Effects of Caragana microphylla on Vegetation and Soil in Desertified Grassland Restoration (Postprint)

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Date: 2024-12-16T00:00:00+00:00

Abstract

Caragana microphylla is a commonly used shrub species for promoting vegetation restoration in desertified grasslands. Analyzing its effects on vegetation and soil physicochemical characteristics within shrub patches at different stages of desertified grassland restoration is of great significance for sandy land vegetation restoration and sustainable development. This study examined Caragana microphylla shrub patches in three typical stages of desertified grassland vegetation restoration in the Hulunbuir Sandy Land: semi-fixed sandy land, fixed sandy land, and sandy grassland. Through variance analysis, Pearson correlation analysis, and redundancy analysis, we investigated the changes in vegetation community and soil physicochemical characteristics beneath Caragana microphylla shrub patches and their relationships across different restoration stages. The results indicated: (1) With increasing degree of desertified grassland vegetation restoration, vegetation species richness, Shannon-Wiener index, community height, and biomass within shrub patches increased. Community height and biomass within shrub patches were higher than outside shrub patches, and vegetation species richness within shrub patches was higher than outside shrub patches in the semi-fixed and fixed sandy land stages. (2) In the 0~10cm and 10~20cm soil layers, soil water content exhibited a gradually increasing trend, with the maximum value occurring in the sandy grassland stage (1.2%), and was higher within shrub patches than outside shrub patches. Clay and silt contents gradually increased with increasing vegetation restoration degree and were higher within shrub patches than outside shrub patches, while sand content showed the opposite trend. (3) With increasing vegetation restoration degree, soil organic carbon gradually increased, with the maximum value in the sandy grassland stage (4.12g·kg-1), and was higher within shrub patches than outside shrub patches. Soil total nitrogen increased from the semi-fixed sandy land to the fixed sandy land stage, and was higher within shrub patches than outside shrub patches at all stages. With increasing vegetation restoration degree, soil pH within shrub patches decreased. Soil total phosphorus showed no significant changes. (4) Soil physicochemical characteristics explained 59.6% and 46.9% of vegetation variation inside and outside shrub patches, respectively, with the main influencing factors being soil particle size, total nitrogen, water content, and organic carbon. This study demonstrates that during the vegetation restoration process of desertified grasslands, Caragana microphylla shrub patches promote vegetation growth and development by improving soil physicochemical properties beneath the shrubs, including soil particle size, water content, organic carbon, and total nitrogen.

Full Text

Arid Zone Research, Vol. 41, No. 11, Nov. 2024

Effects of Caragana microphylla on Vegetation and Soil in the Restoration of Desertified Grasslands

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Abstract

Caragana microphylla, a shrub species commonly used to promote vegetation recovery in desertified grasslands, plays a significant role in the ecological restoration and sustainable development of sandy lands. Understanding its impact on understory vegetation and soil physicochemical characteristics during different stages of desertified grassland recovery is crucial. This study examined C. microphylla shrublands in three typical stages of desertified grassland vegetation recovery in the Hulun Buir sandy land: semi-fixed sandland, fixed sandland, and sandy grassland. Using ANOVA, Pearson correlation analysis, and redundancy analysis, we explored changes in understory plant communities and soil physicochemical characteristics beneath C. microphylla shrubs across different restoration stages and their interrelationships. The results indicate that as vegetation recovery progresses, understory species richness, Shannon-Wiener index, community height, and biomass increase. Community height and biomass are higher inside shrublands than outside, while species richness inside shrublands exceeds that outside during the semi-fixed and fixed sandland stages. In both the 0–10 cm and 10–20 cm soil layers, soil water content shows an increasing trend, peaking in the sandy grassland stage (1.2%) and being higher inside shrublands than outside. Clay and silt contents increase with vegetation recovery and are higher inside shrublands than outside, while sand content shows the opposite pattern. Soil organic carbon increases with vegetation recovery, reaching a maximum of 4.12 $g \cdot kg^{-1}$ in the sandy grassland stage, and is higher inside shrublands than outside. Total nitrogen increases from the semi-fixed to fixed sandland stage and remains higher inside shrublands than outside at all stages. Soil pH inside shrublands decreases as vegetation recovery advances, while total phosphorus shows no significant change. Soil physicochemical characteristics explain 59.6% and 46.9% of vegetation variation inside and outside shrublands, respectively, with the main influencing factors being soil particle size, total nitrogen, water content, and organic carbon. This study demonstrates that during desertified grassland vegetation recovery, C. microphylla shrublands promote vegetation growth and development by improving soil physicochemical characteristics beneath the shrubs, including soil particle size, water content, organic carbon, and total nitrogen.

