Effects of Vegetation Restoration on Soil Ecological Stoichiometry in the Eastern Kubuqi Desert (Postprint)

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Abstract

To elucidate the effects of vegetation restoration on the ecological stoichiometric characteristics of aeolian sandy soils, this study investigated mobile sandy land, semi-fixed sandy land, Artemisia ordosica-fixed sandy land, and Salix psammophila-fixed sandy land in the eastern section of the Kubuqi Desert, analyzing the spatiotemporal variations and correlations of vegetation biomass and soil C, N, P stoichiometric characteristics across different soil depths (0–60 cm). The results showed that: (1) Soil C and N contents increased significantly with vegetation restoration, while the increase in soil P content was relatively small, with all reaching maximum values in Salix psammophila-fixed sandy land (5.86 $g \cdot kg^{-1}$, 0.41 $g \cdot kg^{-1}$, 1.74 $g \cdot kg^{-1}$). Soil C, N, and P contents at each stage gradually decreased with soil depth, with relatively small differences in soil P content among soil layers. (2) Soil stoichiometric ratios differed significantly among different stages or soil layers. With vegetation restoration, soil C:N first decreased and then increased, whereas both C:P and N:P increased gradually. Soil C:P and N:P both decreased gradually with soil depth, while C:N showed no obvious change pattern. (3) Soil C, N, and P were all extremely significantly positively correlated with each other, and all showed significant positive correlations with aboveground and litter biomass. Soil C:N was not significantly correlated with either C:P or N:P, whereas soil C:P was significantly positively correlated with N:P. Moreover, both soil C:P and N:P showed significant positive correlations with aboveground, belowground, and litter biomass. In summary, vegetation restoration through artificial planting can significantly affect soil C, N, P contents and stoichiometric characteristics, thereby effectively improving soil physicochemical properties and enhancing the C and N sequestration capacity of desert ecosystems.

Full Text

Effects of Vegetation Restoration on Soil Ecological Stoichiometry in the Eastern Kubuqi Desert

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Abstract

To elucidate the effects of vegetation restoration on the stoichiometric characteristics of aeolian sandy soils, we selected mobile sandy land, semi-fixed sandy land, Artemisia ordosica-fixed sandy land, and Salix psammophila-fixed sandy land in the eastern Kubuqi Desert as study sites. We analyzed temporal and spatial variations in vegetation biomass and soil carbon (C), nitrogen (N), and phosphorus (P) contents and their stoichiometric ratios across different soil depths (0–60 cm). The results revealed three key patterns. First, soil C and N contents increased significantly with vegetation restoration, whereas soil P content showed only a modest increase, with all three elements reaching maximum values in Salix-fixed sandy land ($5.86\ \mathrm{g\cdot kg^{-1}}$, $0.41\ \mathrm{g\cdot kg^{-1}}$, and $1.74\ \mathrm{g\cdot kg^{-1}}$, respectively). Soil C, N, and P contents all decreased with soil depth, though differences in P content across layers were relatively small. Second, soil stoichiometric ratios varied significantly among restoration stages and soil layers. The soil C:N ratio initially decreased then increased with vegetation restoration, while C:P and N:P ratios increased progressively. Both C:P and N:P ratios decreased with soil depth, whereas the C:N ratio showed no clear vertical pattern. Third, soil C, N, and P contents were significantly and positively correlated with aboveground and litter biomass. While soil C:N ratio was not significantly correlated with C:P or N:P ratios, the C:P ratio was positively correlated with N:P ratio. Furthermore, both C:P and N:P ratios exhibited significant positive correlations with aboveground, belowground, and litter biomass. In conclusion, artificial planting that promotes vegetation restoration can significantly influence soil C, N, and P contents and their stoichiometric characteristics, thereby effectively improving soil physicochemical properties and enhancing carbon and nitrogen sequestration capacity in desert ecosystems.

Keywords: Kubuqi Desert; vegetation restoration; biomass; soil; stoichiometric characteristics

1. Introduction

Carbon, nitrogen, and phosphorus constitute the primary elements of soil nutrients and plant nutrition, playing vital roles in regulating plant growth and nutrient cycling. Plants absorb nutrients from soil to support their development and return these elements to the soil through litter decomposition, creating a continuous cycle of material and elemental exchange among soil layers that maintains the functional integrity of ecosystems. Ecological stoichiometry, a crucial ecological discipline, examines ecosystem energy balance, multi-element equilibrium, and their interactions through the lens of elemental ratios (primarily C:N:P), offering novel perspectives for ecosystem conservation and restoration. Investigating the effects of vegetation restoration on soil C, N, and P contents and stoichiometry is therefore essential for understanding ecosystem restoration principles and evaluating plant-soil coupling relationships during recovery processes.

