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Original article

Precipitation intensity is the primary driver of moss crust-derived CO_2 exchange: Implications for soil C balance in a temperate desert of northwestern China

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ABSTRACT

Precipitation is the major driver of ecosystem functions and processes in semiarid and arid regions. Although re-wetting pulses generate a significant portion of the total annual CO_2 exchange between atmosphere and soil, there has been little recognition of the importance of photosynthetic and respiratory activities of biological soil crusts (biocrusts) in desert soil CO_2 exchange. In this study in the Gurbantunggut Desert of northwestern China, our objective was to determine the extent to which precipitation intensity could influence soil CO_2 exchange of the desert ecosystem and the role played by moss crust in soil C balance during this process. In field experiments, net CO_2 exchange (NCE) was measured in moss crusted soil and in bareland once a month from March to November in 2013. In laboratory experiments, simulated precipitation treatments (0 mm, 2 mm, 5 mm, 10 mm and 15 mm) were applied to moss crust, and NCE of moss crusted soil and its three flux components (crust photosynthesis, crust respiration, and subsoil respiration) were measured. Temporal variation of NCE varied with soil moisture and temperature. Soil moisture alone can explain 71–74% of variation in NCE. Soil type (moss crusted soil or bareland) also had a significant effect on NCE ($P < 0.01$), but this was dependent on soil moisture which is directly linked to precipitation pulse. The response of NCE to precipitation pulse in moss crust differed significantly from that of bareland. After a 2 mm precipitation pulse, the crust gross photosynthetic rate (GPc) was lower than the crust respiration rate (Rc), resulting in C efflux. When precipitation intensity was equal to or greater than 5 mm, GPc fully offset total respiration, resulting in an increase in C uptake. C gain was positively correlated with intensity of precipitation pulse. Regardless of different precipitation intensities, Rc was significantly higher than that of subsoil respiration. Thus, precipitation primarily drives moss crust-derived CO_2 exchange, which significantly influences the balance of soil-level CO_2 exchange in desert ecosystems. Overall, this study demonstrates that in desert ecosystems, the regulation of atmospheric-soil C balance by moss crusts depends on the intensity of precipitation.

1. Introduction

Ecosystem processes in arid regions are principally dependent on water, the most limiting factor determining the activity of desert organisms [1]. Water availability is directly linked to precipitation and the majority of precipitation events occur as small (<5 mm) short-duration events [2]. Therefore, the majority of arid ecosystems exhibit a pulse-dynamic response to precipitation, and soils which are almost continuously dry are sporadically interrupted by transitory periods of saturation following precipitation events [3]. Individual precipitation events can provide brief pulses of resource availability for desert organisms [4]. In such water-limited ecosystems, pulsed water inputs directly control soil CO_2 exchange through a series of soil drying and rewetting cycles [5].

Although re-wetting pulses generate a significant portion of the total annual CO_2 exchange of desert soils, communities of

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heterotrophic and autotrophic micro-organisms in biological soil crusts provide an additional and important contribution to soil CO_2 exchange [6]. Biological soil crusts (biocrusts) are composed of various combinations of cyanobacteria, algae, fungi, lichens and mosses intermixed with mineral grains and colonize the top several millimeters of the soil surface in many arid and semi-arid ecosystems [7]. Biocrusts can completely cover plant inter-space surfaces in undisturbed areas and thus can constitute as much as 70% of the living cover in dryland areas [7]. Autotrophic organisms that comprise biocrusts have the potential to fix atmospheric C during photosynthesis, at rates ranging from 0.1 to 11.5 μmol m^{-2} s^{-1} [8], thus making them the main source of C input to desert ecosystem [9]. Photosynthetic and respiratory activity in biocrusts can be triggered by very small amounts of moisture, including dew and fog and can be sustained over a wide range of moisture conditions, and influence soil CO_2 exchange in arid and semi-arid regions [10].

The soil net CO_2 exchange of desert ecosystems is determined principally by the difference between CO_2 fixation by gross photosynthesis (GPc) of autotrophic soil crust, and combined respiration of soil crusts (Rc) and soil heterotrophs (Rs). Precipitation patterns in deserts determine the tradeoff between C uptake (photosynthesis by autotrophs in biocrusts) and C efflux (respiration by heterotrophs or light respiration from photoautotrophs) [4]. Specifically, both magnitude and duration of C exchange are related to precipitation intensity [4]. Given that biocrusts are concentrated within the first few centimeters of the surfaces of arid soils, biocrusts in hyperarid regions reduce precipitation infiltration [11]. Autotrophic and heterotrophic processes in surface strata can be initiated by small precipitation events [6]. Larger precipitation events are required to initiate belowground root and heterotrophic microbe activity [6]. For example, after a small precipitation pulse, crusts contributed 80% of soil-level CO_2 efflux to the atmosphere in the Sonoran Desert; following a large pulse event, roots and soil microbes contributed nearly 100% of the soil-level efflux [6]. Therefore, precipitation intensity appears to determine the relative contribution of both crust and subsoil to soil-level CO_2 exchange, with important implications for C balance in arid and semiarid ecosystems.