Keywords: desertified grassland vegetation recovery; Caragana microphylla; vegetation characteristics; soil physicochemical characteristics; Hulun Buir

Introduction

The Hulun Buir region represents one of the best-preserved natural grassland pastoral areas in the transitional zone between arid and semi-arid regions of northern China. During the last century, unreasonable activities including natural environmental deterioration, land reclamation, overgrazing, and excessive human excavation intensified grassland desertification in Hulun Buir, forming the Hulun Buir sandy land. Located in an ecological ecotone, the Hulun Buir sandy land is a renowned ecologically fragile zone and a sensitive belt for climate and environmental change. The northern sand belt along the Hailar River constitutes the longest sand belt in the region, stretching approximately 90 km from east to west, dominated by fixed and semi-fixed dunes with a few mobile dunes distributed on the south side of the Hailar River. Since the 1990s, the government has implemented a series of measures including afforestation, aerial seeding, and grazing prohibition to promote vegetation recovery, which has achieved a certain degree of sand fixation and restoration. However, in recent years, the frequent occurrence of extreme climate events, combined with intensified human activities such as local overgrazing, has led to a re-spreading trend of desertified land, seriously constraining regional sustainable development. Introducing stress-resistant shrubs is a key strategy for curbing sand expansion and promoting vegetation ecological restoration. These shrubs fix sandy soil through their well-developed root systems, effectively limiting sand mobility while reducing wind erosion and surface water evaporation. Through positive plant-soil feedback, they improve soil conditions, and their canopies regulate understory microclimate and intercept seeds, thereby positively influencing seed germination and growth of understory vegetation and affecting the structure and function of entire plant communities. Therefore, in-depth research on shrub effects on understory vegetation and soil conditions is crucial not only for revealing restoration mechanisms of desertified grasslands but also for maintaining regional ecosystem stability and enhancing ecological service functions.

Caragana microphylla, a leguminous shrub commonly used in sand fixation and desertification control in arid and semi-arid regions of northern China, plays an important role in resisting wind erosion and promoting sandy land restoration. Recent research on Caragana species has focused on factors including site conditions, shrub patch size, pruning management, and enclosure duration to explore community structure changes and effects on herbaceous vegetation characteristics. Yu et al. studied the succession of herbaceous communities under Caragana korshinskii forests of different planting ages in Lingwu Baijitan, indicating that as planting age increases, the understory vegetation community gradually approaches near-natural sand-fixing vegetation. Wang et al. investigated the nursing effects of artificial C. korshinskii forests on understory herbaceous communities in desert steppe, demonstrating that C. korshinskii has a nursing effect on understory plants, especially Poaceae vegetation. Bao et al. studied community characteristics of artificial C. microphylla of different ages in the Horqin sandy land after pruning, showing that as stand age increases, C. microphylla has difficulty achieving seed regeneration, subsequently promoting vegetative propagation, and that pruning increases understory vegetation biomass but does not increase its diversity. These findings demonstrate that exploring the effects of C. microphylla on understory vegetation communities is significant for sandy land vegetation recovery and sustainable development.

However, the influence of C. microphylla extends beyond aboveground vegetation, profoundly altering soil physicochemical properties. With the advancement of sandy land vegetation restoration projects in China, research on the role of dominant shrubs in desertification prevention and water-soil conservation in fragile ecological regions of northwest China has increased. Studies show that shrublands regulate understory microclimate and soil temperature and moisture through canopy effects and affect the spatial distribution of soil nutrients through belowground biological processes, forming a "fertile island effect" that promotes understory vegetation growth and development. This aboveground-belowground interaction drives vegetation community succession from single shrubs to shrub-herb complexes. However, the "fertile island effect" varies among different plant species and is regulated by environmental stress. The Stress Gradient Hypothesis suggests that facilitation among shrub community species increases with increasing biotic or abiotic stress, while other perspectives propose a hump-shaped relationship between stress and facilitation, where facilitation helps expand the niche of low-tolerance species under moderate to high stress conditions but may weaken under extremely harsh environmental conditions. During the early stages of Hulun Buir desertified grassland vegetation recovery, environmental pressures such as wind erosion and sand burial are substantial, gradually decreasing as vegetation restoration progresses. Systematic research on the effects of C. microphylla shrublands on understory vegetation communities and soil physicochemical characteristics and their evolution during different restoration stages remains relatively scarce. Therefore, evaluating the potential of C. microphylla shrublands to promote ecological restoration under environmental stress and in arid ecosystems is particularly important.

