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Non-growing season soil CO_2 efflux patterns in five land-use types in northern China

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HIGHLIGHTS

- CO_2 exchange patterns were evaluated during the non-growing season.
- Grazing influenced vegetation and soil characteristics.
- Land-use types altered temporal patterns of CO_2 fluxes.
- Precipitation during the growing season had a large legacy effect on CO_2 fluxes.
- Annual weather variation overshadowed the influence of land-use types.

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ABSTRACT

Heavy grazing and unsuitable farming practices have led to grassland degradation in northern China. This study examined soil CO_2 efflux (Fc) from five land-use types during the non-growing season on the southeastern edge of the Mongolian Plateau in China. The land-use types included three native vegetation steppes subjected to differing stocking rates [ungrazed (UG), moderately grazed (MG) and heavily grazed (HG)], a fertilized annual cropland (CL) and a perennial pasture (PP) used for haying and winter grazing. Values of Fc were measured at 3-day to 2-week intervals during the non-growing season in two contrasting hydrological years (2012-13 and 2013-14) using closed chambers. The Fc during 1 Oct. 2013 to 30 April 2014 averaged 475 mg C m^{-2} for all sites compared to a significantly ($P < 0.05$) lower Fc (102 mg C m^{-2}) during 1 Oct. 2012 to 30 April 2013. The seasonal Fc patterns followed the same trend during the two non-growing seasons with greater Fc observed in the autumn and spring freeze-thaw periods compared to the winter permanently frozen period, which accounted for 4.8% of accumulated total non-growing season Fc. The heavily grazed site showed less soil CO_2 efflux compared to UG, MG, PP and CL land-use types due to a larger reduction in gross primary productivity (GPP) compared to ecosystem respiration. Grazing reduced Fc by 23% for MG and 32% for HG compared to UG. Soil CO_2 efflux from the PP land-use type, which was grazed during the non-growing season, was 23% greater than that from the UG and CL land-use types. Air temperature during the non-growing season was the main factor controlling soil CO_2 efflux ($R^2 = 0.40$, $P < 0.001$), although soil water content also played a role. Precipitation received during the growing season had a large legacy effect on Fc. Annual weather variation overshadowed the influence of land-use types on Fc.

1. Introduction

Grasslands cover nearly 400 million hectares of the earth's land area and are extensive in China. About 78% of the grasslands in China occur in the northern temperate zone, which are an integral component of the Eurasian steppe and play an important role in

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supporting animal and crop production and providing ecological services (Kang et al., 2007). Soils in China's grassland are an important sink for C, storing 41.03 Pg C or about 13-fold more C than aboveground grassland vegetation (Ni, 2002). About 90% of China's grasslands exhibit some degree of degradation from heavy grazing, and large grassland areas have been converted to cultivated land and perennial pastures due to increasing food demand (SEPA, 1998). For example, 20 million hectares of China's grasslands have been ploughed since 1949 (SEPA, 1998). Meta-analysis indicated that soil C stocks declined 59% when land was converted from grassland to cultivated land (Guo and Gifford, 2002). Grassland conversion in China has resulted in a 2.3–2.8% decrease of soil organic C each year with a total soil C loss of 30–35% (Wang et al., 2011). Moderate and heavy degradation has resulted in a 1.24 Pg total net C loss from temperate grasslands in northern China during 1960–1990 (Wang et al., 2011). Therefore, it is critical to understand how land use impacts the process and magnitude of the C cycle and sink activity in China's grasslands.

Net ecosystem exchange (NEE) is the difference between C fixation by plants and heterotrophic and autotrophic respiration. The growing season of temperate grasslands in northern China is typically about six months. During the remainder of the year, grassland vegetation is primarily dormant, and NEE is comprised mainly of soil CO_2 efflux (Fc), primarily soil respiration (R_s). Previous studies indicated that significant levels of R_s can occur during the non-growing season on grasslands (Monson et al., 2006; Panikov et al., 2006; Chen et al., 2013), which can result in important losses of C captured during the growing season (Wang et al., 2007; Chen et al., 2013). The rate of CO_2 loss during the dormant period is mainly a function of soil temperature (T_s) and soil water content (SWC) (Frank et al., 2002; Gilmanov et al., 2004; Chen et al., 2013). Interannual variation of soil CO_2 efflux can be considerable depending on annual weather patterns (Polley et al., 2008; Zhang et al., 2010).

The reported effects of livestock grazing on Fc are inconsistent. Some studies showed that grazing reduced soil CO_2 efflux (Zou et al., 2007; Chen et al., 2013), while other studies found that grazing increased soil CO_2 efflux (Frank et al., 2002; Klumpp et al., 2007; Paz-Ferreiro et al., 2012). Moreover, Liebig et al. (2013) found that soil CO_2 efflux differed among grazing treatments during spring (March–May) and fall (September–November), but did not differ during winter (December–February) and summer (June–August) in the Northern Great Plains of the USA. In addition, soil CO_2 effluxes were greater from cultivated pastures compared to grazed and ungrazed grasslands during the growing season in the Northern Great Plains (Frank et al., 2002). These studies mainly focused on the growing season rather than the non-growing season and did not compare soil CO_2 efflux from grasslands subjected to different stocking rates, cultivated pasture and annual cropland.

