Catena 160 (2018) 252–260

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

The differential effects of sand burial on CO_2, CH_4, and N_2O fluxes from desert biocrust-covered soils in the Tengger Desert, China

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A R T I C L E I N F O

Keywords:
Biocrusts
Sand burial
Greenhouse gas
Desert

A B S T R A C T

Biocrusts are a crucial component of desert ecosystems, playing a significant role in greenhouse gas fluxes when they cover soils. However, little is known about whether, and how sand burial, one of the most common disturbances affecting the biodiversity and ecological function of biocrusts, influences fluxes of CO_2, CH_4, and N_2O from the desert biocrust-covered soils. Based on measurements of the fluxes of three greenhouses gases from soils covered with two kinds of biocrusts separately dominated by mixed (i.e., approximately 50% algal coverage and 50% lichen coverage of *Endocarpon pusillum* Hedw., here cyanobacteria are classed as algae) and moss (i.e., 100% coverage of *Didymodon vinealis* (Brid.) Zand.) crusts respectively, followed by zero (control), 1 mm (shallow burial), and 10 mm (deep burial) burial depths of sand, we studied the effects of short (20 days) and relatively long periods (one year) of sand burial on the fluxes of three greenhouse gases as well as their relationships with soil temperature and moisture at Shapotou on the southeastern edge of the Tengger Desert. The results of this study showed that sand burial had a significantly positive effect on emission fluxes of CO_2 and a negative effect on uptake of CH_4 by soils covered with the two types of biocrusts ($P < 0.05$), but had a differential effect on N_2O fluxes depending on burial depth. Shallow burial dramatically increased N_2O emissions from the biocrust-covered soils ($P < 0.05$), but the opposite was observed under deep burial. As burial time increased, the increase of CO_2 emissions decreased, but changes in fluxes of CH_4 and N_2O varied with biocrust types and burial depths, respectively. In addition, results showed that CO_2 fluxes from the two biocrusts were closely related to soil temperature and moisture; thereby increased with the raised soil temperature at 5 cm depth and soil moisture caused by sand burial. In contrast, CH_4 and N_2O emissions were not clearly related to temperature or moisture. Overall, the increase in global warming potential caused by sand burial indicates that this kind of deposition may aggravate the greenhouse effect of desert areas covered with biocrusts.

1. Introduction

The existence of global climate change is widely accepted (IPCC, 2013). Greenhouse gases, as important drivers of this change, have recently become one key research focus of environmental sciences. Desert regions make potentially marked contributions to the volume of global greenhouse gases and play an important role in climate change feedback because of their huge areas and stored amounts of soil carbon and nitrogen (Lal and Kimble, 2000; Wohlfarth et al., 2008). A number of studies have suggested that desert soils are the main contributors to soil respiration and contribute significantly to N_2O and CH_4 fluxes in desert (Peterjohn and Schlesinger, 1990, 1991; Strieg et al., 1992; Hartley and Schlesinger, 2000; Abed et al., 2013). However, due to their fragility and susceptibility, desert regions are more susceptible to climate change compared with other ecosystems. Small absolute changes can lead to huge impacts on desert ecosystem function and therefore feedback into climate change (Lal and Kimble, 2000; Belnap et al., 2003).

In many desert areas around the world, soil surfaces are often covered with biocrusts (Li, 2012). The biological community of these crusts comprises cyanobacterium, algae, lichen, moss, fungi, and other bacteria in differing proportions, which may dominate living desert cover to 70% or more (Belnap et al., 2003). Thus, desert biocrusts make important contributions to the circulation of energy, materials, and nutrient flows in these regions and greatly benefit ecosystem productivity. An increasing number of studies have shown that biocrusts comprise major pools of soil organic carbon and nitrogen in deserts (Belnap et al., 2003; Evans and Lange, 2003; Elbert et al., 2012; Li et al., 2012) and play dominant roles in soil respiration (Castillo-Monroy et al., 2011) and nitrogen cycling in many such ecosystems (Evans and

