Variations in Physicochemical Properties of Biological Soil Crusts among Different Shrub Communities in the Gonghe Basin: Postprint

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Abstract

This study investigated the differences in physicochemical properties of biological soil crusts (BSCs) among different shrub communities in the Gonghe Basin of Qinghai, providing a theoretical reference for strengthening the protection and rational utilization of BSC resources. BSCs at different developmental stages in Artemisia desertorum, Caragana microphylla, and Salix cheilophila communities in the Gonghe Basin were selected as research subjects, and their particle composition and nutrient characteristics were studied through field sampling combined with laboratory analysis. The results showed that the particle composition of BSCs in the three shrub communities was dominated by sand particles (45%~90%), with the sand particle content in C. microphylla > S. cheilophila > A. desertorum, and all contents were significantly lower than those in bare sand between shrubs. The contents of total nitrogen, total carbon, organic matter, available phosphorus, readily available potassium, alkali-hydrolyzable nitrogen, and total phosphorus in BSCs of the S. cheilophila community were significantly higher than those in the A. desertorum and C. microphylla communities, and each content showed an increasing trend in the three shrub communities with BSC development. Shrub communities had the highest degree of influence on the physicochemical properties of BSCs, and shrub biomass was significantly positively correlated with BSC coverage, thickness, total nitrogen, total carbon, organic matter, available phosphorus, readily available potassium, alkali-hydrolyzable nitrogen, and total phosphorus, and significantly negatively correlated with sand particle content ($P<0.05$). Shrub communities effectively improved the soil structure of BSCs in the sandy land of the Gonghe Basin, with A. desertorum communities being more conducive to soil fining and S. cheilophila communities being more conducive to nutrient accumulation.

Differences in the Physical and Chemical Properties of Biological Soil Crusts in Different Shrub Communities in the Gonghe Basin

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Abstract

This study investigates the differences in physicochemical properties of biological soil crusts (BSCs) among different shrub communities in the Gonghe Basin of Qinghai Province, providing theoretical reference for the protection and rational utilization of BSC resources. BSCs at different developmental stages within *Artemisia desertorum*, *Caragana microphylla*, and *Salix cheilophila* communities in the Gonghe Basin were selected as research subjects. Through field sampling combined with laboratory analysis, their particle composition and nutrient characteristics were examined. The results showed that the particle composition of BSCs in all three shrub communities was dominated by sand particles (45%–90%). The sand content followed the order: *C. microphylla* > *S. cheilophila* > *A. desertorum*, and all were significantly lower than that of bare sand between shrubs. The contents of total nitrogen, total carbon, organic matter, available phosphorus, available potassium, alkali-hydrolyzable nitrogen, and total phosphorus in BSCs of the *S. cheilophila* community were significantly higher than those in the other two communities, and these contents showed an increasing trend with BSC development across all three shrub communities. Shrub communities had the greatest influence on the physicochemical properties of BSCs, and shrub biomass was significantly positively correlated with BSC coverage, thickness, total nitrogen, total carbon, organic matter, available phosphorus, available potassium, alkali-hydrolyzable nitrogen, and total phosphorus, while being significantly negatively correlated with sand content ($P < 0.05$). Shrub communities effectively improved the soil structure of BSCs in the Gonghe Basin's sandy land; the *A. desertorum* community was more conducive to soil refinement, while the *S. cheilophila* community was more favorable for nutrient accumulation.

Keywords: biological soil crusts; shrub communities; differences in physicochemical properties; Gonghe Basin

1 Introduction

Arid zones are characterized by harsh environmental conditions, scarce water resources, and limited plant groups, with average vegetation coverage typically below 30%–40%. Biological soil crusts (BSCs) are widely distributed, covering more than 70% of the surface area in some arid regions. BSCs are complex surface covers formed by the cementation of soil surface particles through hyphae, rhizoids, and secretions from algae, lichens, mosses, and microorganisms. The developmental stages of BSCs mainly include microbial crusts, algal crusts, and moss crusts. The formation and development of BSCs can provide favorable environments for vegetation survival, thereby promoting plant growth. Additionally, BSCs can effectively alter soil physicochemical properties, influence surface runoff in desert areas, reduce soil erosion (wind and water erosion), and promote nutrient cycling.

