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Response of soil CO_2 efflux to precipitation manipulation in a semiarid grassland

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A B S T R A C T

Soil CO_2 efflux (SCE) is an important component of ecosystem CO_2 exchange and is largely temperature and moisture dependent, providing feedback between C cycling and the climate system. We used a precipitation manipulation experiment to examine the effects of precipitation treatment on SCE and its dependences on soil temperature and moisture in a semiarid grassland. Precipitation manipulation included ambient precipitation, decreased precipitation (−43%), or increased precipitation (+17%). The SCE was measured from July 2013 to December 2014, and CO_2 emission during the experimental period was assessed. The response curves of SCE to soil temperature and moisture were analyzed to determine whether the dependence of SCE on soil temperature or moisture varied with precipitation manipulation. The SCE significantly varied seasonally but was not affected by precipitation treatments regardless of season. Increasing precipitation resulted in an upward shift of SCE–temperature response curves and rightward shift of SCE–moisture response curves, while decreasing precipitation resulted in opposite shifts of such response curves. These shifts in the SCE response curves suggested that increasing precipitation strengthened the dependence of SCE on temperature or moisture, and decreasing precipitation weakened such dependences. Such shifts affected the predictions in soil CO_2 emissions for different precipitation treatments. When considering such shifts, decreasing or increasing precipitation resulted in 43 or 75% less change, respectively, in CO_2 emission compared with changes in emissions predicted without considering such shifts. Furthermore, the effects of shifts in SCE response curves on CO_2 emission prediction were greater during the growing than the non-growing season.

Introduction

Semiarid grassland ecosystems are among the most vulnerable, and are highly susceptible to global climate change (Carbone et al., 2011; Morgan et al., 2011). They are also increasingly important drivers of the inter-annual variability of the global carbon (C) cycle (Poulter et al., 2014). Precipitation and the availability of soil water are the major limiting factors in

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semiarid ecosystems (Austin et al., 2004). Precipitation most directly affects soil moisture, which is a key driver of biological processes and plays a prominent role in terrestrial ecosystems by affecting plant productivity and soil processes (Ehrenfeld et al., 2005; Rodríguez-Iturbe and Porporato, 2005; Cruz-Martínez et al., 2012), which in turn modulate the impacts of other drivers of global change such as elevated atmospheric CO_2 levels, temperature, and nitrogen deposition (Wan et al., 2007; Jia et al., 2012). The responses of ecosystem processes to variations in soil moisture due to changes in precipitation have thus become the focus of current ecological and environmental research.

Responses of ecosystem processes to precipitation changes (both increasing and decreasing precipitation) have been studied in various ecosystems (Reichstein et al., 2002; Huxman et al., 2004; Lee et al., 2004; Xu and Baldocchi, 2004; Pereira et al., 2007; Chen et al., 2009), but considerable uncertainty remains about the directions and magnitude of the responses (Knapp et al., 2002; Hellmann, 2014), especially for arid or semiarid regions. This uncertainty complicates the accurate prediction of responses to future scenarios of precipitation change, which can impact C dynamics and fluxes in ecosystems (Doughty et al., 2015).

Soil CO_2 efflux (SCE) is the release rate of CO_2 from soil produced by autotrophs (roots) and heterotrophs (microbes and fauna), and is an important component of ecosystem CO_2 exchange (Monson et al., 2006; Carbone et al., 2011; Karhu et al., 2014). Soil CO_2 efflux thus provides feedbacks between C cycling and the climate system (Luo et al., 2001; Davidson and Janssens, 2006; Heimann and Reichstein, 2008). Soil CO_2 efflux increases with soil temperature, but has a quadratic relationship with soil moisture, *i.e.*, is limited by extremely dry and wet conditions (Harper et al., 2005; Wan et al., 2007). Such dependences provide the scientific basis for accurately predicting CO_2 emission and have been incorporated into models of C cycling (Kim et al., 2014). Changes in precipitation will undoubtedly alter soil temperature and moisture and thus the dependence of CO_2 release on these variables (Luo et al., 2001; Harper et al., 2005). The effect of precipitation manipulation on the dependence of SCE on temperature or moisture, however, has received little attention, but this knowledge is essential for understanding the adaption of SCE to changes in precipitation and thus for predicting CO_2 emission in future scenarios of climate change, because changes in precipitation regimes in dry ecosystems are expected to have significant feedback effects on CO_2 flux and the terrestrial C cycle (Shen et al., 2009).