This study focused on artificially introduced C. microphylla shrublands in the northern sand belt of the Hulun Buir sandy land, selecting three typical stages of desertified grassland vegetation recovery (semi-fixed sandland, fixed sandland, and sandy grassland) to compare herbaceous plant communities and soil physicochemical characteristics inside and outside C. microphylla shrublands, revealing the effects of C. microphylla on understory vegetation at different sandy land vegetation recovery stages. The aim is to provide theoretical support for vegetation restoration and community maintenance mechanisms in this region.

1. Materials and Methods

1.1 Study Area

The study area is located in the hinterland of the northern sand belt in Hulun Buir City, at 49°13 N, 118°27 E, with an elevation of approximately 617 m, belonging to Chen Barag Banner of Hulun Buir City. This region represents a typical area of grassland desertification in the Hulun Buir sandy land. The climate is a typical temperate continental climate, with an average annual temperature of -0.5°C, average annual frost-free period of 109 days, average annual precipitation of approximately 351.3 mm (concentrated in June–August), average annual evaporation of 1385.8 mm, and average sunshine duration of 1414 h. To prevent further desertification and spread since 2000, the area has undergone continuous annual aerial seeding, and C. microphylla shrublands were planted in 2005 to fix sandy land, promoting the stabilization of mobile sand dunes and accelerating vegetation succession. Presently, the sandy land has achieved varying degrees of restoration, forming a vegetation mosaic pattern of semi-fixed sandland (vegetation coverage 15%–40%), fixed sandland (vegetation coverage 40%–60%), and sandy grassland (vegetation coverage >60%). In semi-fixed sandland, shrubs are sparse, the surface is largely exposed with no biological crust, and herbaceous plants are mainly annual and biennial psammophytes. In fixed sandland, patchy sand flow occasionally appears on the surface, with psammophytes as companion species. In sandy grassland, understory vegetation coverage is high with no desertification occurrence.

The vegetation in the study area is dominated by sand-fixing shrubs and understory herbaceous plants. Common shrubs include Caragana microphylla, Hedysarum fruticosum, and Artemisia halodendron. Common herbaceous species include Corispermum maorocarpum, Artemisia frigida, Lespedeza davurica, Oxytropis hailarensis, and Elymus dahuricus.

1.2 Experimental Design and Field Survey

At the end of the growing season in September 2022, based on comprehensive reconnaissance, we selected sample plots covered by Caragana shrublands. According to the degree of desertified grassland vegetation recovery, we chose semi-fixed sandland (Sandy Fixed), fixed sandland (Sandy Fixed), and sandy grassland (Sandy Grassland) as research subjects within the study area and completed sample collection. Three 20 m × 20 m sample plots were established for each desertified grassland vegetation recovery type (with plot intervals of 20–50 m). Within each plot, three similar-sized C. microphylla shrubs were randomly selected (Table 1). Understory vegetation coverage was measured using the needle-point method, with selected shrubs spaced >5 m between canopies. A 1 m × 1 m quadrat was placed within each shrub canopy, and an identical herbaceous quadrat was demarcated outside the canopy (at a distance of 1–2 m from the shrub edge). Each sandland fixation stage had 9 quadrats, totaling 54 quadrats. Plant species, quantity, and height were surveyed in each quadrat, and aboveground biomass was collected and weighed after oven-drying at 105°C. Simultaneously, soil samples were collected from herbaceous quadrats inside and outside three C. microphylla shrubs. After removing surface cover, soil samples were collected from 0–10 cm and 10–20 cm layers (these two layers were selected considering the root distribution of understory herbaceous vegetation and field workload). Soil samples from the same layer were mixed, and the quartering method was used to discard excess soil. Each soil sample was divided into two portions: one collected in aluminum boxes for water content determination, and the other air-dried and passed through a 2 mm sieve for physicochemical index determination.

