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# Biocrusts beneath replanted shrubs account for the enrichment of macro and micronutrients in semi-arid sandy land

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ABSTRACT

After 30 years of rehabilitation, moss-dominated crusts (biocrusts) formed under the canopies of *Caragana microphylla* shrubs on shifting sand dunes in the Horqin Sandy Land, China. Their impact on the spatiotemporal distribution of macro/micronutrients beneath the shrubs was determined. Soils were collected from 0 to 1 and 1–5 cm layers at three locations: two beneath shrubs (with/without biocrusts), the third at between-shrub interspaces, at end August 2013 (end wet season) and early June 2014 (end dry season). The biocrusts beneath shrubs enhanced macro/micronutrient enrichment (except extractable Ca), particularly in the 0–1 cm layer. Such positive effects exhibited seasonal dependence, i.e., the availability of phosphorus and micronutrients (iron, manganese, copper, zinc) in the 0–1 cm layer under biocrusts was significantly higher than at the other two sampling sites at end of dry season; no similar trend was observed at end of wet season. Significant increases in phosphorus and micronutrient availability were observed at end of dry season compared to wet season in both sampling layers at all sites, except topsoil beneath *C. microphylla* without biocrusts. This means that the colonization of moss-dominated crusts beneath *C. microphylla* can accumulate essential macro/micronutrients and partly compensate for the deficiency of essential nutrients in Horqin Sandy Land.



## 1. Introduction

The spatiotemporal distribution pattern of soil nutrients, particularly carbon (C) and nitrogen (N), in arid and semi-arid shrublands, has been widely investigated in order to understand nutrient cycling between soil and plants. In many cases, the enrichment of C and N, as well as phosphorus (P) and potassium (K), has been reported under the canopy of perennial shrubs relative to the adjacent interspaces. Such a 'fertile island' effect has been described as occurring on all continents (except Antarctica), particularly in the Great Basin of United States, the Negev Desert of Israel, and the Loess Plateau and Mongolian Plateau of China (Garner and Steinberger, 1989; Jia et al., 2010; Morris et al., 2013; Schlesinger and Pilmanis, 1998; Schlesinger et al., 1990; Su and Zhao, 2003; Titus et al., 2002; Tongway and Ludwig, 2005; Xie and Steinberger, 2001; Yang et al., 2011; Yu and Steinberger, 2012; Zhao et al., 2007).

Abiotic environments and processes (e.g., geomorphology, wind, and water erosion), shrub features (such as species, canopy size, and quantity and quality of litters), and soil biotic activities can affect the enrichment processes beneath shrubs (Jiang et al., 2007; Li et al., 2008a, 2008bbib_Li_et_al_2008b; Thompson et al., 2005; Zhang et al., 2010). For example, the entrapment of dry atmospheric deposition such as dust and/or clay particles by shrubs is one mechanism of nutrient accumulation under the shrub canopy (Puigdefábregas, 2005; Zhang et al., 2011). Nutrient enrichment under shrubs having a small canopy (compared to those with a large canopy) or in the early stages of the life cycle may be weak or negligible since a smaller amount of soil particles and/or chemical compounds can be entrapped (Li et al., 2008b; Wezel et al., 2000). Moreover, the extent of enrichment of different nutrients beneath a particular shrub species varies greatly from that of other species. Due to greater biotic activity, e.g., root uptake, microbial decomposition, and free or symbiotic $N_2$ fixation, the concentrations of organic C, total N, available P, and exchangeable K in topsoil were 50–2000% higher under shrub canopies compared with the interspaces (Kondo et al., 2012; Li et al., 2008b; Morris et al., 2013; Su and Zhao, 2003; Wezel et al., 2000; Yin et al., 2010). For non-

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limiting elements, such as calcium (Ca) and magnesium (Mg), no such enrichment was reported (Kondo et al., 2012; Wezel et al., 2000).

In addition, the formation of biocrusts at the interspaces between shrubs may also influence the transport of soil nutrients from those areas to the shrubs (Chamizo et al., 2012; Housman et al., 2007). Biocrusts are a thin, biotic mantle penetrating the upper millimeters of the soils, and are regarded as a natural boundary between above- and below-ground systems (Castillo-Monroy et al., 2011). On the one hand, biocrusts increase the stability of topsoil that may reduce or prevent the transport of fine soil particles, organic matter, and/or nutrients from the interspaces to shrubs via wind erosion. On the other hand, crustal organisms, such as cyanobacteria, can perform C and N fixation, and release them rapidly into surrounding soils (Belnap, 2002; Belnap et al., 2004; West, 1990). Furthermore, the higher abundance and richness of soil microfauna and mesofauna in soils under biocrusts, relative to bare areas at the interspaces, can also enhance soil nutrient cycling and accumulation. These processes may partly counteract the enrichment of soil nutrients beneath shrubs and, consequently, reduce the heterogeneity in soil nutrient availability in a patchy shrubland (Chamizo et al., 2012; Housman et al., 2007).