Since the 1990s, Chinese scholars have conducted extensive research on BSCs, primarily in regions such as the Tengger Desert, Gurbantunggut Desert, Kubuqi Desert, Hunshandake Sandy Land, and Mu Us Sandy Land. However, research on the Gonghe Basin sandy land remains relatively limited. Existing studies have focused on BSC distribution, their effects on soil erosion resistance, and their impacts on soil moisture and physicochemical properties. Nevertheless, there remains room for deepening our understanding of BSC spatiotemporal distribution and influencing factors, particularly regarding the physicochemical properties of BSCs under higher vascular plants. Comparative studies on soil physicochemical properties of BSCs among different vegetation communities are also relatively scarce.

In the Ordos Sandy Land, research by Li et al. [14] found that nutrient contents in BSC layers distributed within *Sabina vulgaris* communities were higher than those in *Artemisia ordosica*, *Salix psammophila*, and *Hedysarum leave* communities. Zhou et al. [15] reported that soil nutrient contents in BSCs under *Salix psammophila* and *Artemisia ordosica* communities in the Mu Us Sandy Land were higher than those under *Pinus sylvestris* var. *mongolica* communities. In desert regions, research data on how BSC coverage, thickness, and physicochemical properties vary with shrub community type are very limited, especially in the Gonghe Basin, a high-cold sandy area, where it remains unknown whether differences exist in the interactions between different shrubs and BSCs.

The sandy land of the Gonghe Basin in Qinghai is located in the northeastern Tibetan Plateau, with a unique geographical position representing a typical area of land desertification in northwestern China. Due to its high altitude, the region experiences low temperatures, low precipitation, high evaporation, frequent and strong winds, and intense radiation, making it difficult for psammophytic vegetation to naturally recover on mobile sand dunes. Various plant-based sand fixation models have been implemented to actively combat desertification, establishing large-scale artificial sand-fixing vegetation restoration areas. The main afforestation species used on mobile sand dunes include *Caragana microphylla*, *Artemisia desertorum*, and *Salix cheilophila*, forming a mosaic sandy landscape of different shrub sand-fixing forests.

Artemisia desertorum has numerous clustered stems with good sand-blocking effects. *Caragana microphylla* is a deep-rooted species with a prominent taproot and well-developed lateral roots, exhibiting strong sand-fixing capacity. *Salix cheilophila*, a cold-resistant and drought-tolerant shrub or small tree with developed root systems, was introduced to the Gonghe Basin 40–60 years ago. Three shrub communities were planted on sand dunes with identical topography and initial environmental conditions. After years of development, extensive BSCs have emerged between shrubs, covering the surface and playing a crucial role in maintaining dune stability and slowing desertification. This study analyzes the particle composition and nutrient characteristics of BSCs developed in *Artemisia desertorum*, *Caragana microphylla*, and *Salix cheilophila* communities in the Gonghe Basin sandy land. The aim is to explore whether the physicochemical properties of BSCs vary among shrub communities under the same environmental conditions within a single sandy area, providing theoretical basis for comprehensively understanding the interaction between shrub communities and BSCs, enhancing assessment of soil functional stability, and deepening knowledge of BSC formation, development, and ecological functions in the Gonghe Basin sandy land.

1.1 Study Area Overview

The study area is located at the Shazhuyu Township Sand Control Experimental Station (100°25 E, 36°24 N) under the Qinghai Provincial Forestry and Grassland Bureau, situated in the Gonghe Basin on the northeastern Tibetan Plateau. The station experiences frequent and intense wind erosion, low temperatures, strong solar radiation, scarce water resources, fragile ecological conditions, and low vegetation coverage, representing a typical desertification area in northwestern China. The region has an altitude of approximately 2871 m, mean annual temperature of 1.0–2.4 °C, annual precipitation of 311–402 mm, mean annual wind speed of 2.1–2.7 $\mathrm{m \cdot s^{-1}}$, and annual evaporation as high as 1716.7 mm. Soil types include brown calcic soil and chestnut soil, with non-zonal soils comprising meadow soil, saline soil, and aeolian sandy soil.