1.3 Sample Analysis and Data Processing

Soil water content (SWC) was determined using the traditional oven-drying method. Soil particle size analysis was conducted using a Malvern MS2000 laser particle size analyzer, with results classified according to the USDA soil particle size classification system. Soil organic carbon (SOC) content was determined using the potassium dichromate external heating method. Total nitrogen (TN) content was measured using an automatic Kjeldahl nitrogen analyzer. Total phosphorus (TP) content was determined using the alkali fusion-molybdenum antimony anti-colorimetric method. Soil pH was measured using the potentiometric method.

1.4 Data Calculation and Analysis

Community species richness (R, Patrick index), community height (H), and Shannon-Wiener index (Hi) were calculated as follows:

$$R = S$$

$$H = \sum_{i=1}^{S} H_i$$

$$Hi = -\sum_{i=1}^{S} P_i \ln P_i$$

where S is the total number of species in the quadrat; H_i is the average height of the ith species; P is the proportion of the ith species in the total community count; and n is the number of species categories for standard output.

Origin software was used for statistical analysis and graphing, with data presented as mean ± standard deviation. Two-way ANOVA and three-way ANOVA were employed to analyze differences in vegetation characteristics (species richness, Shannon-Wiener index, community height, and biomass) and soil physicochemical characteristics (SWC, particle size, SOC, TN, TP, and pH) among different sandland fixation stages and inside/outside shrubs. The least significant difference (LSD) method ($\alpha = 0.05$) was used to compare differences among restoration stages, while t-tests ($\alpha = 0.05$) were used for differences inside/outside shrubs and between soil layers. Pearson correlation analysis revealed relationships between vegetation and soil physicochemical characteristics. The "vegan" package in R software was used for redundancy analysis (RDA) to quantify the contribution of soil physicochemical characteristics to aboveground vegetation and screen important influencing factors.

2. Results and Analysis

Two-way ANOVA indicated that desertified grassland vegetation recovery stage significantly affected understory vegetation community characteristics (richness, Shannon-Wiener index, community height, and biomass) ($P < 0.01$), while shrubland location (inside/outside) significantly affected richness, community height, and biomass ($P < 0.01$). The interaction effect was significant only for richness and biomass ($P < 0.01$). The Shannon-Wiener index, community height, and biomass of understory vegetation all increased with vegetation recovery degree, showing the pattern: sandy grassland > fixed sandland > semi-fixed sandland. Species richness and biomass peaked in the fixed sandland stage (Figure 1). Across all vegetation recovery stages, richness, community height, and biomass differed significantly between inside and outside shrublands ($P < 0.05$). Species richness inside shrublands was higher than outside during semi-fixed and fixed sandland stages ($P < 0.01$), while in the sandy grassland stage, the opposite pattern occurred. Community height and biomass inside shrublands were higher than outside across all stages ($P < 0.05$), with community height increasing by 51.2%, 42.0%, and 31.6%, and biomass increasing by 110.7%, 110.1%, and 18.0% compared to outside shrublands in semi-fixed sandland, fixed sandland, and sandy grassland stages, respectively.

2.2 Effects of Caragana microphylla Shrublands on Soil Physicochemical Characteristics

2.2.1 Soil Physical Properties Three-way ANOVA results showed that desertified grassland vegetation recovery stage, shrubland location (inside/outside), and soil layer all significantly affected SWC and particle size composition ($P < 0.01$). The interaction between recovery stage and shrubland location significantly affected soil particle size composition ($P < 0.01$), while the interaction between shrubland location and soil layer significantly affected silt content ($P < 0.05$). The three-way interaction significantly affected silt content ($P < 0.05$). In both soil layers, SWC showed an increasing trend with vegetation recovery degree, peaking in the sandy grassland stage (1.2%).

