

Effects of Mechanical Sand Barriers for Sand Fixation on Formation and Development of Biological Soil Crusts: Postprint

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Abstract

Biological soil crusts play an important role in maintaining the stability of desert ecosystems. Therefore, utilizing mechanical sand barrier auxiliary measures to promote the formation and development of biological soil crusts in arid sandy areas is of great significance. This study employs microbial high-throughput sequencing combined with soil physicochemical property measurements to investigate the effects of mechanical sand barrier sand fixation (straw checkerboards, grids, and netting) on the formation and development of biological soil crusts. The results show that: the crust color in straw checkerboards and grids is similar to that of algal crusts, while the crust coverage is highest and thickness greatest under netting; the proportions of clay and silt particles in crusts under all three mechanical sand barrier types are significantly higher than in shifting sand, and the nutrient enrichment level, i.e., pedogenic degree, is highest in crusts under netting; analysis of the composition of fungi, bacteria, and cyanobacteria in crusts from the three mechanical sand barrier types reveals that the proportion of Cyanobacteria in the bacterial composition and *Leptolyngbya* in the cyanobacterial composition of netting crusts is higher than that in straw checkerboard and grid crusts, while the proportion of Dothideomycetes in the fungal composition and *Microcoleus* in the cyanobacterial composition is lower, and the number of unique microbial OTUs is highest. Based on previous studies on the pedogenic processes and microbial succession patterns of biological soil crusts in arid regions, it is speculated that the developmental degree of crusts under netting is likely higher than that under straw checkerboards and grids, and their formation and developmental trajectory differs from the latter two. Therefore, among the three mechanical sand barrier sand fixation methods, netting is most conducive to the formation and development of biological soil crusts.

Full Text

Effects of Mechanical Sand Barriers on the Formation and Development of Biological Soil Crusts

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Abstract

Biological soil crusts play a crucial role in maintaining stability in desert ecosystems. Therefore, utilizing mechanical sand barriers as auxiliary measures to promote the formation and development of biological soil crusts in arid sandy regions is of great significance. This study investigated the effects of three mechanical sand barrier types—straw checkerboard, nylon grid, and covered net—on biological soil crust formation and development using microbial high-throughput sequencing combined with soil physicochemical property measurements. The results showed that the crust color in straw checkerboard and grid barriers was similar to that of algal crusts, while the covered net treatment produced the highest crust coverage and thickness. The proportions of clay and silt particles in crusts from all three barrier types were significantly higher than those in moving sand, with the covered net treatment showing the highest degree of nutrient enrichment, indicating the highest level of soil formation. Analysis of fungal, bacterial, and cyanobacterial composition revealed that the covered net crust had higher proportions of Cyanobacteria and Leptolyngbya compared to straw checkerboard and grid crusts, but lower proportions of Dothideomycetes and Microcoleus, along with the highest number of unique microbial OTUs. Based on previous research on biological soil crust formation processes and microbial succession patterns in arid regions, we infer that the development stage of crusts under covered nets likely exceeds that of straw checkerboard and grid treatments, with a distinct formation and development trajectory. Therefore, among the three mechanical sand barrier types, covered nets are most conducive to biological soil crust formation and development.

Keywords: biological soil crust; mechanical sand barrier; microbial succession; high-throughput sequencing

Introduction

Mechanical sand barriers represent one of the earliest engineering measures applied for wind prevention and sand fixation. These structures control wind-sand flow direction, velocity, and structure while altering erosion and deposition patterns to achieve wind resistance, sand blocking, and modification of geomorphic processes. The formation of biological soil crusts has emerged as a novel biological approach to sand fixation, which first requires a stable sand surface. Previous sand control practitioners have stabilized sand surfaces using vertical straw checkerboards, nylon grid barriers, and flat-laid nylon nets.

Common barrier materials include plant materials such as wheat straw, willow branches, and straw ropes; inorganic materials such as gravel, nylon nets, and plastic nets; and organic chemical materials such as polylactic acid (PLA) fibers. Based on configuration, mechanical sand barriers can be classified as either flat-laid or vertical. Flat-laid barriers can be further divided into concealed and semi-concealed types, while vertical barriers include high-standing and medium-standing forms. Currently, the wide variety of barrier types and configurations leads to varying sand fixation effects.

Biological soil crusts (BSCs), known as the Earth's "living skin," cover approximately 12% of the terrestrial surface and are primarily distributed in arid and semi-arid regions where plant growth is limited. Cyanobacteria are their main biological component. This study compares the physicochemical properties and bacterial, fungal, and cyanobacterial composition of physical and algal crusts formed under different mechanical sand barriers to elucidate their effects on BSC formation and development.