The Gonghe Basin sandy land is extensive and high-altitude, with alpine and arid climatic conditions that result in relatively few vegetation species and simple community structures in the Shazhuyu area. Shrub species mainly include *Artemisia desertorum*, *Caragana microphylla*, *Salix cheilophila*, and *Hippophae rhamnoides*, while herbaceous plants consist primarily of *Leymus secalinus*, *Glycyrrhiza uralensis*, *Stipa capillata*, and *Poa pratensis*. The *Artemisia desertorum*, *Caragana microphylla*, and *Salix cheilophila* communities represent three typical shrub communities in the artificial sand-fixing vegetation of the Gonghe Basin sandy land, with community coverage of 40%–60% and average heights of approximately 0.8–3.1 m (*S. cheilophila* reaching up to 5.4 m).

BSCs at different developmental stages are distributed between shrubs in the three communities, with basic characteristics as follows (Fig. 1). Microbial crusts appear grayish-white, thin and brittle, easily broken, and have poor wind erosion resistance, with thickness generally less than 2 mm. Algal crusts typically appear dark brown with uneven, wrinkled surfaces, with thickness ranging from 3–8 mm. Lichen crusts are symbiotic aggregates of fungi and algae or cyanobacteria, generally appearing crustose, foliose, and gelatinous, with thickness of 5–10 mm. Moss crusts appear black or dark brown when dry and green when moisture is sufficient, with dense moss growth on the surface and thickness generally ranging from 10–12 mm.

1.2 Sample Plot Setup and Sample Collection

In late August 2019, sample plots were established in plant communities dominated by *Artemisia desertorum*, *Caragana microphylla*, and *Salix cheilophila*. Three 100 m × 100 m plots were selected for each sand-fixing shrub species. Within each plot, 5 m × 5 m shrub community quadrats were set up, and ten 10 cm × 10 cm BSC sub-quadrats were randomly established for investigation. Coverage was calculated using the quadrat method, while crust thickness was measured with vernier calipers (three replicate measurements) to obtain BSC coverage and thickness results (Table 1). Within each plot, bare sand and different types of BSCs were collected according to standard sampling methods. Bare sand samples were collected at a depth of 0–5 cm. In each plot, three samples of each developmental stage (microbial crust, algal crust, moss crust) were randomly collected and thoroughly mixed to form one composite sample. A total of 108 samples were collected, including nine bare sand samples and 33 samples from each of the *Artemisia desertorum*, *Caragana microphylla*, and *Salix cheilophila* community plots. Collected samples were placed in sterile sealed bags for subsequent analysis. Samples in sealed bags were passed through a 2 mm sieve to remove gravel and plant residues, then divided into two portions: one portion was stored at 4 °C for prompt determination of ammonium nitrogen and nitrate nitrogen, while the remaining portion was air-dried for determination of total nitrogen, total carbon, organic matter, available phosphorus, available potassium, alkali-hydrolyzable nitrogen, total potassium, and total phosphorus.

1.3 Sample Physicochemical Property Measurement

The indicators and methods for determining BSC physicochemical properties were as follows: total carbon and total nitrogen contents were measured using an elemental analyzer (2400II CHN elemental analyzer, Perkin Elmer). Organic matter content was analyzed using the potassium dichromate external heating method. Available potassium content was determined using 1 $\text{mol} \cdot \text{L}^{-1}$ ammonium acetate extraction-flame photometry. Alkali-hydrolyzable nitrogen content was measured using the alkali-hydrolysis diffusion method. pH was measured in 50 mL distilled water using a pH meter. Available phosphorus content was determined using the molybdenum-antimony anti-colorimetric method. Ammonium nitrogen and nitrate nitrogen contents were extracted with 2 mol · L^{-1} potassium chloride solution and measured on a flow analyzer (Autoanalyzer II, Technicon). Total phosphorus content was determined using sulfuric acid-perchloric acid digestion-molybdenum-antimony anti-colorimetric method. Total potassium content was measured using flame photometry. Particle composition was analyzed using a laser particle size analyzer (SALD-3001), with results classified according to the USDA soil particle size classification standard: sand (>50 m), silt (2–50 m), and clay (0–2 m).