Moss crust is a characteristic type of biocrusts found in arid lands. Biocrust mosses play a major role in crust structure and function, and appear to be particularly sensitive to environmental change [12]. Change in the intensity of precipitation is predicted to significantly affect desert moss C balance and belowground processes [13]. In North America desert, biocrust moss (such as *Syntrichia caninervis*) displays higher C balances in winter than in summer [14]. However, little is known about the way in which biocrust mosses affect soil surface C flux in central Asia arid deserts, especially, the contribution of moss crust to ecosystem C flux and how it balances soil-level CO_2 exchange following precipitation pulses.

The Gurbantunggut Desert is a typical temperate desert, which is located at the central Asia. In the desert, biological soil crusts cover more than 40% of the land surface and moss crust is one of the dominant types of soil crust [15]. Special geographic location cast dry climate and conditions, which has been becoming more extreme in the summer months. Precipitation events are usually small, isolated and sporadic; the period between precipitation events lasts at least several days and may extend to many weeks in the desert [16]. Global climate models predict that annual precipitation in this area will increase by 25% by the next century [17], therefore, a better understanding of the contribution made by moss crust to C flux in the desert is essential for evaluating desert C balance.

We carried out experiments on moss crusted soil in the field and in the laboratory. The objectives of this study were (1) to explain the temporal variation in soil net CO_2 exchange in both moss crusted soil and in bareland; (2) to gain an understanding of the way in which precipitation intensity and moss crust influence soil CO_2 exchange and soil C balance. We hypothesized that (1) biocrusts significantly drive soil net CO_2 exchange after precipitation pulses; and (2) the contribution of biocrust CO_2 exchange to ecosystem C exchange is dependent on pulse intensity.

2. Material and methods

2.1. Study area

An *in situ* experiment was conducted in the Gurbantunggut Desert (44°11′–46°20′N, 84°31′–90°00′E), in the Junggar Basin of the Xinjiang Uygur Autonomous Region of China. The area is characterized as a temperate desert ecosystem. Annual precipitation varies from 70 mm to 160 mm; mean potential annual evaporation is 2606.6 mm. The average annual temperature is 7.26 °C. Natural vegetation is dominated by *Haloxylon ammodendron* (C.A. Meyer) Bunge and *Haloxylon persicum* Bunge ex Boissier & Buhse (Amaranthaceae), as well as shrubs and small semi-shrubs including *Ephedra distachya* L., *Calligonum leucocladum* (Schrenk) Bunge, *Artemisia campestris* subsp. *inodora* Nyman (syn. *Artemisia arenaria* D.C.) and *Seriphidium terrae-albae* (Krasch.) Poljakov. In spring and early summer, ephemerals and ephemeroids can grow vigorously and cover extensive areas. Vegetation cover can be as high as 40% in May [15]. Biocrusts are widely distributed on soil between shrubs and cover more than 40% of the whole desert. They are most abundant in the central and southern regions of the desert where there are two dominant crust types based on species composition: lichen/cyanobacteria crusts and moss crusts [18]. Lichen/cyanobacteria crusts are usually dominant throughout the desert, with the exception of the crests of high dunes. Moss crusts are typically found in the inter-dune areas where they form a patchwork mosaic with lichen/cyanobacteria crusts, the thickness of moss crust is about 2–2.5 cm. Moss crusts are usually dominated by *S. caninervis* Mitt., together with *Bryum argenteum* Hedw. and *Tortula muralis* Hedw [15].

2.2. *In situ* experiment: measurement of net CO_2 exchange in moss crusted soil and in bareland

In March 2012, one year prior to the start of CO_2 exchange measurement, a site with well-developed moss crust was selected in the southern part of the desert. The site, 10 m × 15 m, was fenced to protect the ground from disturbance by people and/or animals prior to the commencement of the study. Twelve 1 m × 1 m plots

Table 1
Soil organic matter content (SOC), soil microbial biomass carbon (MBC), soil total nitrogen content (TN), bulk density (BD), and chlorophyll *a* content (Chl *a*) in moss crusted soil and bare soil at soil layers of 0–3 cm.

Soil type	SOC (g kg^{-1})	MBC (μg g^{-1})	TN (g kg^{-1})	BD (g cm^{-3})	Chl *a* (10^{-3} mg/g)
Moss crusted soil	8.47 ± 1.34	486.22 ± 45.15	1.67 ± 0.23	1.46 ± 0.12	2.22 ± 0.50
Bare soil	2.66 ± 0.43	10.22 ± 1.82	0.83 ± 0.33	1.76 ± 0.06	0.35 ± 0.17