Soil Nutrient Characteristics 38 Years After the Establishment of the Jilantai Salt Lake Shelterbelt System: Postprint

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Abstract

To scientifically evaluate the effects of the Jilantai Salt Lake protection system on soil nutrient accumulation, different protection system types (mobile sand fixation belt, sand enclosure and grass cultivation belt, windbreak and sand barrier belt, and salt lake shelterbelt) served as study objects. Using a combination of field sampling and laboratory experiments, soil nutrient accumulation was comparatively studied to provide a theoretical basis for management of the Jilantai Salt Lake shelterbelt. Results showed that: (1) The increases in soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), alkali-hydrolyzable nitrogen (AN), and available phosphorus (AP) contents ranged between 0.45~1.92 $g \cdot kg^{-1}$, 0.03~0.58 $g \cdot kg^{-1}$, 0.15~0.43 $g \cdot kg^{-1}$, 1.33~13.31 $mg \cdot kg^{-1}$, and 0.12~12.94 $mg \cdot kg^{-1}$, respectively, with soil depth, protection system type, and their interaction exerting significant effects on the increases in soil SOC, TN, TP, and AP contents. (2) Construction of the salt lake protection system had significant positive effects on soil nutrients in the 0~100 cm soil layer, and soil depth, protection system type, and their interaction significantly affected the relative interaction intensity of soil TP (RIITP), AN (RIIAN), AP (RIIAP), and total relative interaction intensity (RII_{total}). (3) Soil nutrient recovery indices revealed that soil nutrients in different protection system types showed varying degrees of improvement, with values of 7.83%, 37.72%, 185.12%, and 252.36% for the mobile sand fixation belt, sand enclosure and grass cultivation belt, windbreak and sand barrier belt, and salt lake shelterbelt, respectively. The Jilantai Salt Lake protection system, following 38 years of establishment, effectively promotes soil nutrient accumulation, thereby facilitating ecological restoration and reconstruction in the surrounding area.

Full Text

Abstract

This study was conducted to scientifically evaluate the effects of the Jilantai Salt Lake protection system on soil nutrient accumulation. Using a combination of field sampling and laboratory analysis, we compared soil nutrient accumulation across different protection system types (shifting sand fixation zone, sand enclosure for grass recovery zone, windbreak and sand barrier zone, and salt lake shelter forest zone) within the Jilantai Salt Lake protection system, providing a theoretical basis for management of the shelter forest. The results showed that: (1) Increases in soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), available nitrogen (AN), and available phosphorus (AP) ranged from 0.45–1.92 $g \cdot kg^{-1}$, 0.03–0.58 $g \cdot kg^{-1}$, 0.15–0.43 $g \cdot kg^{-1}$, 1.33–13.31 $mg \cdot kg^{-1}$, and 0.12–12.94 $mg \cdot kg^{-1}$, respectively. Soil depth, protection system type, and their interaction had significant effects on soil nutrient content increases. (2) Construction of the salt lake protection system had significant positive effects on soil nutrients in the 0–100 cm soil layer, with soil depth, protection system type, and their interaction significantly affecting total relative interaction intensity (RII). (3) The soil nutrient recovery index indicated that soil nutrients in different protection system types improved to varying degrees, with recovery indices of 7.83%, 37.72%, 185.12%, and 252.36% for the shifting sand fixation zone, sand enclosure for grass recovery zone, windbreak and sand barrier zone, and salt lake shelter forest zone, respectively. The Jilantai Salt Lake protection system, after 38 years of construction, can effectively promote soil nutrient accumulation, which is beneficial for ecological restoration and reconstruction around Jilantai Salt Lake.

Keywords: vegetation restoration; nutrient accumulation; relative interaction intensity; protection system type; salt lake protection system

Introduction

Establishing artificial shelter forests is the most important means of combating desertification. Artificial protection systems play a crucial role in soil formation processes. Soil provides the material basis for vegetation growth, while vegetation development in turn affects the soil environment. Soil nutrients, as important indicators reflecting soil characteristics, play a dominant role in organic matter decomposition and transformation, influencing material cycling and energy flow in ecosystems. Soil nutrient status varies significantly depending on climate type, vegetation type, hydrology, and soil type. Therefore, accurately understanding soil nutrient status and its change patterns in shelter forests is essential for achieving ecological restoration and sustainable soil resource utilization in desert regions.

