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Response of evapotranspiration and CO_2 fluxes to discrete precipitation pulses over degraded grassland and cultivated corn surfaces in a semiarid area of Northeastern China

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ABSTRACT

The effects of precipitation pulses on evapotranspiration (ET) and CO_2 fluxes were evaluated over different land surfaces in a semiarid area using eddy covariance technique. ET responded to rain events throughout the growing season, but the degree of responses varied among seasons. In spring and fall, ET slightly responded to precipitation pulses, because the precipitation amount in the rainfall event was small and very discrete. As the rainy season started in early summer, responses of ET to precipitation pulses significantly increased. In late summer, the intensity of responses in ET was weakened because the soils retain moisture by the high-frequency rainfall events and the antecedent soil moisture. Regarding CO_2 exchange, in early summer, the net CO_2 uptake slightly increased at the cultivated corn site after rain pulses, while the degraded grassland site experienced comparatively greater responses. In late summer, the cultivated corn site exhibited more negative CO_2 flux after rain than the grassland site, and the responses of net CO_2 uptake to rain pulses were much stronger than those in early summer. The soil moisture content and vegetation cover are the key factors in determining the responses of ET and CO_2 fluxes to precipitation pulses in these two semiarid ecosystems.

1. Introduction

Discrete precipitation pulses, usually defined as rainfall events < 5 mm, account for a large proportion of the precipitation received in arid and semiarid areas (Noy-Meir, 1973; Sala and Lauenroth, 1982). The role of precipitation pulses was firstly described by a pulse-reserve paradigm proposed by Noy-Meir (1973), which was recently modified by Reynolds et al. (2004). The timing and magnitude of the pulses not only stimulate the biological activities of plants and soil microbes (Reynolds et al., 2004), but also has a significant impact on water, energy, and carbon cycles in these arid or semiarid ecosystems (Austin et al., 2004; Cable et al., 2008; Robertson et al., 2009). However, to date, the knowledge of precipitation pulses is still a mechanistic understanding of their role (Huxman et al., 2004a). The effects of the variation in precipitation, such as the pulse size or frequency, on the structure and function of ecosystems in arid and semiarid areas remain unclear, and hence more detailed studies across a wide range of arid or semiarid ecosystems are required (Huxman et al., 2004a).

In water-limited area (without river or reservoir), evapotranspiration (ET) is a key component of the ecological and hydrological processes of the ecosystem (Allen et al., 1998). The major or the sole source of ET is rainfall (Sala et al., 1992; Kurc and Small, 2007). Thus, the annual total ET is almost equal to the amount of precipitation (Liu and Feng, 2012). Precipitation pulses in these areas show significant effects on ET, particularly by affecting the soil moisture. The processes of the transformation of precipitation to ET are complex, including antecedent soil water content (SWC), infiltration, runoff, evaporation, and hydraulic redistribution (Loik et al., 2004; Ivans et al., 2006). If the precipitation events are small but with long intervals, canopy interception may be significant and the precipitation can only wet the top few centimeters of soil, and most of the water is removed by soil evaporation (Reynolds et al., 2004). By contrast, if the precipitation events are small but shortly clustered, the soil moisture can accumulate to a certain level and simulate evaporation for a long period. If the precipitation event is large enough to allow deeper infiltration, then the excess water in the entire root zone can be absorbed by plant; thus, the absorbed water is transported within the plant and is used for the physiologic

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activities, which then returns to the atmosphere through stomata by transpiration. This process is expected to last for a few days, and would be influenced by vegetation cover and meteorological elements (Kurc and Small, 2004). The time lag between the rainfall event and the ET peak is crucial for successful modeling of ET response on a short time scale (Williams et al., 2009).

The relationship between the net ecosystem CO_2 exchange (NEE) and precipitation pulses is associated with precipitation pattern, soil microbial community, plant root depth, the different response time of soil microbe, and plants to rainfall events (Huxman et al., 2004a). Soil microbial respiration responds rapidly to precipitation pulses, and even a very small amount of rainfall can initiate significant biogeochemical processes driven by soil microbes near the ground surface, leading to CO_2 release into the atmosphere (Austin et al., 2004). Large pulse size makes soil water available for plant roots; thus, negative CO_2 flux could be observed, suggesting CO_2 assimilation and biomass production activities by the plants (Hibbard et al., 2001; Kurc and Small, 2007). An increase in the leaf area index (LAI) may affect plant responses to precipitation pulses, thus resulting in an increase in the photosynthetic rates and uptake of CO_2. The combined effect of soil microbe and plant activities may alter the NEE. However, the degree and timing of the responses would be highly variable among different species of the ecosystems. Huxman et al. (2004b) applied the same amount of simulated precipitation pulse to different grass surfaces and found that the there was a significant difference in the level of accumulated carbon between the native and the invasive species.