However, it is still unknown whether biocrusts reinforce the accumulation of soil nutrients, especially the macro and micronutrients, in soils beneath shrubs. To answer this question, the present study was initiated in the Horqin Sandy Land, the largest semiarid sandy-land in northern China. Owing to inappropriate human activities and a variety of climatic factors, this area has been suffering rapid degradation and desertification since the 1950s. Planting indigenous shrubs, such as *Artemisia frigida*, *Caragana microphylla*, and *Salix gordejevii*, in straw checkerboards on shifting sand dunes, has been proved to be an effective approach to prevent desertification and promote vegetation rehabilitation in this area (Huang et al., 2012; Su et al., 2004; Zhao et al., 2007). After seedling establishment, soil water-holding capacity, organic C, total N, total and available P, microbial biomass C and N, and enzyme activities in the topsoil beneath shrubs increase constantly with plant stand age (Cao et al., 2008; Dong et al., 2009; Su and Zhao, 2003; Zhao et al., 2007). In addition, the emergence of biocrusts, including cyanobacteria-, lichen- and moss-dominated crusts, under shrub canopies is also found to accompany vegetation rehabilitation (Zhao et al., 2010). The present study was, therefore, initiated to answer two questions: 1) Does the formation of moss-dominated crusts beneath *C. microphylla* canopies reinforce the enrichment of macro and micronutrients; and 2) does such an effect exhibit spatial (soil depth) and/or temporal (season) dependence?

## 2. Materials and methods

### 2.1. Study site

This study was conducted in the vicinity of the Wulanaodu village (43°02′N, 119°39′E, 479 m a.s.l.) in the Horqin Sandy Land, Inner Mongolia, China. The climate in this area is characterized by a temperate, continental, monsoon climate, and the growth season is from April to September. The multi-annual mean temperature is 6.3 °C with the extremely low temperature (−29.3 °C) in January and high temperature (39 °C) in July, respectively. The multi-annual mean precipitation (rain and snow) and pan-evaporation amounts are 311 mm and 2500 mm, respectively, with 70% of the yearly precipitation occurring between June and August. The landscape is characterized by undulating moving and semi-moving sand dunes. The thickness of the surface sand deposits is 20–120 m, and the soils are classified as cambic arenosols (FAO, 2006).

Since the early 1980s, the native perennial shrubs *C. microphylla* have been extensively planted in straw checkerboards (sizes of 1.0 m × 1.0 m, 1.0 m × 2.0 m, and 2.0 m × 2.0 m) on the windward slopes of shifting sand dunes in this area in order to prevent desertification. After approximately 30 years of restoration, biocrusts composed mainly of the *Barbula constricta* and *Bryum argenteum* species of moss were found to form under *C. microphylla* shrubs, especially under those planted in the 1.0 m × 1.0 m straw checkerboards. Although the fenced, restored sand dunes suffer mainly one month (or two months during extremely dry years) of light grazing at the end of the growth season (September) in recent years, biocrusts formed under *C. microphylla* shrubs survive cattle trampling due to the spines on the shrub stems (Kondo et al., 2012; Valiente-Banuet and Ezcurra, 1991). The amounts of chlorophyll a, bulk density, and the thickness of the moss-dominated crusts were 6.33 ± 0.82 μg $g^{-1}$, 1.45 ± 0.06 g $cm^{-3}$, and 6.25 ± 0.05 mm, respectively.

### 2.2. Soil sampling and pretreatment

Soil samples were collected on August 24th, 2013, and June 4th, 2014. On the one hand, the sampling times represent the end of the wet season and the end of the dry season, respectively; on the other hand, they can largely minimize the influence of cattle grazing on soil sampling and nutrient measurement as the grazing generally initiates from early September. Four 8 × 8 $m^2$ plots as four replicates were set up on the windward slope of a sand dune characterized by *C. microphylla* shrubs planted in straw checkerboards (size of 1.0 m × 1.0 m) in 1984 at the study site. The interval between two neighboring plots was no less than 10 m. At each plot, biocrust/soil was sampled from the 0–1 cm top layer and the 1–5 cm sublayer at three sites: two under the *C. microphylla* canopy, i.e., with biocrusts (treatment 1) and without biocrusts (treatment 2), and the third one at the interspaces between the shrubs (treatment 3). In order to reduce sampling bias caused by soil nutrient heterogeneity, five 0–1 cm layer soil samples were collected randomly by inserting five 90-mm ultra-pure plastic Petri dishes into soil for each treatment in the same plot, and the 1–5 cm layer soil samples were subsequently collected using a small shovel. The samples of the same treatment collected in the top layer or sublayer in each plot were combined and placed in a plastic bag, respectively, in the field as one replicate. All biocrust/soil samples collected from the four plots (n = 4) were kept in an insulated container with ice bags in order to prevent overheating, and then transported to the laboratory. Prior to chemical analyses, moss-dominated crust samples kept in 90 mm Petri dishes were gently transferred into a 2 mm sieve. Soils directly under the crusts were separated from the crusts by gentle sieving, and defined as 'topsoil' samples under the moss-dominated crusts. All other soil samples were sieved through a 2 mm mesh to remove stones, roots, and other organic debris, and then air-dried for analysis. Soil pH, organic carbon and total nitrogen contents of each soil layer at the three sampling sites were determined and listed in Table 1 as soil background information.

### 2.3. Measurement of soil chemical properties

(1) Soil pH was measured with an Orion Star A211 pH meter (Thermo Scientific, Beverly, MA) using a 1:2.5 soil:water ratio.
(2) Soil organic carbon ($C_{org}$) and total nitrogen (TN) were determined via combustion of ground subsamples (passing through a 0.16 mm mesh) using an elemental analyzer (Model CN, vario Macro Elementar Analyser System, GmbH).
(3) Available phosphorus was extracted using 0.5 mol $L^{-1}$ (pH 8.5) sodium bicarbonate, and its concentration was