Current research on soil stoichiometry during ecosystem restoration has primarily focused on forests, grasslands, and wetlands, with study areas predominantly distributed in the Loess Plateau hilly regions and abandoned cropland-grassland transition zones. These studies have mainly explored how stoichiometric characteristics respond to climate change and environmental factors. As one of the countries most severely affected by desertification worldwide, China has approximately 24.48% of its territory affected by desertification. While some scholars have examined stoichiometric characteristics of different shrub and herb components and soils in desert ecosystems, comprehensive studies remain limited. For instance, research in the Horqin Sandy Land investigated soil stoichiometry under different stand ages of Mongolian pine, while studies in the Gurbantunggut Desert examined leaf and soil stoichiometric trends in herbaceous plants. The Kubuqi Desert, China’ s seventh largest desert, features a fragile ecological environment with severe soil wind erosion, making it a major sand source in northern China. Through decades of artificial planting efforts that have promoted vegetation restoration, this region represents a typical vulnerable ecosystem undergoing repair. Previous research in this area has concentrated on soil moisture, soil respiration, and biological soil crusts, yet studies on soil ecological stoichiometric characteristics across different restoration stages remain scarce. To address this knowledge gap, we selected mobile sandy land, semi-fixed sandy land, Artemisia ordosica-fixed sandy land, and Salix psammophila-fixed sandy land as study sites to analyze spatial variation patterns and correlations between vegetation biomass and soil C, N, and P contents and stoichiometric ratios at different soil depths. Our objectives were to clarify the effects of vegetation restoration, soil depth, and their interactions on soil ecological stoichiometry, accurately assess soil nutrient status at various restoration stages, reveal the successional processes of vegetation restoration on sandy land, and provide a theoretical basis for desertification control, ecosystem restoration, and vegetation management interventions in this region.

2. Materials and Methods

2.1 Study Area Overview The study area is located in Jungar Banner, Ordos City, Inner Mongolia, at the eastern edge of the Kubuqi Desert (110°48 30 E, 40°3 42 N; elevation 1100-1300 m). The region encompasses various desert landforms including mobile, semi-fixed, and fixed sandy lands. Characterized by a temperate continental climate, the area experiences dry conditions with large diurnal temperature variations. The mean annual temperature is 7.2°C, mean annual precipitation is 335.5 mm (concentrated in June–September), and mean annual evaporation reaches 2560.6 mm. Prevailing winds are southwesterly and northwesterly, with an average annual wind speed of 3.3 $\mathrm{m \cdot s^{-1}}$. The predominant soil type is aeolian sandy soil, and the main plant species include Salix cheilophila, Artemisia ordosica, Hedysarum mongolicum, and Caragana korshinskii.

2.2 Experimental Design Based on vegetation restoration degree, coverage, and constructive species, we established four plot types: (1) Mobile sandy land (MSL) comprised bare sand with severe wind erosion, sparse annual herbaceous vegetation, and minimal coverage; (2) Semi-fixed sandy land (SFSL) featured natural seeding of pioneer shrubs (Artemisia) and annual herbs with gradually weakening erosion; (3) Artemisia-fixed sandy land (AFSL) was established through aerial seeding in 2012, forming a fixed sandy land with Artemisia as the constructive species, increased vegetation coverage, and reduced wind erosion; and (4) Salix-fixed sandy land (SFSL2) was created through 2012 aerial seeding combined with 2013 row planting of Salix (3 m × 1 m spacing), ultimately forming a climax community dominated by Salix with a thick litter layer and essentially no wind erosion. Both AFSL and SFSL2 were situated on dune windward slopes with consistent topographic, climatic, and habitat conditions.

Field surveys and sample collection were conducted in July 2020. We randomly established 10 m × 10 m shrub quadrats and 1 m × 1 m herb and litter quadrats in each plot, recording plant species, individual count, height, crown width, and coverage. Basic plot information is presented in .