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http://dx.doi.org/10.1016/j.catena.2017.09.031
Received 15 March 2017; Received in revised form 5 September 2017; Accepted 29 September 2017
Available online 05 October 2017
0341-8162/

Ehleringer, 1993; Castillo-Monroy et al., 2011). It has recently been suggested that biocrusts may be responsible for CO_2 (Castillo-Monroy et al., 2011; He, 2012), CH_4 (Strieg et al., 1992; Laure and Verchot, 2007), and N_2O (Billings et al., 2002; Abed et al., 2013; Zaady et al., 2013) fluxes in desert ecosystems, and previous studies have shown that these greenhouse gases are affected by the impacts of climate change and other disturbances, including atmospheric warming (Dijkstra et al., 2011; Wang et al., 2011; Xu et al., 2014), elevated CO_2 (Dijkstra et al., 2011; Evans et al., 2014), grazing (Wang et al., 2002; Thomas, 2012), and fertilization (Wang et al., 2002; Wang et al., 2011).

Sand burial is a common disturbance in many sandy desert areas. However, compared to vascular plants, biocrusts are more susceptible to burial stress because they inhabit the soil surface and are small in size (Jia et al., 2008). Sand burial thus affects many aspects of biocrusts as well as the soil microenvironment, altering temperature and the availability of light, moisture, nutrients, oxygen (Harris and Davy, 1988; Maun, 1994, 2008), and micro-organisms (Maun, 2008). Burial time and depth are significant factors for biocrust survival and function (Wang et al., 2007). While a short and shallow burial may affect the physiological activities of biocrusts, longer and deeper burials can modify biocrust microbial communities and species composition. In spite of these dramatic impacts, few reports have been published on the effects of sand burial on the development and defense mechanisms of biocrusts (Jia et al., 2008; Maun, 2008; Williams and Eldridge, 2011; Rao et al., 2012), fewer still have addressed the impacts of sand burial on greenhouse gases fluxes from biocrust-covered soils.

Greenhouse gases are produced via different mechanisms and are variably affected by a range of environmental factors. For example, the main cause of N_2O flux in desert ecosystems appears to be denitrification (Peterjohn and Schlesinger, 1991; Abed et al., 2013) under anoxic conditions, limited by available water, carbon, and soil NO_3^- (Peterjohn and Schlesinger, 1991). In contrast, CO_2 exchange is driven by soil moisture and temperature (Castillo-Monroy et al., 2011), while flux of CH_4 is thought to be driven by diffusion in topsoil (Born et al., 1990; Dörr et al., 1993), controlled by physical structure and soil moisture content. The different response mechanisms of these three greenhouse gases to environmental factors may lead to variable responses in the fluxes of the three gases from biocrust-covered soils. Thus, the following questions can be asked: How and to what extent does sand burial differentially affect the fluxes of these three gases from biocrust-covered soils? The objectives of this study were therefore to: (1) Determine whether sand burial exerts differential effects on greenhouse gas fluxes from biocrust-covered soils; (2) Explore how sand burial affects the greenhouse gas fluxes of soil covered with biocrusts, and (3) Evaluate the relationships between greenhouse gas fluxes and environmental factors (i.e., soil temperature and moisture) changed by sand burial.

Our hypotheses are that sand burial will increase emissions of CO_2 and N_2O from biocrusts, and at the same time decrease CH_4 uptake from soil. We also hypothesize that, over time, changes caused by shallow burial can be relieved, while those that result from deep burial may be exacerbated. To test these hypotheses, we measured greenhouse gas fluxes and their relationships with temperature and moisture in soil covered with two dominant biocrust types, algae-*Endocarpon pusillum* Hedw. and *Didymodon vinealis* (Brid.) Zand., under different burial depths and durations at Shapotou in the southeastern edge of the Tengger Desert.