SWC was higher inside shrublands than outside across all stages, increasing by 30.1%, 48.2%, and 96.6% in the 0–10 cm layer, and by 28.4%, 44.7%, and 64.0% in the 10–20 cm layer, respectively. Clay and silt contents increased with vegetation recovery degree, with the highest values in the sandy grassland stage (clay: 21.0%; silt: 39.0%), while sand content gradually decreased, with the highest value (77.0%) in semi-fixed sandland. In both layers, clay and silt contents inside shrublands were higher than outside, while sand content showed the opposite pattern. In the sandy grassland stage, clay and silt contents inside shrublands were significantly higher than outside ($P < 0.05$), while sand content was significantly lower inside than outside ($P < 0.05$).

2.2.2 Soil Chemical Properties Three-way ANOVA results showed that vegetation recovery stage, shrubland location, and soil layer significantly affected SOC, TN, and pH ($P < 0.05$). Vegetation recovery stage and shrubland location did not significantly affect TP, while soil layer had a significant effect on TP ($P < 0.01$). The interaction between recovery stage and shrubland location significantly affected SOC, TP, and pH ($P < 0.05$), while the interaction between recovery stage and soil layer significantly affected TN and TP ($P < 0.05$). The three-way interaction significantly affected TN and TP ($P < 0.05$).

Across different vegetation recovery stages, SOC differed significantly ($P < 0.05$), gradually increasing with vegetation recovery degree and peaking in the sandy grassland stage ($4.12 \text{ g} \cdot \text{kg}^{-1}$). SOC was higher inside shrublands than outside, being 56.5% and 93.9% higher inside than outside in semi-fixed and fixed sandland stages, respectively, though the difference was not significant in the sandy grassland stage. TN increased significantly from semi-fixed to fixed sandland stage ($P < 0.05$) and was higher inside shrublands than outside across all stages, increasing by 73.0% and 20.5% in the 0–10 cm layer, and by 60.0% and 10.0% in the 10–20 cm layer, respectively. Soil pH inside shrublands decreased with increasing vegetation recovery degree. No significant change in TP was observed across vegetation recovery stages or between inside/outside shrublands.

2.3 Relationships Between Soil Physicochemical and Vegetation Characteristics of Caragana microphylla Shrublands

Pearson correlation analysis showed that in the 0–10 cm soil layer (Figure 4), vegetation biomass was significantly or extremely significantly positively correlated with SWC, silt content, SOC, and TN ($P < 0.01$). Community height was significantly correlated with SWC, clay and silt contents, SOC, and TN ($P < 0.01$), and extremely significantly negatively correlated with sand content ($P < 0.01$). Shannon-Wiener index and richness index were both significantly positively correlated with clay and silt contents, SOC, and TN ($P < 0.01$), and extremely significantly negatively correlated with sand content and pH ($P < 0.01$).

In the 10–20 cm soil layer, vegetation biomass was significantly positively correlated with SWC, SOC, and TN ($P < 0.05$). Community height was significantly positively correlated with clay content, SOC, and TN ($P < 0.05$). Shannon-Wiener index was significantly positively correlated with clay and silt contents, SOC, and TN ($P < 0.05$), and significantly negatively correlated with sand content and pH ($P < 0.05$). Species richness was significantly positively correlated with SWC, clay, silt, SOC, and TN ($P < 0.01$), and significantly negatively correlated with sand content and pH ($P < 0.01$).

Redundancy analysis results showed that in the 0–10 cm soil layer, soil physicochemical characteristics explained 59.6% of vegetation variation inside and outside shrublands, with the first two axes accurately reflecting relationships between vegetation characteristics and soil environmental factors, explaining 47.5% and 12.1% of vegetation variation, respectively. Soil particle size content and TN were the key factors significantly affecting aboveground vegetation community changes (Figure 5). In the 10–20 cm soil layer, soil physicochemical characteristics explained 46.9% of vegetation variation, with the first two axes explaining 37.7% and 9.2% of vegetation variation, respectively. SWC, TN, and SOC were the key factors significantly affecting aboveground vegetation community changes (Figure 5).