2.3 Measurements 2.3.1 Vegetation Biomass Determination

Based on measured average growth parameters (height, crown width, basal diameter) within quadrats, we selected three standard shrub individuals. Using the complete excavation method, we obtained shrub root systems and harvested aboveground components, separating stems and leaves. We measured total fresh weight of roots, stems, and leaves and collected 200 g samples. For herbaceous plants, we completely excavated belowground parts and used the harvest method for aboveground components and litter, measuring fresh weight and collecting 200 g samples. All vegetation samples were placed in kraft paper bags, transported to the laboratory, oven-dried at 105°C to constant weight, and used to calculate biomass.

2.3.2 Soil Physicochemical Properties

We randomly excavated soil profiles in each plot and sampled at 0-10, 10-20, 20-40, and 40-60 cm layers. Bulk density was measured using the ring knife method, and corresponding soil layers were collected in cloth bags (300 g mixed samples). Soil samples were air-dried in the laboratory, crushed, and sieved for analysis. Soil organic carbon was determined by the potassium dichromate oxidation method, total nitrogen by the Kjeldahl method, and total phosphorus by the perchloric acid-sulfuric acid digestion molybdenum-antimony colorimetric method.

2.3.3 Data Processing

We performed data processing and graphing using SigmaPlot 14.0, SPSS 22.0, and Excel. Statistical analysis employed two-way ANOVA to test the effects of vegetation restoration stage, soil depth, and their interactions on soil C, N, P contents and stoichiometric ratios. Multiple comparisons were conducted using the least significant difference (LSD) method at $\alpha = 0.05$. Pearson correlation analysis examined relationships between soil stoichiometric characteristics and vegetation biomass. All data are presented as means ± standard deviation.

3. Results

3.1 Vegetation Biomass Variation Vegetation total biomass differed significantly among restoration stages ($P < 0.05$), increasing progressively from mobile sandy land ($3.31\ \mathrm{g \cdot m^{-2}}$) to semi-fixed sandy land ($32.43\ \mathrm{g \cdot m^{-2}}$), Artemisia-fixed sandy land ($275.87\ \mathrm{g \cdot m^{-2}}$), and Salix-fixed sandy land ($889.39\ \mathrm{g \cdot m^{-2}}$). Aboveground biomass was 1.4-5.6 times greater than belowground biomass across all stages. Except for mobile sandy land (which lacked shrubs), vegetation biomass was dominated by shrubs, accounting for 71.68%, 79.95%, and 96.12% of total biomass in semi-fixed, Artemisia-fixed, and Salix-fixed sandy lands, respectively. Herbaceous biomass, primarily composed of annual species with small stature, constituted a minor proportion of total biomass and decreased with vegetation restoration. Shrub organ biomass allocation followed the pattern: leaves (22.67-49.77%) > stems (27.56-71.68%) > roots (5.60-20.05%). No litter accumulated in mobile sandy land due to wind erosion, while litter biomass increased gradually with vegetation restoration in other stages.

3.2 Soil C, N, and P Content Patterns Soil organic carbon (SOC) and total nitrogen (TN) contents varied significantly among restoration stages ($P < 0.05$), increasing slowly initially then more rapidly with vegetation restoration [Figure 1: see original paper]. Surface layer (0-10 cm) SOC and TN contents showed the most pronounced increases, reaching maxima in Salix-fixed sandy land ($5.86\ \mathrm{g \cdot kg^{-1}}$ and $0.41\ \mathrm{g \cdot kg^{-1}}$, respectively), which were 3.31, 2.69, and 1.52 times higher than values in mobile, semi-fixed, and Artemisia-fixed sandy lands. Increments in deeper layers were relatively modest. Total phosphorus (TP) content increased gradually with vegetation restoration but with smaller amplitude: mobile ($1.45\ \mathrm{g \cdot kg^{-1}}$) < semi-fixed ($1.47\ \mathrm{g \cdot kg^{-1}}$) < Artemisia-fixed ($1.52\ \mathrm{g \cdot kg^{-1}}$) < Salix-fixed sandy land ($1.74\ \mathrm{g \cdot kg^{-1}}$). Across the soil profile, C, N, and P contents all decreased with depth. Two-way ANOVA indicated that vegetation restoration exerted a substantially greater influence on soil C, N, and P contents than soil depth or their interaction .