In sandy areas, construction of artificial shelter forests has significantly improved aeolian sandy soil quality, gradually developing into fixed sandy soil, which fully demonstrates the stabilizing capacity of shelter forests. Studies have shown that after establishing *Pinus sylvestris* var. *mongolica* plantations on sandy grasslands, soil nitrogen fixation capacity can be effectively improved. Research on *Pinus massoniana* plantations indicates that in the early stages of establishment, soil organic carbon and total phosphorus contents increase significantly. Studies on the Ulan Buh Desert protection system show that *Caragana korshinskii*, *Salix matsudana*, and *Populus popularis* have good soil improvement effects, while *Hedysarum laeve* and fast-growing poplar have poorer effects. Research on the Huangyangtan sandy land protection system shows that after shelter forest construction, soil nutrients improved substantially, with an average increase of 203.65%. This demonstrates that shelter forest construction can effectively improve grassland desertification conditions. However, different shelter forest types show varying effects on soil improvement.

The Jilantai Salt Lake protection system is located north of Jilantai Salt Lake. Since 1985, a comprehensive three-dimensional protection system has been formed from north to south, consisting of four integrated zones: shifting sand fixation zone, sand enclosure for grass recovery zone, windbreak and sand barrier zone, and salt lake shelter forest zone, stretching approximately 18 km from east to west. The protection system has played an important role in resisting external harsh wind-sand environments and providing ecological protection benefits. However, after 38 years of succession, how effective is the current salt lake protection system in soil nutrient accumulation? Based on this question, this study systematically investigated nutrient accumulation characteristics across different protection system types to deeply understand the effects of artificial vegetation establishment on soil nutrients, thereby providing a theoretical basis for soil conservation.

1.1 Study Area Overview

This study was conducted in the Jilantai Salt Lake protection system located in Alxa Left Banner, Inner Mongolia (105°42 –105°57 E, 39°45 –39°52 N). The area has a typical continental arid desert climate at an elevation of 960–1030 m. Annual precipitation is 113.6 mm, concentrated in July–September (accounting for 91.77% of total rainfall). Mean annual temperature is 8.6 °C, with annual potential evaporation of 3006 mm and annual sunshine duration of 3316 h. The multi-year average wind speed is 3.6 $m \cdot s^{-1}$, with maximum wind speed reaching 24.0 $m \cdot s^{-1}$. Strong winds are concentrated in spring, with 160 windy days annually, 91 sand-dust days, and a resultant sand transport direction of 180.44°. The main wind direction is northwest, with westerly winds prevailing throughout the year. The total drift potential is 97.26 VU. The study area has flat terrain without human disturbance. Soil types are saline-alkali soil and aeolian sandy soil, with loose surface soil, low soil development degree, and poor soil nutrients. Soil pH ranges from 8.51–9.08, indicating strong alkalinity.

1.2 Basic Conditions of the Protection System

The Jilantai Salt Lake protection system was constructed in 1985. During initial construction, comprehensive control techniques including biological and engineering measures were employed, following the principle of matching tree species to site conditions. The shelter forest configuration adopted patch and strip patterns, forming an organic combination of trees, shrubs, and grasses. After 38 years of construction and improvement, a salt lake protection system integrating the four zones has been formed (Table 1).

Shifting sand fixation zone: This is the first line of defense preventing salt lake invasion. Large moving sand dunes are distributed around the periphery of Jilantai Salt Lake, with dune heights of 2–8 m, mainly oriented northwest-southeast. To effectively prevent dune movement, straw checkerboard sand barriers were established in 1985 and 1995, with preservation rates of 92.30% and 73.21%, respectively.

Sand enclosure for grass recovery zone: In the semi-fixed and fixed dune areas adjacent to the moving dunes, large amounts of natural vegetation are distributed, including *Nitraria tangutorum*, *Artemisia desertorum*, *Sophora alopecuroides*, *Agriophyllum squarrosum*, and *Phragmites australis*. Among these, *Nitraria tangutorum* shrub communities in inter-dune lowlands form the main body of the sand enclosure for grass recovery zone, which can reduce near-surface wind speed, increase surface roughness, and effectively block surface wind-sand flow.