In this study, we investigated the SCE in plots with manipulated levels of precipitation in a semiarid grassland in northwestern China. The response curves of SCE to soil temperature and moisture were analyzed. The objectives were to examine the effects of precipitation manipulation on SCE and its dependence on soil temperature and moisture in semiarid grassland.

1. Materials and methods

1.1. Study site and experimental design

This study was performed in the Yunwushan natural grassland protection zone (36°13′–36°19′N, 106°24′–106°28′E) near Guyuan City, Ningxia Hui Autonomous Region, China, in the center of the Loess Plateau. The grassland protection zone was established in 1984, with an area of 4000 km^2 and elevations of 1800–2148 m a.s.l. The study area has a continental monsoon climate. The mean annual temperature is 6.9°C, and the annual maximum and minimum temperatures occur in July (24°C) and January (−14°C), respectively. The mean annual precipitation is 425 mm. The soil in the study area is a mountain grey-cinnamon soil classified as a Calci-Orthic Aridisol according to the Chinese taxonomic system, equivalent to a Haplic Calcisol in the FAO/UNESCO system. The growing season at the study site is from May to October.

This experiment was established in a *Stipa capillata* L. grassland succeeded from farmland abandoned 30 years ago. The grassland has been protected from clipping and grazing by the Yunwushan Natural Grassland Management Bureau since the abandonment of the farmland. The experiment used a random block design with four replicates and 1.0–2.0 m between blocks. Each block contained three 4.0 × 5.0 m plots randomly arranged, with 1.0 m between plots. The three plots in each block received one of three precipitation treatments: ambient precipitation (AP), decreased precipitation (DP), or increased precipitation (IP). A movable rainout shelter (6.0 m long × 5.0 m wide × 2.1 m high) consisting of a steel frame supporting a clear plastic roof was installed in each block to intercept precipitation in the plots with decreased precipitation. The rainout shelters were manually moved to cover the DP plots before a rain and removed after ca. 1/3 of the duration of the rain. The amount of precipitation excluded was calculated from the measurement of the rainfall over time, recorded with an automatic rain gauge at the site every 10 min. Water equivalent to ca. 15% of the precipitation was added manually and evenly to the IP plots immediately after the end of the rain over both plants and soil so that the rate of application was similar to the rate of infiltration into the soil. Snowfall was not manipulated in this experiment. The precipitation was manipulated starting in July 2013.

To assess the influence of variations in major soil properties on the response of SCE, we measured soil bulk density (BD) and the concentrations of organic carbon (OC) and nitrogen (N) in the top 20-cm depth for each plot before the start of the experiment. Soil bulk density was measured in each plot at 0–20 cm depth using a stainless steel cutting ring 5.0-cm high by 5.0-cm in diameter. The soil cores were dried at 105°C for 24 hr. Three representative soil samples were randomly collected from 0 to 20 cm depth in each plot for measuring soil OC and N concentrations. Visible pieces of organic material were removed, and the moist field soil samples were brought to the laboratory and air-dried for chemical analysis. Soil OC and N concentrations were measured by the Walkley–Black method and Kjeldahl method, respectively. The results showed that these soil properties did not vary among plots, with a range of 0.98–1.03 g/cm^3 for BD, 34.2–36.4 g/kg and 3.53–3.69 g/kg for OC and N concentrations, respectively. We therefore assume that soil properties did not influence the response of SCE to precipitation treatments.

To evaluate the effects of plant biomass on SCE, aboveground biomass was measured by sampling three 1 × 1 m^2 subplots in each plot at the end of each growing season. Five