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The seasonal and successional variations of carbon release from biological soil crust-covered soil

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ABSTRACT

Biological soil crusts play key roles in global carbon cycles in terms of carbon exchange between pedosphere and the atmosphere, yet few explorations have been conducted regarding how seasonal variations and successional patterns of the crusts influence C release in temperate desert ecosystems. The carbon release of four soil cover types (mobile dune sand, algae-, mixed- and moss-crusted) was measured in PVC mesocosms both before, in relatively dry conditions, and immediately after natural rainfall events. Intact crusts at a 10 cm level were removed from the southeast edges of Tengger Desert, China. Amounts of released C from the four soil cover types accounted for 18.4%–23.1%, 46.9%–52.3%, and 27.7%–31.1% of total C released in the spring, summer, and fall seasons, respectively. The annual C release amounts were 56.6 $gCm^{-2}\ yr^{-1}$ for the mobile dune sand, 67.9 $gCm^{-2}\ yr^{-1}$ for the algae-crusted soil, 90.3 and 128.8 $gCm^{-2}\ yr^{-1}$ for the mixed-crusted soil and moss-crusted soil. Linear regression analyses suggest a significant positive relationship between seasonal accumulative rainfall and carbon release amounts. These findings indicate that variations in the amount of seasonal rainfall and the succession of the crusts significantly change the carbon output patterns in the sandy desert ecosystem.

1. Introduction

Biological Soil Crusts (BSCs) are globally widespread communities of cyanobacteria, green algae, lichens, mosses, and other organisms (Belnap and Lange, 2003; Bowker et al., 2006; Li, 2012). In arid and semi-arid regions, BSCs play key roles in global carbon (C) cycles, in terms of both C uptake and its release back into the atmosphere (Elbert et al., 2012). Respiration, which is responsible for a large proportion of the landscape-scale C efflux, is also responsible for C release from BSCs (Zhao et al., 2014). BSC-dominated areas also are the main contributors to the total release of C by soil respiration in desert ecosystems (Castillo-Monroy et al., 2011). In the semi-arid steppe ecosystem of the Iberian Peninsula, BSCs-dominated sites account for 43% of the total release of C by soil respiration, with 37% and 20% from vegetation and bare soil, respectively (Castillo-Monroy et al., 2011). A recent study of a 16-year-old sand-fixed dune showed that during the growing season, algal crusts and subsurface microbial respiration accounted for approximately 60% of the C release in the soil (Zhang et al., 2013). It therefore can be concluded that BSCs contribute to a substantial portion of soil C release in arid and semiarid ecosystems.

The spatial and temporal patterns in water availability limit biological processes in arid and semi-arid ecosystems (Noy-Meir, 1973), including the C cycle (Bowling et al., 2011; Zhang et al., 2015). The C release in desert BSCs ultimately is water-limited, as the ability of BSCs to release C depends on the sufficient and adequate presence of water (Sponseller, 2007; Grote et al., 2010). Rainfall patterns in deserts determine C release. In particular, magnitude and duration of the C flux are related to the amount of rainfall (Huxman et al., 2004a; Xie et al., 2015). In arid regions, patterns of rainfall including magnitude, timing, and seasonality have been predicted to undergo substantial alterations in the future. Desert organisms may be more responsive to such combined and simultaneous changes rather than to the shifts in only mean annual rainfall (Coe et al., 2012). The response of C release by the BSCs to rainfall events also has been well documented. Studies

Abbreviations: ACS, algae-crusted soil; BSCs, biological soil crusts; C, carbon; MDS, mobile dune sand; MICS, mixed-crusted soil; MOCS, moss-crusted soil; SOC, soil organic carbon.

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have been carried out in the Sonoran, Chihuahuan, and Mojave Deserts (Cable and Huxman, 2004), Colorado Plateau (Coe et al., 2012), Tennger Desert (Zhao et al., 2014), and the Gurbantunggut Desert (Su et al., 2013), finding that the crusts' contribution to ecosystem CO_2 exchange was potentially large and increased with the magnitude of rainfall. Seasonal variations in the rainfall amounts showed strong fluctuations in arid and semi-arid regions. However, there is minimal knowledge regarding the seasonal variations of C release from the BSCs-covered soil in temperate deserts (Belnap et al., 2004; Li et al., 2012). In addition, the relationship between the accumulation of rainfall amounts and the release of C from soils with high BSCs content is still under investigation (Wu et al., 2015).

Generally, BSCs develop gradually from cyanobacteria-dominated crusts to lichen- and moss-dominated crusts after sand surfaces stabilize (Belap et al., 2004; Li et al., 2005). Numerous laboratory and field studies have shown that the C release amounts are closely related to the BSCs succession (Lange et al., 1998; Thomas et al., 2008). Both in the field and laboratory conditions, Grote et al. (2010) determined that the dark respiration rates were significantly greater in the dark (i.e., late succession) versus the light (i.e., early succession) BSCs collected from the Canyonlands National Park, Utah, USA. In field conditions, Zhao et al. (2014) also found that the moss-crust in the late succession had significantly higher C release amounts compared to the algae-crust in the early succession in the Tengger Desert, China. However, the quantitative relationship between different BSCs' successional stages requires further research.