3.3 Soil Ecological Stoichiometry Patterns Soil C:N, C:P, and N:P ratios differed significantly among restoration stages and soil layers ($P < 0.05$). During desertification reversal, soil C:N ratio first decreased then increased, while C:P and N:P ratios increased progressively, with greater 增幅 in shallow than deep soils [Figure 2: see original paper]. Vertically, soil C:P and N:P ratios decreased with depth, whereas the C:N ratio showed no consistent pattern. Two-way ANOVA revealed that vegetation restoration contributed far more to variations in soil C:N, C:P, and N:P ratios than soil depth or their interaction .

3.4 Correlations Between Soil Stoichiometry and Biomass Soil C, N, and P contents were significantly and positively correlated with each other ($P < 0.01$) and with aboveground and litter biomass ($P < 0.05$). Soil C:N ratio was not significantly correlated with C:P or N:P ratios. However, soil C:P ratio was positively correlated with N:P ratio ($P < 0.01$), and both C:P and N:P ratios were significantly positively correlated with aboveground, belowground, and litter biomass. Specifically, soil C:P and N:P ratios were significantly positively correlated with aboveground and litter biomass, while soil N:P ratio was also significantly positively correlated with belowground biomass .

4. Discussion

4.1 Vegetation Biomass Changes Across Restoration Stages Vegetation biomass directly reflects plant growth status and local environmental changes, primarily influenced by regional climate, soil, topography, and human activities. Our study revealed significant differences in shrub and herb organ biomass among restoration stages, with aboveground, belowground, and litter biomass increasing markedly with vegetation restoration. This demonstrates that artificial planting to promote vegetation restoration can substantially enhance net productivity in desert ecosystems, consistent with findings from the Horqin and Mu Us sandy lands. In the eastern Kubuqi Desert, mobile sandy land remains bare with sparse annual herbs and no litter accumulation, resulting in minimal biomass. Semi-fixed sandy land, recovering naturally through seed dispersal, showed modest increments in aboveground, belowground, and litter biomass due to its slow recovery rate. In contrast, artificially established fixed sandy lands exhibited relatively stable community structure with increased vegetation richness and coverage.

Biomass also differed between fixed sandy lands with different constructive species, with Salix-fixed sandy land showing significantly higher biomass than Artemisia-fixed sandy land. This disparity arises from several factors. First, the study area' s arid, windy conditions with severe surface erosion and water deficiency hinder seed dispersal, germination, and seedling growth of aerially seeded Artemisia, prolonging community development. Conversely, artificial planting using high-quality Salix seedlings with appropriate timing and site selection achieves high survival rates and rapidly establishes vigorous dominant communities. Second, as an excellent native sand-fixing species in the Kubuqi Desert, Salix possesses stronger sprouting ability, faster growth, and more extensive root systems compared to Artemisia. After planting, Salix quickly forms lush forest belts, whereas Artemisia roots are confined to shallow soil layers, limiting its soil improvement capacity. The Salix community biomass (889.39 $g \cdot m^{-2}$) approximates values reported for Haloxylon ammodendron communities in the Ulan Buh Desert (642-1641 $g \cdot m^{-2}$) and the southeastern Junggar Basin (669-1939 $g \cdot m^{-2}$), while Artemisia community biomass (275.87 $g \cdot m^{-2}$) slightly exceeds values from the Mu Us Sandy Land (235 $g \cdot m^{-2}$). The average biomass of desert ecosystems in eastern Kubuqi (305.43 $g \cdot m^{-2}$) is comparable to the Mojave Desert (247 $g \cdot m^{-2}$) but substantially lower than the global desert ecosystem average (700 $g \cdot m^{-2}$), indicating low plant stock levels, fragile ecosystems, and poor stability. Reasonable land use and scientific management during vegetation restoration are thus crucial for ecosystem recovery and desertification reversal.

4.2 Effects of Vegetation Restoration on Soil C, N, and P Contents

Soil C and N are major nutrient components influenced by litter decomposition, root exudation, soil mineralization, and microbial activity. In mobile sandy land, loose soil texture, severe wind erosion, and extremely low coverage result in nutrient deficiency. Artificial restoration measures gradually increase forest density and vegetation coverage, weakening wind erosion and reducing soil loss while fixing substantial nutrients in plant tissues. Increased aboveground, belowground, and litter biomass promotes soil C and N accumulation. Furthermore, vegetation growth enhances soil nutrient and organic matter contents, facilitates nutrient availability, and improves soil structure through root systems that increase porosity and optimize water and temperature conditions, thereby enhancing microbial activity and accelerating decomposition of litter and animal residues.