1.1 Study Area Description

The study area is located in the Shapotou sand fixation region on the southeastern edge of the Tengger Desert (37°32' N, 105°02' E, elevation 1330 m). This region lies in a transitional zone between the Alxa Plateau desert and desert steppe, characterized by a typical continental monsoon climate. The mean annual temperature is 10.6°C, with absolute minimum and maximum temperatures of -25.1°C and 38.1°C, respectively, and an annual temperature range of 63.2°C. Annual precipitation is 186.2 mm, with high interannual variability concentrated in summer and autumn. The dunes have very weak water retention capacity, with potential evapotranspiration exceeding 3000 mm—approximately five times the annual rainfall—and low relative humidity. Wind speeds average $2.9 \text{ m} \cdot \text{s}^{-1}$ from March to May, with annual sand-driving winds occurring 90-100 times, concentrated in March-May, and maximum wind force reaching $5 \text{ m} \cdot \text{s}^{-1}$.

1.2 Experimental Design and Sample Collection

Approximately 10 years ago, three types of sand barriers were established on gentle dune crests at Shapotou. The first was a $1 \text{ m} \times 1 \text{ m}$ straw checkerboard barrier (referred to as "checkerboard"). The second involved first laying a 1 m

× 1 m white nylon net (referred to as “covered net”), then erecting a 1 m × 1 m nylon grid barrier (referred to as “grid”) on top. The third was a 1 m × 1 m straw checkerboard barrier established in 2015. Moving sand without any barriers served as the control.

At the end of May 2020, sterile masks and gloves were worn, and sterilized spatulas were used to randomly collect surface crust samples from the checkerboard, grid, and covered net treatments. Approximately 2 cm of surface sand was collected from moving sand as the control. All samples were placed in sterile bags, with five replicates for each treatment and control. Each replicate consisted of random sampling from five points. Samples were transported in a cooler and stored in a low-temperature freezer for subsequent analysis.

[Figure 1: see original paper]

1.3 Soil Physicochemical Property Measurements

Crust thickness was measured at five different locations on each crust using vernier calipers, with 20 thickness values measured for each sand barrier type. After air-drying, crust samples were ground and passed through a 2 mm sieve for the following physicochemical analyses: (1) total nitrogen by semi-micro Kjeldahl method; (2) organic carbon by potassium dichromate external heating oxidation method; (3) available nitrogen by alkaline hydrolysis diffusion method; (4) total phosphorus by $\text{HClO}_4\text{-H}_2\text{SO}_4$ digestion with molybdenum-antimony anti-colorimetry; (5) available phosphorus by NaHCO_3 extraction with molybdenum blue colorimetry; (6) available potassium by NH_4Ac extraction with atomic absorption spectrophotometry; (7) total salt and electrical conductivity by conductivity meter; (8) pH by potentiometry; and (9) soil particle composition by laser particle size analyzer.

1.4 Microbial Experiments

DNA was extracted from liquid nitrogen-ground crust and sand samples using a PowerSoil DNA Isolation Kit (Bio Laboratories, Carlsbad, CA). For bacteria, cyanobacteria, and fungi, amplification was performed using primers listed in , followed by gene library construction and Illumina Miseq sequencing. After sequencing, data were processed using Trimmomatic, FLASH, Pear, and usearch software. Representative sequences were aligned and analyzed against the Silva Release128/132 database (<http://www.arb-silva.de>), with similarity levels controlled at 97% to obtain taxonomic information.

1.5 Data Analysis

Data were expressed as means ± standard deviation. One-way ANOVA and multiple comparisons (Duncan’s method) were performed using SPSS 22.0 software. Bar charts and Venn diagrams were generated using the ggplot2, VennDiagram, and cowplot packages in R.

2 Results and Analysis

2.1 Crust Morphological Characteristics and Sand-Fixing Effects

The crusts formed on straw checkerboard and grid surfaces exhibited similar gray-white colors characteristic of early-stage algal crusts, indicating they were algal crusts. In contrast, crusts formed under covered nets displayed a color similar to moving sand, representing physical crusts in the early stages of BSC formation. The sand-fixing effectiveness of the three barrier types could be evaluated through crust coverage and thickness measurements.

As shown in [Figure 2: see original paper], crust thickness on straw checkerboard surfaces averaged 1.81 cm, while grid surfaces showed similar thickness. Covered net crusts were significantly thicker at 4.05 cm. Although the color of covered net crusts differed from typical algal crusts, they demonstrated the best sand-fixing performance, with crust coverage reaching 90%-100%, compared to 50%-60% for grids and only 20%-30% for checkerboards.

2.2 Crust Physicochemical Properties

Chemical characteristics of straw checkerboard crusts were similar to those under covered nets, except for total salt content and electrical conductivity. Grid crusts showed significantly lower organic carbon and total nitrogen but higher available phosphorus and available potassium compared to the other two barrier types. Overall, pH values decreased significantly, indicating that all three barrier types substantially improved surface chemical properties compared to moving sand. Except for straw checkerboards, total salt content and electrical conductivity in grid and covered net crusts showed no significant difference from moving sand, suggesting these parameters are more resistant to change during soil formation.