1.4 Data Processing

Data were processed, statistically analyzed, and mapped using SPSS 24.0 software. One-way ANOVA was used to compare differences in physicochemical properties of BSCs at different developmental stages among the three shrub communities. Two-way ANOVA was employed to analyze the interaction between shrub communities and BSCs and identify the main sources of variation. The Least Significant Difference (LSD) test was used for post-hoc significance testing, with $P < 0.05$ indicating statistically significant differences. Spearman correlation analysis was also used to examine correlations between BSCs, shrub communities, and various BSC physicochemical factors.

2 Results and Analysis

2.1 Particle Composition of Biological Soil Crusts in Different Shrub Communities

The particle composition of BSCs in *Artemisia desertorum*, *Caragana microphylla*, and *Salix cheilophila* communities was dominated by sand particles, accounting for approximately 45%–90% of all particles, with relatively low silt and clay contents (Fig. 2). The sand content of different BSC types (microbial crust, algal crust, moss crust) was highest in the *C. microphylla* community (84.54%) and lowest in the *A. desertorum* community (46.81%). Silt content in the *C. microphylla* community (8.11%) was significantly lower than that in the *A. desertorum* community (10.25%) and *S. cheilophila* community (27.53%). Clay content followed the order: *A. desertorum* (22.08%) > *S. cheilophila* (11.38%) > *C. microphylla* (7.07%). The sand content of BSCs in all three shrub communities was lower than that of bare sand, while silt and clay contents were higher, indicating that BSCs have a soil-refining effect.

Further comparison of soil particle composition of BSCs at different developmental stages across shrub communities revealed distinct trends. Regarding sand content, it gradually decreased with BSC development in *A. desertorum* and *C. microphylla* communities, while in the *S. cheilophila* community, it first increased then decreased. For silt content, it gradually increased with BSC development in the *A. desertorum* community, first increased then decreased in the *C. microphylla* community, and first decreased then increased in the *S.*

cheilophila community. For clay content, it gradually increased with BSC development in the *A. desertorum* community, while in *C. microphylla* and *S. cheilophila* communities, it first decreased then increased.

2.2 Nutrient Content of Biological Soil Crusts in Different Shrub Communities

As shown in Fig. 3, the contents of total nitrogen, total carbon, organic matter, available phosphorus, available potassium, alkali-hydrolyzable nitrogen, and total phosphorus in different BSC types (microbial crust, algal crust, moss crust) were significantly higher in the *S. cheilophila* community than in the *A. desertorum* and *C. microphylla* communities. Nitrate nitrogen content showed no significant differences among the three shrub communities ($P > 0.05$). Ammonium nitrogen content in the *A. desertorum* community ($1.94\ \mathrm{mg \cdot kg^{-1}}$) was significantly higher than that in the *S. cheilophila* community ($0.49\ \mathrm{mg \cdot kg^{-1}}$) and *C. microphylla* community ($1.26\ \mathrm{mg \cdot kg^{-1}}$). Total potassium content was highest in the *A. desertorum* community ($19.46\ \mathrm{g \cdot kg^{-1}}$), with no significant differences between the other two communities ($P > 0.05$).

Further comparison of nutrient characteristics of BSCs at different developmental stages revealed that the contents of total nitrogen, total carbon, ammonium nitrogen, organic matter, available phosphorus, available potassium, total phosphorus, and total potassium generally increased with BSC development across all three shrub communities. Nitrate nitrogen content showed no significant changes with BSC development in *A. desertorum* and *C. microphylla* communities ($P > 0.05$), but gradually decreased with BSC development in the *S. cheilophila* community. Alkali-hydrolyzable nitrogen content gradually increased with BSC development in the *A. desertorum* community, first increased then decreased and increased again in the *C. microphylla* community, and first decreased then increased in the *S. cheilophila* community. The pH of BSCs gradually increased with development in the *A. desertorum* community, while in *C. microphylla* and *S. cheilophila* communities, pH first increased then decreased.

