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# Irregular precipitation events in control of seasonal variations in $CO_2$ exchange in a cold desert-shrub ecosystem in northwest China

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ABSTRACT

Net ecosystem productivity (NEP) of a cold desert-shrub ecosystem was continuously monitored during 2012 and 2013 using the eddy covariance method. The aim was to examine the influence of irregular precipitation in control of seasonal variations in NEP at multiple timescales. The ecosystem was a weak annual carbon sink. Difference in NEP between 2012 and 2013 (2013, having higher NEP) was caused by a suppression in gross ecosystem productivity (GEP; 55 g C $m^{-2}$) compared to ecosystem respiration (ER; 33 g C $m^{-2}$) in 2012, as a result of (i) fewer frequent and low-intensity rainy days and more carbon-source days in summer, (ii) lower annual mean air and soil temperature, and (iii) lower daily mean photosynthetically active radiation. Daily GEP and ER both decreased during dry periods, with GEP decreasing more than ER, causing NEP to decrease. Persistent and high available soil water associated with frequent and low-intensity precipitation during DOY 207 to 224 was central to maintaining carbon-sink strength in 2013, resulting in a noticeable increase in daily NEP from 0.3 g C $m^{-2}$ to 1.2 g C $m^{-2}$. Frequent and low-intensity precipitation was responsible for maintaining plant growth, while sporadic and high-intensity precipitation decreased NEP.



## 1. Introduction

Arid and semi-arid lands collectively cover between 30% and 45% of the global terrestrial surface (Hastings et al., 2005; Chen et al., 2013). These lands are documented to be rapidly expanding due to increasing human population growth, land-surface conversion, and global climate change (John et al., 2013). Such a large portion of land surface area, carbon (C) fluxes from arid and semi-arid lands are important to the global C budget (Eamus et al., 2013). Since these ecosystems account for approximately 20% of total terrestrial net primary productivity (Whittaker, 1975). However, C dynamics of cold desert-shrub ecosystems and their responses to environmental factors are less well understood compared to those of forests and grasslands (Jia et al., 2014) because measurement of net ecosystem production (NEP) in desert environments is very difficult (Wohlfahrt et al., 2008).

The C-sink capacity at the ecosystem-level in arid and semi-arid lands was variable, depending on the ecosystem type, inorganic C pool, temperature, and rainfall timing during the growing season (Serrano-Ortiz et al., 2012). The C cycling in desert ecosystems is particularly sensitive to environmental factors, such as precipitation and air temperature (Huxman et al., 2004; Serrano-Ortiz et al., 2012). For example, Li et al. (2005) have reported that the seasonality of C fluxes were closely associated with precipitation dynamics in grassland (steppe) ecosystems. Whether an arid and semi-arid ecosystem is a net C sink or a C source is determined by how NEP respond to prevailing environmental factors (Liu et al., 2012). Changes in precipitation may have a greater impact on NEP than any other singular environmental factor in arid and semi-arid lands, because water availability dominates plant growth processes (Potts et al., 2006). In such ecosystems, precipitation often falls as infrequent pulse events (Huxman et al., 2004; Ivans et al., 2006).

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Birch (1964) has reported that precipitation events tended to stimulate mineralization of soil organic C, leading to rapid releases of $CO_2$ from desert soils. During extended dry periods, Li et al. (2005) and Pereira et al. (2007) have reported that some ecosystems changed from a C sink to a C source. Also, during rainy days, Hastings et al. (2005) have reported that precipitation was initially able to change the system from a C source to a C sink and the C-sink strength increased following precipitation after extended periods of low soil water availability. Additionally, in the cold deserts of North America, the seasonality of precipitation is a better predictor of grassland productivity than the total annual amount (Bowling et al., 2010). Thus, the responses of C cycling of arid and semi-arid ecosystems to the precipitation events are complex and unpredictable (Liu et al., 2012; Jia et al., 2014), suggesting a lack of understanding concerning arid and semi-arid ecosystem responses to water stress.

The NEP is the result of interactions between gross ecosystem production (GEP) and ecosystem respiration (ER), both of which respond differently to the same set of environmental variables (Baldocchi, 2008). It is widely reported that ER rates increase with soil temperature and GEP rates increase with photosynthetically active radiation, when soil water is not limiting (Reichstein et al., 2005; Baldocchi, 2008). Yet, dry conditions can lead to reductions in both GEP and ER (Granier et al., 2007; Jassal et al., 2008). This is because dry conditions can cause stomatal closure and restrict photosynthesis of vegetation and thus reduce ecosystem gross primary production (Meir and Woodward, 2010; Schwalm et al., 2012). Low available soil water may reduce plant root activity and thus limit ER (Wang et al., 2014). Moreover, often, GEP does not respond favorably to the amount of rain pulses in semi-arid regions, despite the fact these are water-limited ecosystems (Baldocchi, 2008). Rain events as small as 5 mm or 6 mm could provide enough moisture to trigger metabolic activity and enhance photosynthesis in desert vegetations (Huxman et al., 2004; Bowling et al., 2010). In contrast, there is a growing number of studies reporting that ER of arid and semi-arid ecosystems increases immediately after rain events, especially when rain occurs during the dry season (Huxman et al., 2004; Ivans et al., 2006; Jarvis et al., 2007).