2. Material and methods

2.1. Study site

This study was carried out at the Shapotou Desert Research and Experimental Station, Chinese Academy of Sciences (referred to as Shapotou Station). This station is located at Zhongwei, in the Ningxia Hui Autonomous Region of China, in the southeastern fringe of the Tengger Desert (37°27′ N, 104°57′ E) at an altitude of 1339 m above sea level. This area is typical of the ecotone between desertified steppe and sandy desert; based on meteorological records from the period 1956 to 2003, average air temperatures is 9.6 °C and mean annual precipitation is approximately 186 mm, 80% of which falls between May and September. Mean annual potential evaporation is about 3000 mm, while the sand burial stress encountered by biocrusts in this region is either because of windblown sand and its re-deposition in winter and spring, or burial caused by mound-building creatures in summer and autumn.

Soils covered with biocrusts were collected from an area of natural vegetation, 46.5 km to the west of Shapotou Station (37° 25′ N, 104°36′ E). This region exhibits sparse vegetation that is distributed in patches; dominant shrubs and herbs include *Caragana korshinskii* Kom., *Artemisia ordosica* Krasch., *A. capillaris* Thunb., and *A. frigida* Willd. This region also boasts extensive distribution of moss, algae, and lichen species in biocrusts, including *Bryum argenteum* Hedw., *Didymodon vinealis* (Brid.) Zand., *Syntrichia caninervis* Mitt., *Microcoleus vaginatus* Gom., *Navicula cryptocephala* Kütz., *Lyngbya cryptovaginatus* Schk., *Scytonema javanicum* Kütz., and *Endocarpon pusillum* Hedw. The soil samples used in this experiment were taken from two kinds of biocrust dominated separately either by mixed (i.e., approximately 50% algal coverage and 50% coverage by the lichen *Endocarpon pusillum* Hedw.) or moss (100% coverage of *Didymodon vinealis* (Brid.) Zand.) crusts, distributed separately on the top, south-facing slopes, or north-facing sandy slopes of dunes.

2.2. Soil sampling and sand burial treatments

Intact soil samples covered with either mixed or moss crusts were collected in July 2014 using PVC tubes that had an inner diameter of 20 cm and a height of 22 cm. These tubes were pushed into the soil to collect intact columns; all samples had a thickness of approximately 20 cm to ensure that active rhizines, organisms, and most surface organic matter layers of the biocrust were collected. Samples were then taken to the Water Balance Observation Field at Shapotou Station and buried in soil (inside PVC tubes), ensuring that the biocrust surface was flushed with the local soil surface, after being subjected to sand burial treatments at different depths. Samples were then randomly divided into two groups and subjected to sand burials for different durations. The group that was subjected to a relatively long time period (one year) was buried immediately, while the group that was subjected to a relatively shorter time (20 days) was left untreated for one year and then buried in the same way in early August 2015.

For each treatment, three sand depths (i.e., zero (control), 1 and 10 mm, equivalent to 0, 31.4 and 314 ml of sand, respectively) were randomly, gently, and evenly distributed over all samples. These sand burial depths were determined based on actual wind-driven burial levels recorded in the study area, and three replicates of each sand burial treatment were carried out for each crust type.

2.3. Greenhouse gases fluxes and environment factors

Fluxes of greenhouse gases from all samples, including short- and long-period burial treatments, were measured in late August 2015 using static chamber and gas chromatography techniques. These chambers measured 25 cm in diameter and 40 cm in height; details of methods for gas sampling and analysis were similar to those reported in Ma et al. (2006) and Lin et al. (2009). Briefly, non-transparent chambers were closed for 30 min and four gas samples (ca. 25 ml each) were manually collected every 10 min between 9:00 am and 11:00 am using 50 ml plastic syringes. Gas concentrations in samples (i.e., CO_2, CH_4, and N_2O) were analyzed using chromatography (Agilent 6820, Agilent Technologies, Palo Alto, CA, USA) within 24 h.

During the process of gas sample collection, volumetric soil moisture of the 0–5 cm layer as well as temperature at 5 cm depth were