Windbreak and sand barrier zone: To improve windbreak effectiveness, this transitional zone lies behind the sand enclosure for grass recovery zone and before the salt lake shelter forest zone. Large numbers of *Populus tomentosa* were planted to form a field-network shelter forest belt, with outer zones sequentially planted with *Populus alba* var. *pyramidalis*, *Elaeagnus angustifolia*, and *Hedysarum scoparium* shelter forest belts.

Salt lake shelter forest zone: The salt lake shelter forest network mainly comprises artificially planted *Elaeagnus angustifolia*, *Hedysarum scoparium*, *Tamarix chinensis*, *Haloxylon ammodendron*, and *Calligonum mongolicum*. The forest interior is dominated by *Sophora alopecuroides* and *Phragmites australis*, along with Poaceae weeds, while *Elaeagnus angustifolia* is mainly planted in inter-dune lowlands. The purpose is to intercept partially suspended dust while preventing sand initiation around the salt lake.

1.3 Experimental Design and Methods

In late August 2022, experimental plots were established in the field. Five sample belts were laid out along the northwest-southeast direction, with each belt spaced 500 m apart. The belts started at the shifting sand fixation zone and ended at the salt lake shelter forest zone. The four protection system types served as four experimental treatments, with two sample plots established on each side of each protection system type as controls (comparative method design, Fig. 1). Specifically, 10 m × 10 m plots were established in the shifting sand fixation zone, 10 m × 10 m plots in the sand enclosure for grass recovery zone, 20 m × 20 m plots in the windbreak and sand barrier zone, and 20 m × 20 m plots in the salt lake shelter forest zone. As control plots, corresponding 10 m × 10 m or 20 m × 20 m plots were established in each protection system type, totaling 40 plots.

Late August is the peak vegetation growth period. Based on vegetation surveys, soil samples were collected using an "S" shaped sampling method from soil layers at depths of 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm within each protection system type. Each plot had five replicates, and soil from the same layer at five sampling points was uniformly mixed and placed in numbered plastic bags.

After air-drying in the laboratory, plant and animal residues were removed, and soil samples were reduced using the quartering method and sieved for determination of soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), available nitrogen (AN), and available phosphorus (AP) following conventional methods in *Soil Agrochemical Analysis*.

1.4 Calculation Methods

1.4.1 Soil Nutrient Accumulation Calculation Relative Interaction Intensity (RII) was used to represent the effect of vegetation on soil nutrients within different protection system types, with values between −1 and 1. Positive values indicate that the salt lake protection system has an increasing effect on nutrient content, while negative values indicate a decreasing effect. The farther the value is from 0, the stronger the effect. The calculation is as follows:

$$RII = \frac{X_n - X_i}{X_n + X_i}$$

where X_n and X_i represent soil nutrient values at different soil depths within protection system types and corresponding controls, respectively. In this study, soil nutrient content includes SOC, TN, TP, AN, and AP.

1.4.2 Soil Nutrient Recovery Status Calculation The Nutrient Recovery Index (NRI) was used to quantitatively describe the degree of influence of vegetation restoration on soil nutrients by calculating differences between soil in different protection system types and control plots, then averaging and summing these differences:

$$NRI = \frac{1}{n} \sum_{i=1}^{n} \frac{X_i - X_i'}{X_i'} \times 100\%$$

where NRI is the soil nutrient recovery index, X_i is the soil nutrient value of the ith soil layer within the protection system type, X_i' is the soil nutrient value of the ith soil layer in the control plot, and n is the number of soil layers.

Experimental data were pre-processed, and Excel 2013 was used for plotting. SPSS 22.00 was used for two-way ANOVA, and Origin 2021 was used for one-way ANOVA.

2 Results and Analysis

2.1 Soil Nutrient Content in Different Protection System Types

The increases in soil SOC, TN, TP, AN, and AP contents ranged from 0.45–1.92 $g \cdot kg^{-1}$, 0.03–0.58 $g \cdot kg^{-1}$, 0.15–0.43 $g \cdot kg^{-1}$, 1.33–13.31 $mg \cdot kg^{-1}$, and 0.12–12.94 $mg \cdot kg^{-1}$, respectively. Soil nutrient increases showed the pattern: salt lake shelter forest zone > windbreak and sand barrier zone > sand enclosure for grass recovery zone > shifting sand fixation zone, indicating that soil nutrient increases gradually rose from the outer to inner parts of the Jilantai Salt Lake protection system.