2.3 Effects of Biological Soil Crusts and Shrub Communities on Different Physicochemical Factors

To investigate the effects of BSC developmental stage, shrub community, and their interaction (developmental stage × shrub community) on 11 physicochemical factors, two-way ANOVA was conducted. As shown in Table 2, developmental stage, shrub community, and their interaction had significant effects on 10 physicochemical factors (excluding available phosphorus) ($P < 0.05$), with shrub community showing the highest significance. For total nitrogen, total carbon, ammonium nitrogen, organic matter, alkali-hydrolyzable nitrogen, total phosphorus, total potassium, sand, silt, and clay contents, the significance order was: shrub community > developmental stage > developmental stage interaction. For nitrate nitrogen, available potassium, and pH, the significance order was: developmental stage > shrub community > developmental stage interaction. For available phosphorus content, the significance order was: shrub community > shrub community × developmental stage interaction > developmental stage.

This study conducted Spearman correlation analysis between measured BSC particle composition and nutrient characteristic factors and shrub biomass, BSC coverage, and thickness. As shown in Table 3, shrub biomass was significantly positively correlated with BSC coverage, thickness, total nitrogen, total carbon, organic matter, available phosphorus, available potassium, alkali-hydrolyzable nitrogen, and total phosphorus, and significantly negatively correlated with sand content ($P < 0.05$). BSC coverage and thickness showed the strongest correlation with organic matter content ($r = 0.998$, $P < 0.05$), while shrub biomass showed the strongest correlation with available phosphorus ($r = 0.772$, $P < 0.05$).

3 Discussion

Biological soil crusts are important components of desert ecosystems and play a significant role in combating soil desertification. Numerous studies have shown that BSCs can alter soil physicochemical properties, promote nutrient cycling, and regulate soil eco-hydrological cycles to varying degrees. However, due to regional differences in geographical environments, conclusions drawn by different scholars vary across study areas. Our results indicate that the soil particle composition of BSCs in three typical shrub communities in the Gonghe Basin sandy land is dominated by sand particles (Fig. 2), with low silt and clay contents, consistent with findings from Cui et al. [24] in the Ordos Sandy Land, Wang et al. [25] in the hilly-gully region of the Loess Plateau, and Du et al. [26] in the Tengger Desert.

During BSC formation and development, the contents of total nitrogen, total carbon, ammonium nitrogen, organic matter, available phosphorus, available potassium, total phosphorus, and total potassium generally increase. This occurs because as BSCs develop, litter, secretions, and residues in the community are continuously decomposed by microorganisms to form humus soil, effectively promoting the accumulation of soil organic matter and nutrients. The presence of bacteria, fungi, algae, and moss plants enriches the contents of organic matter, available phosphorus, available potassium, and other nutrients, while dead algae and mosses during BSC succession further increase nutrient content. Zhang et al. [27] found that nitrogen fixation rates of moss and algal crusts were 14–133 $\mathrm{mol \cdot m^{-2} \cdot h^{-1}}$ and 4–28 $\mathrm{mol \cdot m^{-2} \cdot h^{-1}}$, respectively, indicating that BSCs provide an important nitrogen source for arid region soils.

Different shrub communities have distinct effects on BSC soil particle composition, with *C. microphylla* showing significantly higher sand content, consistent with the findings of Guo et al. [29] in the southeastern margin of the Mu Us Sandy Land. Silt and clay contents followed the order: *A. desertorum* > *S. cheilophila* > *C. microphylla*, possibly because *A. desertorum* is lower-growing than *C. microphylla* and *S. cheilophila*, being a multi-branched subshrub with numerous basal branches that facilitate the accumulation of extremely fine materials on the surface, resulting in higher silt and clay contents in BSCs. Additionally, from microbial to algal to moss crusts, surface coverage and roughness gradually increase, enhancing the ability to capture atmospheric dust and thereby increasing crust thickness and fine particle content. The sand content of BSCs in all three shrub communities was lower than that of bare sand, while silt and clay contents were higher, indicating that BSCs refine soil texture, consistent with the findings of Guo et al. [30] in the Horqin Sandy Land.