Previous studies have investigated the role of precipitation pulses in plant function and productivity (Laio et al., 2001; Chesson et al., 2004; Huxman et al., 2004a, 2004b; Loik et al., 2004; Ogle and Reynolds, 2004; Porporato et al., 2001; Reynolds et al., 2004; Rodriguez-Iturbe et al., 2001; Schwinning and Sala, 2004). Except for few studies (Ivans et al., 2006; Williams et al., 2009), information on the effects of size and distribution of precipitation pulses on ET and CO_2 flux is still lacking. In the semiarid areas with limited water content, better understanding of the mechanism of precipitation pulses and their influence on fluxes can help improve water use efficiency and agricultural production. In this paper, we focus on the responsiveness of ET and CO_2 fluxes to the intermittent precipitation pulses over the degraded grassland and cultivation corn ecosystems, both of which are typical land surface types in the semiarid area of China. The primary objectives of this study are to (1) provide detailed information on the responsiveness of ET and CO_2 fluxes to intermittent precipitation pulses for grassland and corn ecosystems, and (2) find out key factors in determining the responses of ET and CO_2 fluxes to precipitation pulses. The results of this study should help understand the critical factors in determining water vapor and carbon-exchange processes in this semiarid area.

2. Materials and methods

2.1. Site description

The research site is located in a semiarid area of Tongyu (44°25′N, 122°52′E, 184 m a.s.l), in northeastern China, which is also one of the reference sites of the CEOP (Coordinate Enhanced Observation Period, Bosilovich and Lawford, 2002). The site has a semiarid terrestrial climate of the mid-temperature zone. According to the historical data in Tongyu weather station, about 30 km northeast of the observation site, the mean annual precipitation measured from 1961 to 2002 is 389.6 mm. The annual mean air temperature in the same period is 5.7 °C. Approximately 80% of the annual precipitation occurs in the growing season from May to September. Land degradation occurred in the form of soil salinization and desertification in this area due to overgrazing and intensive farming.

Measurements were performed over the degraded grassland and the cultivated corn land, with about 5 km from each other. The terrain in this area is fairly open and flat with terrain slope < 1° in all directions; thus, the terrain effect on the observation is minor. The soils in this area are mainly composed of sandy soil, slight chernozem, salty alkaline soil, and meadow soil. The height of the vegetation in the degraded grassland site is usually < 10 cm, and the percentage of vegetation cover is < 70% in summer. The main crop is corn mixed with sunflower within 1000 m of the measured location in the cultivated corn ecosystem during the growing season, while in winter there is bare soil. The maximum height of the corn is about 2 m in the growing season. Footprint analysis following the method proposed by Kormann and Meixner (2001) indicates that approximately 85% of the measured scalar fluxes originated from within 650 m of the tower in each direction. Further details have been provided by Liu and Feng, 2012.

2.2. Observation

The instrumental setup for each site included a 20-m micrometeorological tower and an eddy covariance (EC) system. The observation contents were the same at both sites. The EC system mainly included a sonic anemometer (CSAT3, Campbell Scientific) and an open-path infrared gas analyzer (LI-7500, Li-Cor). The EC sensors were installed at 2 and 3.5 m above the soil surface at the degraded grassland site and cultivated corn site, respectively. Both of the systems were operated at the sampling rate of 10 Hz. Meteorological elements including wind speed and director (034B, Metone), air temperature and humidity (HMP45C, Vaisala) at multiple levels, net radiation (Kipp & Zonen, NR Lite), air pressure (CS105, Texas Elect Inc.), and precipitation (TE525MM, Texas Electronics) were measured. We also measured the soil heat flux (HFP01SC, Hukseflux), the profiles of soil temperature (107_L, Campbell Scientific), and the SWC (CS616_L, Campbell Scientific). More details of the instrumental setup have been presented in the study by Liu et al. (2008), Liu and Feng (2012).

2.3. Data analysis

With respect to post-processing, EddyPro software (published by Li-Cor Inc.) was used to process the 10-Hz raw data. Double rotations of u, v, and w were carried out so that the mean vertical wind velocity for 30 min was zero. Correction to the initial flux values was made for high-frequency losses due to separation of sensors, path averaging, and sensor frequency response (Massman and Lee, 2002). In addition, the water vapor and CO_2 fluxes were corrected for the effect of density fluctuations (Webb et al., 1980). Anomalous data obtained due to instrument malfunction, weather condition, and calibration were excluded in this study. In order to fill the missing and bad data, a linear interpolation method was used for small blocks (less than a few hours) of missing or bad data. Larger gaps were filled with values derived from mean diurnal ensemble values (Fagle et al., 2001). The gaps in precipitation were filled using data documented at the Tongyu weather station.

2.4. Estimation of LAI

LAI was not measured at our sites. In order to analyze the canopy development, we first studied the normalized difference vegetation index (NDVI) data obtained from the Moderate Resolution Imaging Spectrometer (MODIS) sensor on the EOS-1 Terra satellite. NDVI is an alternative measure of vegetation amount and condition (Hunsaker et al., 2003). The values of NDVI for the vegetated land