growth and ecological restoration.

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