The Salix-fixed sandy land exhibited the highest soil C, N, and P contents due to its greatest biomass and superior soil improvement capacity. Salix possesses nitrogen-fixing bacteria in its rhizosphere that promote soil N accumulation, causing N increase rates to exceed C increase rates in semi-fixed sandy land where the C:N ratio was minimal. In fixed sandy lands, substantial biomass increases during vegetation restoration led to rapid C accumulation, causing C increase rates to exceed N increase rates. Consequently, soil C and N contents increased gradually with vegetation restoration, consistent with previous research. Soil P, derived primarily from rock weathering, is less influenced by vegetation and more affected by parent material, climate, and land use, resulting in only modest increases with restoration.

Soil depth significantly influences nutrient distribution. Our results showed that soil C, N, and P contents decreased significantly with depth, with pronounced surface enrichment in the 0-10 cm layer, which contained 30.83-46.34% of total profile contents. This vertical pattern stems from surface litter decomposition, environmental factors, and nutrient return concentrated in topsoil. With increasing depth, reduced root distribution and microbial activity lead to decreasing nutrient content. Soil P showed minimal vertical variation, consistent with most studies and likely related to regional climate (precipitation, temperature, wind speed), vegetation type, and differential nutrient release rates across restoration stages, resulting in non-uniform nutrient distribution.

4.3 Effects of Vegetation Restoration on Soil Stoichiometric Characteristics Soil C:N:P stoichiometry serves as an important indicator of soil nutrient status and cycling, exhibiting high spatial heterogeneity due to regional climate, site conditions, and vegetation type. In the Kubuqi Desert, C:N ratios in fixed sandy land shrub communities (10.9-14.3) exceeded those in the Gurbantunggut Desert but approximated the Chinese terrestrial soil average (10-12). The C:N ratio first decreased then increased with vegetation restoration, directly related to differential accumulation rates of soil C and N across restoration stages. Studies indicate that C:N ratio is negatively correlated with organic matter decomposition rate. The initial decrease in C:N ratio during early restoration stages reflects accelerated decomposition due to improved soil conditions, while subsequent increases result from faster C accumulation relative to N in later stages.

Soil C:P and N:P ratios increased gradually with vegetation restoration because C and N accumulation rates exceeded P accumulation rates. These ratios represent key indicators of P effectiveness and organic matter mineralization. Our study area’ s low C:P and N:P ratios, well below Chinese terrestrial and global averages, indicate severe N limitation and high P effectiveness with net mineralization. The C:P and N:P ratios also decreased with soil depth due to reduced nutrient return and microbial activity in deeper layers, while the C:N ratio showed no consistent vertical pattern, possibly due to varying influences of surface litter decomposition and environmental factors across restoration stages.

5. Conclusions

Our study in the eastern Kubuqi Desert revealed three major conclusions regarding vegetation restoration effects on soil stoichiometry. First, species richness and vegetation coverage increased progressively from mobile to Salix-fixed sandy land, with total biomass increasing significantly from 3.31 $g \cdot m^{-2}$ to 889.39 $g \cdot m^{-2}$. Vegetation growth effectively improved soil structure, increased organic matter content, and promoted C and N accumulation, while P content increased only modestly due to constraints from parent material and land use. Second, soil stoichiometric ratios differed significantly across restoration stages. The C:N ratio first decreased then increased with vegetation restoration, while C:P and N:P ratios increased gradually. Vertically, soil C, N, and P contents decreased with depth, with C and N showing pronounced surface enrichment (0–10 cm layer), whereas the C:N ratio exhibited no clear vertical pattern. Third, soil C, N, and P contents were highly positively correlated with each other and significantly positively correlated with aboveground and litter biomass. Soil C:P and N:P ratios were also significantly positively correlated with belowground biomass. These findings demonstrate that artificial planting to promote vegetation restoration substantially influences soil C, N, and P contents and stoichiometric characteristics, ultimately enabling effective and stable desertification reversal.

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