Various land-use types are present in a mosaic pattern in the agro-pastoral region of northern China, and these types can change markedly with social-economic conditions (Zhao et al., 2002). Understanding the magnitude and being able to predict soil CO_2 efflux from various land-use types during the non-growing season is critical to accurately estimate C budgets in northern China. In this study, we hypothesized that interannual variability effects are greater than land-use effects on Fc during the non-growing season in dominant land-use types of northern China. The objectives of our study were to: 1) evaluate and quantify Fc from various land-use types including grasslands grazed at different stocking rates, perennial pasture and cropland and 2) clarify the coupling effects between land-use types and environmental factors for Fc in the agro-pastoral region of northern China.

2. Material and methods

2.1. Study site

Experiments were conducted at Guyuan County (41°46′ N, 115°41′ E, elevation 1380 m), located in Hebei Province, China. Geographically this region is part of the southeastern edge of the Mongolian Plateau and is temperate steppe. Large areas of the steppe have been converted to grain production. The region has a semiarid continental climate and receives approximately 320–400 mm mean annual precipitation, nearly 60–80% of which is received during the growing season (June to August). Annual mean temperature is 1 °C, with monthly mean temperature ranging from −18.6 °C in January to 17.6 °C in July. The mean frost-free growing period is 85–95 days (Rong et al., 2015a, 2015b).

Five land-use types were used in this study and were 1.5–5 ha in size (Rong et al., 2015a, 2015b). Land-use types included grazed grasslands (1.5 ha each) subjected to three different stocking rates (UG: ungrazed site, MG: moderately grazed site, HG: heavily grazed site) since 2010, perennial pasture (PP) since 2010 and permanent annual cropland (CL) since 1980. UG was ungrazed since 2010, MG was grazed at a stocking rate of 6.7 sheep ha^{-1} during the growing season with 50–55% biomass removal (1.4 sheep units ha^{-1} $year^{-1}$), and HG was grazed at a stocking rate of 9.3 sheep ha^{-1} during the growing season with 75–85% biomass removal (2.3 sheep units ha^{-1} $year^{-1}$) (Rong et al., 2015a, 2015b). Vegetation in the grazed land-use types was dominated by *Leymus chinensis* (Trin.) Tzvelev and *Stipa krylovii* Roshev., accompanied with *Cleistogenes chinensis* (Maxim.) Keng, *Phragmites communis* (Trin.), *Carex duriuscula* C.A. Mey, *Taraxacum mongolicum* Hand.-Mazz., *Artemisia frigida* Willd. and *Polygonum sibiricum* Laxm.

PP included an area of 5 ha that was converted from native grassland to *L. chinensis* pasture in 2009. PP was hayed during 15–20 Aug. each year, and the remaining stubble was grazed by cattle and sheep during the autumn and winter since 2010. The estimated stocking rate for PP during the non-growing season was 2.3 sheep units ha^{-1} $year^{-1}$. CL included an area of 5 ha that has been plowed and cropped each year since 1980, with a crop rotation of two years of *Avena nuda* L. and one year of *Linum usitatissimum* L. No irrigation was applied to any of the land-use types; fertilizers were only applied to CL at a rate of 100 kg/ha manure each year before sowing and 40 kg/ha urea at sowing (Rong et al., 2015a, 2015b). Soil in this area is a sandy soil and classified as a Kastanozems soil (FAO, 2006) or a Calciorthic Aridisol by the USA classification system (Soil Survey Staff, 2014).

In early Aug. of 2012 and 2013, vegetation and soil properties in each land-use type were sampled and measured. Aboveground biomass was determined inside a 0.5 m × 0.5 m quadrat with five replications in each land-use type. Plants were clipped to a 1-cm height, and clipped herbage was dried to constant weight in an oven at 80 °C for 48 h. Belowground biomass was sampled for the five land-use types at the locations where the aboveground biomass was clipped using a soil auger (6.5-cm inside diameter) to a 12-cm depth. Belowground samples were placed separately into a 0.02-mm nylon mesh bag, washed with water, dried in an oven at 80 °C for 48 h and weighed. Soil bulk density was determined using the ring-knife method with five replicate samples (ISSCAS , 1978). For analysis of soil characteristics, five soil samples (a mixture of five sampling points bulked into one sample) were collected in each land-use type to a 12-cm soil depth and dried at room temperature prior to analysis. Subsamples were ground to pass a 0.25-mm sieve and analyzed for soil organic carbon (SOC) and total N. A Rapid C Analyzer (Elementer, Germany) was used to determine SOC, whereas total N was determined by the Kjeldahl Method. Soil characteristics at the study sites are listed in Table 1.