The differential effects of different shrub communities on BSC soil nutrient content are consistent with the findings of Deng et al. [28] in the middle reaches of the Heihe River. Ammonium nitrogen content in BSCs at different developmental stages was higher than that in bare sand, as microorganisms in BSCs mineralize organic nitrogen, enabling rapid nitrogen absorption and resulting in higher ammonium nitrogen content.

Two-way ANOVA results showed that shrub community had a significantly greater effect on BSC physicochemical properties than developmental stage and the developmental stage × shrub community interaction (Table 2). Different shrub communities significantly affected BSC coverage, thickness, and physicochemical properties, leading to differences in soil fine particle content and organic matter and other nutrient contents. *Artemisia desertorum* is a low-growing, multi-branched subshrub; BSCs between its shrubs have finer soil texture, smaller particle size, and higher silt content, which increases BSC coverage, reduces wind erosion impacts, and enhances the ability to bind fine particles and interact with other factors. *Salix cheilophila* is a shrub or small tree with larger crown width, dense branches and leaves, and developed root systems. BSCs in this community capture more nutrient particles from the atmosphere and rainfall, promoting increased crust thickness and preventing large-scale soil erosion to protect these nutrients.

Shrub biomass was significantly positively correlated with organic matter, total nitrogen, available potassium, alkali-hydrolyzable nitrogen, total carbon, total phosphorus, total potassium, silt, clay, available phosphorus, BSC coverage, and BSC thickness, and significantly negatively correlated with sand content ($P < 0.05$), further confirming that nutrient content was highest in the *S. cheilophila* community with the greatest biomass. BSC coverage and thickness were significantly positively correlated with soil organic matter, total nitrogen, available potassium, alkali-hydrolyzable nitrogen, total carbon, total phosphorus, silt, available phosphorus, and ammonium nitrogen ($P < 0.05$), and significantly negatively correlated with sand content ($P = 0.000$) (Table 3), indicating that BSC formation and development increase fine particle content and organic matter and other nutrient contents in the soil environment.

Salix cheilophila, as a Salicaceae shrub or small tree with larger crown width and dense branches and leaves, accumulates substantial soil nutrients from wind-blown sand, with most litter decomposing into the soil. Its well-developed root system produces numerous root exudates, resulting in significantly higher total nitrogen, total carbon, organic matter, available phosphorus, available potassium, alkali-hydrolyzable nitrogen, and total phosphorus contents in BSCs compared to other communities. In contrast, *A. desertorum* and *C. microphylla* with sparser branches and smaller crown widths have relatively less litter and accumulate fewer soil nutrients from wind-blown sand. Although their main root systems are less developed than *S. cheilophila*, their lateral roots are well-developed and absorb nutrients from surrounding soils, which may reduce nutrient enrichment in BSCs.

Our results showed that organic matter content had the strongest correlation with BSC coverage and thickness ($P < 0.05$), and organic matter content was highest in the *S. cheilophila* community and lowest in the *C. microphylla* community, further confirming that crust thickness and coverage were highest in the *S. cheilophila* community with the highest organic matter content. BSC formation and development is a dynamic process; BSC development can improve soil physicochemical properties, while conversely, changes in soil particle composition and increases in water and nutrients can also improve BSC structure and promote BSC development. This study only analyzed the physicochemical properties of BSCs in different shrub communities in the Gonghe Basin sandy land. Further in-depth research from multiple perspectives, such as microclimate, litter, or secretions from different plants, is needed to investigate the relationship between different shrubs and BSCs.

4 Conclusions

Artemisia desertorum, *Caragana microphylla*, and *Salix cheilophila* communities can all significantly improve the physical structure of BSCs and increase BSC nutrient content. Among them, the *A. desertorum* community is more conducive to soil refinement, while the *S. cheilophila* community is more favorable for nutrient accumulation. Shrub community has the greatest influence on BSC physicochemical properties, and shrub biomass is significantly correlated with BSC coverage, thickness, and physicochemical factors. As three excellent sand-fixing vegetation types in the Gonghe Basin sandy land with significant differences in physicochemical properties, fully considering the influence of vegetation type on BSC development during ecological construction in arid desert areas is important for effectively improving soil structure, deepening understanding of BSC formation, development, and ecological functions in the Gonghe Basin sandy land, and providing basis for vegetation restoration and reconstruction.

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