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Soil CO_2 emissions from five different types of land use on the semiarid Loess Plateau of China, with emphasis on the contribution of winter soil respiration

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HIGHLIGHTS

- Annual total and winter soil CO_2 emissions are considerable even in semiarid site.
- Mean winter soil CO_2 efflux rate was 11–25% of that in growing season.
- Soil CO_2 emission is related to soil organic carbon, total nitrogen contents, and C/N.
- Oak forest is most carbon economical among five land use types in the region.

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ABSTRACT

Many studies have investigated the response of soil respiration to environmental factors. However, there are few studies estimating soil CO_2 emissions in the land use of the Loess Plateau, China. Five different types of land use including a natural oak (*Quercus liaotungensis*) forest, a natural oriental arborvitae (*Platycladus orientalis*) forest, a black locust (*Robinia pseudoacacia*) plantation, a natural shrubland, and bare land were investigated from April 2010 to April 2012 in the semiarid Loess Plateau region. Total and winter season soil CO_2 emissions were estimated using integration and interpolation methods based on periodic measurements of soil respiration and environmental factors. The integrated average annual and winter soil CO_2 emissions (555.73–937.53 g C m^{-2} and 96.57–146.70 g C m^{-2}) were higher than the interpolated values (480.52–805.83 g C m^{-2} and 82.83–102.31 g C m^{-2}). The mean soil CO_2 efflux and mean winter soil CO_2 efflux during the 2 years ranged from 2.03 to 3.23 μmol m^{-2} s^{-1} and 0.52–0.80 μmol m^{-2} s^{-1} among different types of land use. The mean winter soil CO_2 efflux was 11–25% of that of the mean growing season. Q_{10} values for the five types were negatively correlated with average soil temperature and moisture. Soil organic carbon content, soil total nitrogen content and C/N ratio were not correlated with the amount of winter soil CO_2 emission, but correlated with annual total CO_2 emission and the contribution rate from winter period in positive and negative trends, respectively. Model improvement may improve the estimation accuracy of soil CO_2 emissions using the integration method, and increasing the frequency of soil respiration measurements is important for the interpolation method. It is inferred that the annual carbon sequestration, CO_2 emission, and the economical conditions of carbon budget follow a descending sequence as oak forest > shrubland > oriental arborvitae forest > black locust plantation > bare land.

1. Introduction

Soil respiration is one of the major processes controlling the carbon budget of terrestrial ecosystems (Schlesinger and Andrews, 2000). The total emission of CO_2 from soils is recognized as one of the largest fluxes in the global carbon cycle, with small changes in

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the amounts of soil carbon release potentially affecting atmospheric CO_2 concentrations (Kuzyakov, 2006; Piao et al., 2009; Shi et al., 2012c). Accurate estimates of and integrated studies on soil carbon release are urgently needed to develop a comprehensive understanding and to tackle global climate change.

Many measurements of soil CO_2 efflux have been carried out in various ecosystems in recent decades. Until now, most of the measurements have been conducted during the growing season, in part because of the difficulty in measuring CO_2 efflux in winter, but also reflecting an assumption that microbial activity in frozen or snow-covered soils is negligible (Fahnestock et al., 1998; Wang et al., 2010). However, some recent findings indicate that soil microbial biomass may actually peak in winter (Monson et al., 2006), and that soils can release considerable CO_2 even in winter (Hubbard et al., 2005; McDowell et al., 2000; Schindlbacher et al., 2007; Shi et al., 2012c; Wang et al., 2010). This suggests the need to include soil carbon release in winter for accurate estimation of carbon budgets.

Previous research on winter soil respiration has focused on Arctic and boreal ecosystems, especially tundra and alpine systems (Brooks et al., 1997; Elberling, 2007; Elberling and Brandt, 2003; Groffman et al., 2006; Ludwig et al., 2006; Oechel et al., 2000; Schimel et al., 2006), because high-latitude ecosystems are dominated by a long winter season covering nearly half a year. Given that high-latitude ecosystems are not deemed to be major terrestrial carbon sinks in the northern hemisphere, other areas may be relatively more important (Schimel et al., 2001). However, soil respiration during winter is seldom determined in those other areas (Shi et al., 2012c; Wang et al., 2010).

The Loess Plateau covers a large area in China, is approximately 9 °C latitude by 11 °C longitude in size, and includes arid, semiarid and subhumid climates (Du et al., 2007; Zhu et al., 1983). Several studies have investigated carbon cycling of this region (Shi et al., 2011, 2012b), but few researches have been conducted on CO_2 emissions, including those in the winter period.

