Soil Biology & Biochemistry 42 (2010) 773–787

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

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

Effects of soil moisture and temperature on CO_2 and CH_4 soil–atmosphere exchange of various land use/cover types in a semi-arid grassland in Inner Mongolia, China

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ARTICLE INFO

Article history:
Received 11 September 2009
Received in revised form
15 January 2010
Accepted 19 January 2010
Available online 4 February 2010

Keywords:
Carbon dioxide
Methane
Soil moisture
Temperature
Land use/cover
Xilin River catchment

ABSTRACT

The aim of this study was to investigate the combined effects of soil moisture and temperature as well as drying/re-wetting and freezing/thawing on soil–atmosphere exchange of CO_2 and CH_4 of the four dominant land use/cover types (typical steppe, TS; sand dune, SD; mountain meadow, MM; marshland, ML) in the Xilin River catchment, China. For this purpose, intact soil cores were incubated in the laboratory under varying soil moisture and temperature levels according to field conditions in the Xilin River catchment. CO_2 and CH_4 fluxes were determined approximately daily, while soil CH_4 gas profile measurements at four soil depths (5 cm, 10 cm, 20 cm and 30 cm) were measured at least twice per week. Land use/cover generally had a substantial influence on CO_2 and CH_4 fluxes, with the order of CH_4 uptake and CO_2 emission rates of the different land use/cover types being $TS \geq MM \geq SD > ML$ and $MM > TS \geq SD > ML$, respectively. Significant negative soil moisture and positive temperature effects on CH_4 uptake were found for most soils, except for ML soils. As for CO_2 flux, both significant positive soil moisture and temperature effects were observed for all the soils. The combination of soil moisture and temperature could explain a large part of the variation in CO_2 (up to 87%) and CH_4 (up to 68%) fluxes for most soils. Drying/re-wetting showed a pronounced stimulation of CO_2 emissions for all the soils —with maximum fluxes of 28.4 ± 2.6, 50.0 ± 5.7, 81.9 ± 2.7 and 10.6 ± 1.2 mg C m^{-2} h^{-1} for TS, SD, MM and ML soils, respectively—but had a negligible effect on CH_4 fluxes (TS: -3.6 ± 0.2; SD: 1.0 ± 0.9; MM: -4.1 ± 1.3; ML: -5.6 ± 0.8; all fluxes in μg C m^{-2} h^{-1}). Enhanced CO_2 emission and CH_4 oxidation were observed for all soils during thawing periods. In addition, a very distinct vertical gradient of soil air CH_4 concentrations was observed for all land use/cover types, with gradually decreasing CH_4 concentrations down to 30 cm soil depth. The changes in soil air CH_4 concentration gradients were in accordance with the changes of CH_4 fluxes during the entire incubation experiment for all soils.

1. Introduction

The atmospheric trace gases carbon dioxide (CO_2) and methane (CH_4), the two most important greenhouse gases besides water vapor, play a key role in the radiative balance of the earth's atmosphere (Forster et al., 2007). The global atmospheric carbon budget has been reported to be significantly affected by anthropogenic activities, such as land use/cover change (Ojima et al., 1993; Houghton et al., 1999; IPCC, 2007). Grasslands comprise approximately 25% of the earth's land surface and play a critical role in the global carbon cycle. However, at present most of the published data of CO_2 and CH_4 fluxes from soils refer to agricultural and forest ecosystems in the temperate zones of Europe and North America (e.g. Mosier et al., 1996; Hütsch, 1998; Butterbach-Bahl and Papen, 2002; Groffman et al., 2006), whereas only a few studies are available for grassland ecosystems and particularly for semi-arid grassland in Eurasia (Dong et al., 2000; Wang et al., 2005a; Liu et al., 2007).

The semi-arid grasslands of Inner Mongolia are representative for large areas of the Eurasian grassland belt. However, anthropogenic disturbances such as over-grazing and over-cropping may have already significantly affected biosphere–atmosphere

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doi:10.1016/j.soilbio.2010.01.013

exchange processes (Liu et al., 2007; Wang et al., 2008). Moreover, rapid population increase coupled with poor management over the last decades resulted in severe degradation and desertification of grasslands of Inner Mongolia (Li et al., 2000). However, the effects of such conversion on soil–atmosphere exchange of CO_2 and CH_4 are not well constrained. Since the intrinsic mechanisms probably depend on the specific soil characteristics (e.g., carbon content and availability, soil texture, soil water content), which in turn are affected by land use/cover change (Shrestha et al., 2004; Wang and Fang, 2009), investigations on carbon fluxes from different land use types are vital for constructing more reliable regional estimates.

Soil–atmosphere exchange of trace gases is mainly controlled by the simultaneous kinetics of production, consumption and diffusion processes in the sequential biochemical reactions (Conrad, 1996; Matthews et al., 2000a; Jassal et al., 2004). Soil moisture, temperature and soil disturbance have been identified as important factors controlling these processes (Gulledge and Schimel, 2000; Shrestha et al., 2004), which have been implemented in biogeochemical models used as tools to improve current estimates of CO_2 and CH_4 fluxes and to reduce the associated uncertainties (Fang and Moncrieff, 1999; Del Grosso et al., 2000; Kiese et al., 2008). In order to more accurately estimate soil–atmosphere fluxes of CO_2 and CH_4 at the regional, national or global scale, an important scientific priority has to be to gather data on CO_2 and CH_4 soil–atmosphere exchange rates for different land use/cover types under different climatic conditions, especially in regions of the world which have not be studied in detail yet. These results can be used to parameterize and validate biogeochemical models (Potter et al., 1996; Matthews et al., 2000b; Kiese et al., 2008).