Two-way interaction analysis showed that protection system type, soil depth, and their interaction had significant effects on soil SOC, TN, TP, and AP content increases. Soil depth had significant effects on soil AN content increase, while protection system type and the interaction of protection system type × soil depth had no significant effect on AN.

Soil nutrient increases gradually decreased with soil depth across all protection system types. In the 0–20 cm soil layer, increases ranged from 77.31%–209.83%; in the 20–40 cm layer, 39.16%–166.20%; in the 40–60 cm layer, 73.28%–156.30%; in the 60–80 cm layer, 448.19%–1517.01%; and in the 80–100 cm layer, 180.70%–741.10%, indicating obvious surface accumulation of soil nutrients.

2.2 Soil Nutrient Accumulation in the Salt Lake Protection System

The salt lake protection system types had significant positive effects on soil nutrients across different soil depths. Positive RII values ranged from 0.03–0.52 for SOC, 0.01–0.49 for TN, 0.01–0.34 for TP, 0.02–0.68 for AN, and 0.05–0.98 for AP. Overall, different protection system types had significant positive effects on soil nutrients, with total positive effects ranging from 0.10–0.53. This demonstrates that construction of the salt lake protection system is beneficial for soil nutrient accumulation. Except for the salt lake shelter forest zone, positive effects on soil nutrients in other protection system types gradually decreased with soil depth.

Two-way interaction analysis showed that protection system type, soil depth, and their interaction had significant effects on RIISOC, RIITN, RIITP, RIIAN, and RIIAP. Soil depth had significant effects on soil nutrient positive effects, but protection system types showed varying positive effects on soil nutrient content.

Compared with control plots at both ends of the salt lake protection system, soil nutrients in each protection system type improved to varying degrees. In the shifting sand fixation zone, the soil nutrient recovery index was only 7.83%, indicating that frequent wind-sand activities in this area were not conducive to soil nutrient accumulation. The sand enclosure for grass recovery zone, windbreak and sand barrier zone, and salt lake shelter forest zone were 4.8, 23.7, and 32.3 times higher than the shifting sand fixation zone, respectively.

Among different protection system types, the salt lake shelter forest zone had the greatest impact on soil nutrients, being most conducive to soil nutrient accumulation.

3 Discussion

Soil nutrients are important material sources for plant growth and development, and their increase rates are influenced by multiple natural factors such as forest type, density, and soil texture. In this study, the relatively small increases in soil nutrient content indicate that although the salt lake protection system construction improved soil nutrients, the increases were relatively small and soil nutrients remained poor. This is mainly because the study area has aeolian sandy soil with loose structure and poor water-holding capacity, which is not conducive to nutrient accumulation. Compared with the same study area, these results are significantly lower than those of Gao Junliang et al. and Huang Yaru et al. for the Ulan Buh Desert. This difference is mainly related to soil pH; the salt lake protection system is adjacent to Jilantai Salt Lake, with soil pH of 8.51–9.08, representing alkaline soil that is not conducive to nutrient accumulation.

The study found that soil nutrient increases were mainly affected by the dual factors of protection system type and soil depth. Soil nutrient increases gradually increased from the outer to inner parts of the salt lake protection system for three main reasons. First, during establishment of the salt lake protection system, vegetation coverage and biomass gradually increased with the recovery of artificial and natural vegetation, resulting in large amounts of surface litter retention. Combined with plant root exudates and surface microbial accumulation, this improved soil structure and water-holding capacity, increasing soil organic matter input. Second, due to the layered barrier effect of the salt lake protection system, wind speed gradually decreased while surface roughness increased, reducing wind erosion and allowing more fine particles to remain on the surface, improving soil physical properties and laying the foundation for organic matter accumulation. Third, vegetation intercepted wind-sand flow and dustfall, causing more fine particles to settle on the surface and further increasing surface soil organic matter content.