In this study, we conducted a 2-year investigation on five representative land use types in the region. They included two natural forests dominated either by oak (*Quercus liaotungensis*) or the coniferous oriental arborvitae (*Platycladus orientalis*), a plantation of black locust (*Robinia pseudoacacia*), natural shrubland and un-forested bare land. Our objectives were (1) to determine and compare annual soil CO_2 emissions and the magnitude of the winter contribution in the five different types; (2) to evaluate methods of integration and interpolation for estimating soil CO_2 emissions; and (3) to quantify the environmental factors controlling soil respiration, including soil temperature, soil water content, soil organic carbon content and soil total nitrogen content.

2. Materials and methods

2.1. Study area and experimental site

Our study site was on Mt Gonglushan, near Yan'an City, Shaanxi Province, China (36°25.40′N, 109°31.53′E, 1353 m a.s.l.). On the Loess Plateau, the amount of precipitation and forest cover gradually decrease as one travels northwest; our site was in the forest–grassland transition zone (Cheng and Wan, 2002). The 40-year averages (1971–2010) of annual precipitation and annual mean air temperature were 504.7 mm and 10.1 °C, respectively. Seasonal snow cover may be present between December and March.

A permanent plot was set up in each of the five different land use ecosystems in this study: (1) a natural secondary forest dominated by Liaodong oak (*Quercus liaotungensis*), the major natural forest type in the region, on a northeastern slope of 22 °C, with upper-crown trees about 60 years old, (2) a natural forest stand dominated by oriental arborvitae (*P. orientalis*), on a southeastern slope of 10 °C, with upper-crown trees about 50 years old, (3) a plantation of black locust (*R. pseudoacacia*), a main reforestation species in the region, on a southeastern slope of 26 °C, and about 30 years of age, (4) a natural shrubland with a mixture of *Syringa oblata*, *Rosa hugonis*, and *Caragana microphylla*, on a western slope of 10 °C, and (5) an un-forested bare land area close to the black locust plantation, on a southeastern slope of 10 °C. The different ecosystems were about hundreds of meters to each other and share the same climatic conditions.

Main observation plots with dimensions of 20 m × 20 m were established in the five different land use ecosystems. In each plot, five 5 m × 5 m subplots were established at the four corners and the center. A specially designed polyvinyl chloride (PVC) collar was placed in the central part of each subplot for measurements of total CO_2 efflux from the soil.

2.2. Measurement of soil CO_2 efflux, temporal soil temperature, and moisture

Soil respiration was measured using an automated soil CO_2 flux system (LI-8100, LI-COR, USA) equipped with a portable chamber (Model 8100-103). A PVC collar (20.3 cm in diameter and 10 cm in height) was inserted into the soil base to a depth of 2.5 cm at each sampling point, about 2 weeks before the first measurement. Small litter and branches were left in the collar and large items were removed. All collars were left at the site for the entire study period.

Soil respiration data were measured over the 2-year period from 4 April 2010 to 14 April 2012, approximately once every 10 days during April–September 2010, and once every month in other months, except for February, May and August in 2011. Measurements were made between 8:30 and 11:30 local time on each sampling day. The growing season was May to September (Shi et al., 2012b). The winter length at the study site was 4 months from December to March, which was almost consistent with the continuous period with <0.5 °C of mean daily soil temperature at 5 cm depth defined by Grogan and Jonasson (2006).

Temporal soil temperature and moisture near each collar were measured at the same time as soil respiration measurements. Soil temperature was measured at a depth of 12 cm using a handle thermocouple probe, while the soil volumetric water content was measured at 0–12 cm depth, using a time domain reflectometry moisture meter (TDR200, Spectrum, USA). Soil temperature and soil moisture were not measured during the winter because the thermometers and TDR probe could not be fully inserted into the frozen soil. During the wintertime, the temporal soil temperature and moisture were obtained from continuous measurement. The detailed procedure is described in the next section.

2.3. Continuous measurement of climate and driving factors

Six kinds of meteorological instruments were placed in an open area outside the stands in the study site. Environmental data sampled included air temperature and relative humidity measured by a thermohygrograph (HMP50, Vaisala, Finland), and precipitation measured by a tipping bucket rain gauge (Model 7852, Davis Instruments, USA) connected to a CR10X data logger (Campbell Scientific, USA). In each stand, soil temperature was measured at 6 and 12 cm depth by thermo recorders (TR-52, T&D, Japan), and soil moisture was measured at 12 cm by a soil moisture sensor (SMB-M005, Decagon Devices, USA) connected to a HOBO logger (H21-001, Onset Computer, USA). Precipitation was recorded following each event. Other long-term measurements were performed at 30 s intervals, and 30-min averages were recorded.