All three barrier types significantly increased clay, fine silt, and powder particle proportions compared to moving sand, with corresponding decreases in fine and coarse sand proportions, indicating enhanced soil formation. Among the three barriers, covered net crusts showed the highest clay and powder particle proportions and the lowest coarse sand proportion. The particle size composition of covered net crusts was similar to that of grid crusts but differed from checkerboard crusts, which had significantly lower fine sand and higher coarse sand proportions.

2.3 Crust Microbial Composition

Bar charts display the relative abundance of bacterial phyla (Figure 4a: see original paper), eukaryotic classes (Figure 4b: see original paper), and cyanobacterial genera (Figure 4c: see original paper) in moving sand and the three barrier crusts. Cyanobacteria dominated all samples, with relative abundances of 55.4%-92.8%, being highest in covered net crusts. Intramacronucleata, a protozoan, showed highest abundance in covered net crusts, followed by checkerboard

and grid crusts. Dothideomycetes showed highest relative abundance in moving sand (19.0%) and similar levels in checkerboard and grid crusts, but lowest abundance in covered net crusts (14.0%).

Microcoleus showed lowest abundance in moving sand (11.1%), similar levels in grid and covered net crusts, and highest abundance in checkerboard crusts (12.0%). Leptolyngbya abundance was highest in covered net crusts and higher in all barrier crusts compared to moving sand. Venn diagrams ([Figure 5: see original paper]) revealed that covered net crusts contained the highest number of unique microbial OTUs. Pairwise comparisons showed that grid and covered net crusts shared the most bacterial OTUs (242) and fungal OTUs (46), while checkerboard and grid crusts shared the most cyanobacterial OTUs (20). Moving sand shared the most bacterial (20) and cyanobacterial OTUs with checkerboard crusts, but the most fungal OTUs with covered net crusts. Covered net crusts consistently showed higher numbers of unique microorganisms compared to the other treatments.

3 Discussion

In arid desert regions, once moving sand is stabilized by plants or sand barriers, physical crusts initially form through accumulation of atmospheric dust and powder particles on the sand surface, followed by raindrop impact. Subsequently, soil microorganisms and cyanobacteria colonize the surface, gradually evolving the physical crust into BSCs. The early successional stage is typically algal crust. Based on external morphology alone, grid and checkerboard crusts appear similar—gray-white in color and identifiable as early-stage algal crusts. In contrast, covered net crusts remain yellowish-brown, characteristic of physical crusts.

However, covered nets appear to facilitate BSC formation more effectively than checkerboards or grids, exhibiting higher coverage and thickness with stronger wind erosion resistance. BSC formation represents a soil development process where nutrient-poor sand surfaces become enriched through photosynthetic and nitrogen-fixing microorganisms, with surface clayification occurring simultaneously. All three barrier types reduced soil particle size compared to moving sand, particularly grid and covered net treatments. The nutrient enrichment levels were similar between checkerboard and covered net crusts, likely because wheat straw decomposition in checkerboards provides nutrients that accelerate soil formation, while covered nets reduce wind erosion and enhance surface temperature and moisture, favoring microbial growth and metabolism.

BSC formation and development also involves microbial community succession. Most studies indicate that Cyanobacteria dominate both physical and algal crusts, with their proportional abundance increasing during early succession as development progresses. Microcoleus and Leptolyngbya serve as pioneer cyanobacterial genera in BSC formation, likely due to their high drought and heat tolerance, with their proportions also increasing during succession. In typi-

cal arid region BSC succession at Minqin, Dothideomycetes abundance decreases initially then increases later. Based on bacterial, cyanobacterial, and fungal succession patterns, covered net crusts likely follow a different soil formation trajectory. Venn diagram analysis showing high numbers of unique microbial taxa in covered net crusts further demonstrates their distinct developmental pathway.

4 Conclusions

Comparative analysis of crust physicochemical and microbial characteristics from the three mechanical sand barrier types and moving sand yielded the following conclusions:

- 1) Crust colors in straw checkerboard and grid barriers resembled algal crusts, while covered net crusts were yellowish-brown. However, covered net crusts were thicker and achieved the highest coverage (90%-100%) compared to grid crusts (50%-60%) and checkerboard crusts (20%-30%).
- 2) Nutrient levels in all barrier crusts were significantly higher than in moving sand, with significantly reduced pH and enhanced clay content. Nutrient enrichment was similar between checkerboard and covered net crusts, while particle size composition was similar between covered net and grid crusts.
- 3) Microbial composition differed among crusts and moving sand. Covered net crusts showed highest Cyanobacteria abundance but lowest Dothideomycetes abundance. Microcoleus abundance was highest in checkerboard crusts, while Leptolyngbya abundance was highest in covered net crusts, which also contained more unique microbial OTUs than the other barrier types.

Overall, despite their physical crust-like appearance, covered net crusts likely represent a more advanced developmental stage than checkerboard or grid crusts, with distinct nutrient and microbial community succession patterns. Therefore, covered nets are most beneficial for biological soil crust formation and development among the three mechanical sand barrier types.

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