3. Discussion

3.1 Role of Caragana microphylla Shrublands in Desertified Grassland Vegetation Recovery

Shrubland facilitation of vegetation recovery primarily depends on canopy effects and soil improvement. This study shows that across different desertified grassland vegetation recovery stages, community height and biomass inside C. microphylla shrublands are greater than outside, while species richness and Shannon-Wiener index are higher inside than outside during semi-fixed and fixed sandland stages, but lower inside during the sandy grassland stage. These findings align with those of Wang et al. During sandy land vegetation recovery, the canopy acts as a barrier that not only intercepts airborne seeds but also buffers disturbance from sand burial, reduces extreme solar radiation and soil evaporation, and provides suitable environments for seed germination and establishment inside shrublands. This explains why species richness, height, and biomass are significantly higher inside than outside during the early vegetation recovery stages. However, in the sandy grassland stage, as C. microphylla shrub age increases, canopy expansion causes intense shading that hinders photosynthesis of understory vegetation, while interspecific competition among vegetation with different survival strategies intensifies inside shrublands. Consequently, species richness and diversity outside shrublands become higher in the late stable stage, and understory vegetation biomass is significantly lower than during the fixed sandland period.

The Stress Gradient Hypothesis suggests that positive species interactions increase with environmental stress, which is supported by our results showing facilitative effects of shrubs during semi-fixed and fixed sandland stages. However, the relationship between stress and facilitation can change with environmental conditions, with negative correlations emerging between shrubs and understory species when environmental pressure decreases. This explains our observation of higher species richness and Shannon-Wiener index outside than inside shrublands in the sandy grassland stage.

This study found that SWC and clay content inside C. microphylla shrublands are higher than outside, with both increasing as vegetation recovery progresses. This indicates that C. microphylla shrublands can reduce soil water loss and decompose coarse soil particles, transforming large sand particles into finer particles and thereby changing soil particle size distribution. This aligns with Li et al.'s findings that shrubs can buffer surface soil wind erosion and intercept dust, leading to changes in soil particle size. Additionally, SOC increased with vegetation recovery, with higher SOC and TN inside shrublands than outside. As a leguminous shrub, C. microphylla accelerates SOC accumulation through litter decomposition, while abundant root nodules fix atmospheric nitrogen, increasing soil nitrogen content. Furthermore, fixed nitrogen can be transferred to neighboring plants, affecting community composition and structure. No significant differences in TP were observed across vegetation recovery stages or between inside/outside shrublands, as phosphorus exists in soil as sedimentary minerals with relatively weak mobility, making TP content primarily dependent on initial soil parent material conditions. Studies by Erfanzadeh et al. analyzing effects of different shrub species on soil characteristics indicate that the "fertile island effect" of shrubs leads to widespread nutrient accumulation. Increased litter from shrubs and herbaceous plants provides opportunities for nutrient accumulation. Moreover, the nitrogen fixation capacity of C. microphylla and the presence of abundant root microorganisms result in higher rhizosphere soil nutrients than outside the root zone, which, combined with its robust root system, ensures C. microphylla growth in harsh environments. Thus, community vegetation recovery processes are closely related to changes in soil physicochemical characteristics.

3.2 Role of Soil Factors in Vegetation Recovery

Plant-soil synergy and feedback are considered key to shrub-driven restoration succession in desertified grasslands and represent important research content for vegetation recovery in sandy ecosystems. Our results show that soil physical and chemical characteristics are significantly correlated with vegetation characteristics. In the 0–10 cm soil layer, soil particle size content and TN are the main drivers of aboveground vegetation changes, while in the 10–20 cm layer, SWC, TN, and SOC are the key factors affecting vegetation community characteristics. This suggests that C. microphylla primarily alters soil particle size in the surface layer, while changes in soil chemical characteristics at 10–20 cm have less impact on vegetation compared to the 0–10 cm layer. However, SWC, TN, and SOC at 10–20 cm are critical factors influencing vegetation changes. Studies have shown that shrubs or perennial grasses can alter soil carbon distribution, increasing spatial heterogeneity of soil carbon, and that soil nutrients directly affect plant leaf nutrients. Thus, aboveground vegetation recovery is closely related to this interdependent plant-soil cycle, which corroborates our findings. Additionally, Liu et al. demonstrated that in the loess hilly-gully region, SWC, surface chemical properties, and changes in herbaceous biomass and diversity under C. korshinskii shrublands are strongly correlated. Liu et al. found that in desert steppe regions, soil texture, bulk density, SOC, TN, and pH are the main factors changing herbaceous vegetation quantitative characteristics during C. intermedia growth. Wang et al. showed that in the Horqin sandy land, different sandy land community species are affected by different soil factors, with sandy grassland communities strongly correlated with soil nutrients, fixed sandland more related to soil moisture, and mobile sandland less correlated with soil factors. These results align with our findings, all indicating that interactions between dominant shrubs and vegetation are closely related to aboveground and belowground ecological processes, and that vegetation growth and development are important drivers of soil characteristic changes.