Algal-crusts, mixed-crusts, and moss-crusts are the three predominant soil crust types in the re-vegetated fixed sand dune area in the Shapotou region of the Tengger Desert, China. These crusts form a dense green bio-carpet, covering large areas, which amount to more than 95% of the regional surface (Li et al., 2005, 2012). A two-year field study was conducted in this region to answer the following three questions: (1) How does the C release amount vary with the seasonal variations in wetting and drying conditions in the different BSCs types? (2) What is the relationship between the BSCs' C release and the accumulation of rainfall amounts? (3) What is the quantitative relationship among different BSCs' succession stages?

2. Methods

2.1. Study site

The Shapotou region is located on the southeast edge of the Tengger Desert in Northern China (37°33′ N, 105°02′ E), at an elevation of 1339 m. The natural vegetation is dominated by *Hedysarum scoparium* and *Agriophyllum squarrosum*, with a cover of approximately 1%. The soil substrate is made up of loose and impoverished mobile sand. The mean annual air temperature is 9.6 °C, mean annual rainfall is 186.6 mm, and mean annual wind velocity is 2.9 ms^{-1}.

To ensure the smooth operation of the Baotou–Lanzhou Railway in the sand dune area, a protective vegetation system was established along the railway line in 1956 by the Chinese Academy of Sciences and related departments (Li et al., 2005). During this period, a number of native shrubs, including *Caragana korshinskii*, *Artemisia ordosica*, and *H. scoparium*, were planted within the checkerboards. The vegetation in this system plays a vital role in soil rehabilitation and production of this desert ecosystem by stabilizing the dune surfaces and preventing wind erosion, thereby supporting the stability of the local desert ecosystem. Additionally, surface BSCs have expanded to cover 60% of the protective vegetation system during the past 54 years (Li et al., 2005, Fig. 1).

2.2. Experimental design and carbon release measurements

In this study, the three BSCs types in the 1956 re-vegetated area and the mobile dune sand (MDS) were selected for the measurement of the C release rate from March to November (spring: March to May; summer: June to August; fall: September to November) in 2011 and 2012 as follows: (1) algae-crusted soil (ACS, with more than 70% algal-crust); (2) mixed-crusted soil (MICS, algae/lichen/moss; with 45% moss-crust, 45% algal-crust, and 10% lichen-crust); (3) moss-crusted soil (MOCS, with more than 90% moss-crust cover); and (4) mobile dune sand (with no BSCs cover).

To avoid the impacts of vegetation and terrain on the development of BSCs, all samples were randomly collected from undisturbed soil in between-shrub spaces using PVC tubes with inner diameters of 10.4 cm and heights of 12.0 cm in mid-October, 2010. All samples had an 85.0 cm^2 surface area and a thickness of approximately 10 cm to ensure that active rhizines and organisms, as well as the majority of the surface soil organic matter layer in the crust, were included. Each BSCs types and mobile dune sand were taken 6 samples. These samples were taken to a nearby experimental station and randomly buried in soil (still in the PVC tubes), keeping the BSCs surfaces flush with the local soil surface. The bases of the PVC tubes were kept open for drainage in keeping with making test conditions as similar as possible to those found in the local site's environment through maintaining natural soil water and air cycles.

The post-rainfall C release rate in the collected samples was measured using a Li-6400-09 Soil Chamber (LI-COR, Lincoln, NE, USA). Measurements were taken immediately after rainfall and were repeated daily between 9:00 and 10:00, 14:00 and 15:00, and 20:00 and 21:00 (GMT + 8) until the C release rate returned to the pre-rainfall level. For each measurement, soil respiration rates were recorded at 4 s intervals over a 40 s period, once steady-state conditions were achieved within the chamber. If the rainfall magnitude was less than 2 mm, then the measurements were taken immediately after the rainfall and repeated hourly, due to the sample surfaces rapidly drying, until the respiration rate returned to the pre-rainfall level. The rainfall distribution in the Shapotou region during these experimental periods is shown in Fig. A1 and Fig. A2. From 2011 to 2012, 39 rainfall events were recorded; the accumulative rainfall amounts in 2011 and 2012 were 171.6 and 185.6 mm, respectively. Average rainfall amounts and proportions of total accumulative rainfall amounts, respectively, were 34.5 mm and 18.5% (spring), 93.4 mm and 50.8% (summer), and 55.9 mm and 30.7% (fall).

Chlorophyll a and b concentrations were estimated after the sample collection in 2010. The pigments were extracted with 98% ethanol in a dimly lit room. Absorption of the extracted solutions were then measured at wavelengths of 649 and 665 nm using a spectrophotometer (UV-1700 PharmaSpec, Japan), with concentrations then being calculated according to the following relationships (Chappelle et al., 1992; Hui et al., 2013):

$$\text{Chlorophyll a concentration } (\mu g\ cm^{-2}) = 12.7A_{665} + 2.69A_{649} \quad (1)$$

$$\text{Chlorophyll b concentration } (\mu g\ cm^{-2}) = 22.9A_{649} - 4.68A_{665} \quad (2)$$

Where A_{649} and A_{665} are the absorption values at 649 and 665 nm, respectively.

The $K_2Cr_2O_7$ method was used to measure the soil organic carbon (SOC), described in the Agricultural Chemistry Specialty Council, Soil Science Society of China (1983).