To investigate the combined effects of soil moisture and temperature as well as dry/re-wet and freeze/thaw cycles on soil–atmosphere exchange of CO_2 and CH_4 from different land use/cover types, intact soil cores were taken from four representative land use/cover types in the Xilin River catchment, China and incubated in the laboratory under varying soil moisture and temperature levels according to field conditions. The main objectives of this study were (1) to evaluate land use/cover effects on soil emission/uptake of CO_2 and CH_4, (2) to determine the influence of soil moisture and temperature on C trace gas fluxes, and (3) to explore the relationship between CH_4 flux and soil air CH_4 concentration at different depths.

2. Materials and methods

2.1. Site description

The study area was the Xilin River catchment (43°26′–44°39′ N, 115°32′–117°12′ E), a representative geographic area of the Inner Mongolian steppe region with elevations ranging from 900 to 1400 m a.s.l. and an area of 3900 km^2 (Liang et al., 2003). This area has a temperate continental monsoon climate, with a frost-free growing season of 90–110 days (May–September). Annual mean air temperature in this area is 0.7 °C during 1982–2005, with the maximum monthly mean of 19.0 °C in July and the minimum of −21.1 °C in January (Liu et al., 2007). The mean annual precipitation of approximately 335 mm (166–507 mm) is distributed unevenly among seasons, primarily 60–80% falling as rain between June and August (Liu et al., 2007). The vegetation is characterized as a *Leymus chinensis* steppe, which is typical semi-arid grassland in the Eurasian mid-latitude zone. The growing season usually starts in May and ends in late September. The soils are mainly Calcic Chernozems according to IUSS Working Group WRB (2006) with the texture of approximately 20% clay, 20% silt and 60% sand (Wang et al., 2008).

Dominant land use/cover types in the Xilin River catchment consist of typical steppe, sand dunes, mountain meadow and marshland, covering 85%, 6.5%, 4.5% and 0.4% of the total area, respectively. Typical steppe (TS) is distributed widely throughout the whole catchment and is dominated by *L. chinensis* and *Stipa grandis*. Sand dunes (SD) are characterized by undulating topography where sand forms a sequence of depressions and hills. Mountain meadow (MM) areas are found in the east and northeast of the Xilin River catchment and have steep hills with relatively deep valleys. The valleys accumulate water and create good conditions for meadow grassland (*Bromus inermis*, *Agrostis gigantea*, *Carex pediformis*, *Stipa baicalensis* and *Calamagrostis epigeios*). Marshland (ML) areas border most of the Xilin River, its tributaries and bottoms of episodic streams. The vegetation found in these areas is mainly composed of marshland species such as *Phragmites australis*, *Carex appendiculata*, *Iris lactea* var. *chinensis* and *Hippuris vulgaris*.

2.2. Soil sampling and analysis

In order to account for spatial heterogeneity, three sites were chosen to represent each of the four dominant land use/cover types. The location of and the general information about each site are shown in Table 1. In July 2007, six intact soil cores (15 cm inner diameter, 40 cm height) were taken from each sampling site by use of PVC tubes (15 cm inner diameter, 50 cm height), which insured 10 cm of headspace left above the intact soil cores after sampling. It should be noted that during the period of soil sampling the soil moisture was generally rather low in our study region. According to meteorological data the total amount of rainfall in the last two weeks before core sampling was <25 mm. The PVC tubes were carefully driven into the soil with simultaneous cutting and removal of surrounding soil, thereby reducing disturbance of the soil inside the tubes to a minimum. Collected soil cores (72 in total) were transported to the laboratory for further processing and incubation experiments. Half of these soil cores (3 cores from each sampling site) were processed immediately for soil physical and chemical analyses (Table 2), while the second half were natural air-dried and transported to Germany by ship (approx. 2 months). At the laboratory of IMK-IFU soil cores were stored at a constant temperature of +4 °C before processing of the soil cores in the frame of the incubation experiments. Additionally, concentrations of extractable NO_3^- and NH_4^+, gravimetric soil water content (SWC) and microbial biomass C and N were analyzed at the end of the incubation experiments (Table 3).

Table 1
Sampling site locations and soil characteristics.

Sampling site	Coordinates	Altitude (m)	Soil type[a]	Soil texture (%)		
				Sand	Silt	Clay
TS (1)	43°39.9′N, 116°16.4′ E	1140	Chernozems	79.3	12.3	8.4
TS (2)	43°43.6′N, 116°28.8′ E	1237	Phaeozems	60.6	25.1	14.3
TS (3)	43°46.6′N, 116°39.7′ E	1286	Phaeozems	54.7	29.7	15.6
SD (1)	43°41.5N, 116°26.5′ E	1169	Arenosols	80.3	13.4	6.3
SD (2)	43°40.7′N, 116°33.4′ E	1176	Arenosols	73.5	18.2	8.3
SD (3)	43°37.1′N, 116°53.2′ E	1280	Arenosols	85.1	10.0	4.9
MM (1)	43°55.3′N, 116°48.7′ E	1423	Chernozems	28.3	47.7	24.0
MM (2)	43°43.1′N, 117°00.9′ E	1372	Phaeozems	56.5	28.2	15.3
MM (3)	43°45.3′N, 116°57.4′ E	1392	Phaeozems	26.8	48.2	25.0
ML (1)	43°37.0′N, 116°42.9′ E	1181	Gleyosols	91.9	4.9	3.2
ML (2)	43°39.3′N, 117°06.4′ E	1326	Phaeozems	87.2	7.5	5.3
ML (3)	43°46.9′N, 116°10.6′ E	1018	Arenosols	78.7	14.0	7.3

[a] WRB classification (IUSS Working Group WRB, 2006). TS: typical steppe; SD: sand dunes; MM: mountain meadows; ML: marshland, following number in brackets refer to site replications.