Plant-soil interactions promote understory vegetation community development through shrub-soil interactions, with stemflow and litter deposition considered the main sources of nutrients such as nitrogen and trace elements provided by dominant shrubs to understory vegetation. As a leguminous shrub, C. microphylla strongly influences aboveground vegetation patterns and distribution through abundant root nodules and "nitrogen transfer." Studies show that plants can alter soil chemical characteristics including SOC, TN, and pH, which in turn affect vegetation growth and distribution. In this study, C. microphylla shrublands changed soil chemical characteristics by absorbing and releasing soil nutrients and participating in soil material cycling, while using canopies to reduce wind speed, intercept dust and organic matter, and reduce surface soil particle size, thereby affecting soil physical characteristics. This series of processes forms a feedback pathway that completes the "transport" of soil nutrients by aboveground vegetation. Correlation analysis and redundancy analysis both indicate that soil TN and SOC are closely related to vegetation characteristic changes and are the main factors influencing these changes, likely related to the dense root activity of herbaceous plants in shallow soil layers. After vegetation "transports" nutrients to the soil, it promotes SOC and TN formation and accumulation, and as soil nutrient content increases, it creates favorable conditions for aboveground vegetation growth and development.

In sandy land vegetation recovery, moisture is an important factor affecting vegetation succession. During early restoration stages, dominant shrubs promote biological soil crust formation and development through canopy and soil effects, hinder surface soil water evaporation, and cause shallow soil water distribution inside shrublands, thereby accelerating growth of shallow-rooted herbaceous plants. However, during later restoration stages, deep-rooted shrubs may degenerate due to water deficiency, promoting herbaceous vegetation development. This study only sampled the 0–20 cm soil layer, and although results show that the 10–20 cm layer has greater effects on vegetation changes, this is insufficient to illustrate differences between shallow and surface soil properties. Future research should further explore how deeper soil layer physicochemical property changes affect aboveground vegetation to identify important factors limiting vegetation growth at different restoration stages.

4. Conclusion

Planting Caragana microphylla shrublands is an effective measure for preventing desertification spread and accelerating vegetation recovery succession in desertified grasslands. During vegetation recovery, C. microphylla shrublands can increase understory vegetation community biomass, height, and richness, particularly during semi-fixed and fixed sandland stages. Simultaneously, they can increase soil water content and clay content while reducing sand content. As recovery progresses, SWC, clay, silt, SOC, and TN all increase, especially beneath shrublands, while TP shows little change. In the 0–10 cm layer, soil particle size and TN are the main factors influencing aboveground vegetation changes, while SWC, TN, and SOC in the 10–20 cm layer are more critical for vegetation community characteristics. Therefore, C. microphylla shrublands promote vegetation species richness, height, and biomass by improving soil physicochemical characteristics, playing a facilitative role in sandy land vegetation recovery and serving as an important driver of vegetation restoration succession.

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**** Changes in selected shrub size and community profiles by sand revegetation stage

**** Results of two-way ANOVA for the effects of revegetation stages and inside and outside shrubs on vegetation characteristics

**** The results of three-way ANOVA results of soil physical properties at different stages of revegetation, inside and outside shrubs, and soil layers

**** Three-way ANOVA results of soil chemical characteristics at different stages of revegetation, inside, outside shrubs and soil layers

[**Figure 1: see original paper**] Changes in vegetation community characteristics under and outside the C. microphylla at different stages of revegetation

[**Figure 2: see original paper**] Changes in soil water content and particle size distribution within and outside shrubs at different vegetation restoration stages

[**Figure 3: see original paper**] Changes in soil chemical characteristics within and outside shrubs at different vegetation restoration stages

[**Figure 4: see original paper**] Correlation coefficients between soil factors and vegetation characteristics

[**Figure 5: see original paper**] Redundancy analysis ranking of vegetation characteristics and soil physicochemical characteristics, and contribution rate of soil physicochemical characteristics

Note: Figure translations are in progress. See original paper for figures.

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