The study also found that soil nutrient increases gradually decreased with soil depth, indicating obvious surface accumulation of soil nutrients. This result is consistent with Huang Yaru et al.'s research on typical shrub soil nutrients in the Ulan Buh Desert. Because surface soil is rich in organic matter, loose, and well-aerated, providing good conditions for microbial activity, abundant microorganisms and high enzyme activity exist in the surface soil layer. Litter decomposed by microorganisms returns to the soil surface, and microorganisms can break down organic matter into various simple inorganic substances that can be directly absorbed and utilized by vegetation, resulting in surface soil nutrient enrichment.

This study found that construction of the salt lake protection system had significant positive effects on soil nutrients, consistent with Wang Bo et al.'s research on the Kubuqi Desert ecosystem. Artificial vegetation establishment can effectively promote vegetation recovery processes in ecosystems. In desert ecosystems, establishing artificial vegetation accelerates vegetation recovery, effectively increases regional vegetation coverage, and promotes soil nutrient accumulation, gradually driving desert ecosystems toward positive succession.

Two-factor analysis showed that soil depth had significant effects on soil nutrient positive effects, but protection system types showed varying positive effects on soil nutrient content. The main reasons are the same as for soil nutrient increases. Due to differences in vegetation type, coverage, and community composition structure under different protection system types (Table 1), soil nutrient accumulation rates were significantly affected, leading to significant differences in soil relative interaction intensity among protection system types. The study also found that soil SOC and TN interaction intensity was higher than other nutrients, mainly because SOC and TN have functional coupling. Soil humification, mineralization, and microbial activities gradually strengthened with vegetation growth and recovery in the salt lake protection system, leading to soil organic matter decomposition and release of more available nitrogen and phosphorus.

The soil nutrient recovery index is an important indicator characterizing the degree of restoration of degraded soil nutrients by vegetation measures. Analysis of soil nutrient recovery indices across different protection system types showed that indices ranged from 7.83% to 252.36%, indicating that engineering and biological measures can substantially accelerate soil nutrient recovery around Jilantai Salt Lake. Moreover, soil nutrient recovery indices gradually increased from the outer to inner protection system types. This is mainly because in the shifting sand fixation zone, large areas of straw checkerboard sand barriers and straw mat barriers effectively increased surface aerodynamic roughness and reduced surface wind speed for sand initiation, thereby controlling erosion of fine sand materials within the barriers. Additionally, the barriers reduced the sand-carrying capacity of passing wind-sand flow, causing fine sand materials to settle on the surface. Soil particles within the barriers became finer, laying a good foundation for soil nutrient accumulation and vegetation establishment.

In the sand enclosure for grass recovery zone, natural vegetation such as *Nitraria tangutorum*, *Phragmites australis*, and *Sophora alopecuroides* was dominant. Due to the slow natural vegetation recovery process, the effect of plants improving soil structure through root systems was weak. Moreover, vegetation biomass and coverage were low in this zone, resulting in limited litter input and very scarce organic matter input. In the windbreak and sand barrier zone and salt lake shelter forest zone, vegetation mainly consisted of artificially planted trees and shrubs with high biomass and coverage, providing high organic matter input and increasing soil nutrient content. Therefore, soil nutrient recovery indices gradually increased from the outer to inner zones.

4 Conclusion

1) Due to the strong alkalinity of soil in the salt lake protection system, soil nutrient increases were slow. Soil nutrient increases differed significantly among protection system types, with the salt lake shelter forest zone showing the highest increases. Protection system type and soil depth are important indicators affecting soil nutrient spatial distribution.

2) The salt lake protection system had positive effects on soil nutrient accumulation. Construction of the salt lake protection system had significant positive effects on soil nutrients in the 0–100 cm soil layer. Protection system type, soil depth, and their interaction significantly affected RIISOC, RIITN, RIITP, RIIAN, and RIIAP.

3) Construction of the salt lake protection system improved soil quality. Soil nutrient recovery indices for different protection system types were 7.83%, 37.72%, 185.12%, and 252.36%, respectively. The 38-year construction of the Jilantai Salt Lake protection system can effectively promote soil nutrient accumulation and accelerate soil nutrient restoration in the salt lake area.

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