China is the most threatened by desertification (Jia et al., 2014). Overgrazing in shrublands and steppes has led to severe desertification in northern China (Chen and Duan, 2009). Although extensive re-vegetation and conservation programs have been initiated in northern China (Li et al., 2005), terrestrial C sinks of arid and semi-arid ecosystems decreased during the last century in China and some ecosystems changed as C sources (Xiao et al., 2009). Most existing studies of desert ecosystems have been based on small spatiotemporal scales or on non-continuous or limited field measurements (Jasoni et al., 2005; Wilske et al., 2010). The study describes continuous year-round measurements of C fluxes in a cold desert-shrub ecosystem in northwest China using the eddy covariance technique. The objectives of the study are to (1) quantify the current $CO_2$ sink or source strength in an *Artemisia ordosica*-dominated ecosystem for a 2-year period from 2012 to 2013; and (2) clarify the role that the main environmental factors, especially summer precipitation, may play in defining variations in GEP and ER and, thus, NEP, on a daily, seasonal, and annual timescale.

## 2. Materials and methods

### 2.1. Study site

The eddy-flux site is located near the Yanchi Research Station (37.71°N, 107.23°E), Ningxia, northwest China. The study site is located in a typical transitional zone between the Mu Us desert and Loess plateau (*i.e.*, between arid and semi-arid climatic zones). The study site is characterized by flat topography with slopes <10° and an elevation of ~1530 m above mean sea level. The soil is classified as a sierozem with >70% as fine sand (0.02–0.20 mm). The main habitat types consist of shifting, semi-fixed, and fixed sand dunes. Organic matter content in the soil is low, ranging from 0.5 to 0.8%. Soil pH ranges from 7.5 to 8.5, and total nitrogen content in the top 100 cm of the soil complex is 0.15 g $kg^{-1}$. The sandy soil has a bulk density of 1.54 ± 0.08 g $cm^{-3}$ in the upper 10 cm of the soil profile (Chen and Duan, 2009; Jia et al., 2014).

There is abundant sunshine with mean annual air temperature ($T_a$) of 8.1 °C. The lowest and highest monthly mean $T_a$ are −24.2 °C in January and 34.9 °C in July. Mean annual precipitation is ~287 mm, of which 62% falls between July and September. Mean annual potential evapotranspiration is 2024 mm. The frost-free season lasts approximately 165 days. Droughts, hail, sandstorms, high dry-hot winds, and frosts are common occurrences in the study region. Gales (wind velocities >8 m $s^{-1}$) occur frequently, averaging ~23 occurrences per year. Characterization of regional climate is based on 51 years of meteorological data collected at the Yanchi County weather station located nearby. On-site vegetation is dominated by *A. ordosica*, which has recovered over the past ten years following a long history of intensive grazing.

### 2.2. Flux, meteorological, and vegetation measurements

The 4.2-m-tall tower is surrounded in all directions by a uniform cover of *A. ordosica*, extending downwind to ~500 m of homogeneous, unbroken fetch. The $CO_2$ and $H_2O$ exchanges between the ecosystem and the atmosphere are measured using the eddy covariance equipment placed near the top of the tower. The eddy covariance system consists of a closed-path infrared gas analyzer (IRGA; model LI-7200, LI-COR Biosciences, Lincoln, NE, USA) and a sonic anemometer (WindMaster™ Pro, Gill Instruments Ltd, Lymington, England). The IRGA is calibrated every third month using 99.99% nitrogen gas (zero offset calibration) and 650 ppm $CO_2$ and a dew point generator (LI-610, LI-COR Inc., USA) to calibrate the span for $CO_2$ and water vapor, respectively. Continuous high-frequency (10 Hz) data are archived and post-processed to calculate the eddy fluxes at half-hourly intervals.

All processing of eddy covariance data and statistical analyses were conducted using the Statistical Analysis System (SAS) v. 9.2 for Windows software (SAS, Institute, Inc., Cary, NC, USA). Processing steps included spike removal, tilt correction (double axis rotation), correction for sensor separation, spectral correction, detrending (Reynolds averaging), and flux computation (Burba and Anderson, 2010). Correction for density fluctuations (WPL terms) was not used here, as the LI-7200 gas-analyzer is capable of outputting $CO_2$ and $H_2O$ mixing ratios (thermal expansion and water dilution of the sampled air are already accounted for; Burba and Anderson, 2010). Half-hourly $CO_2$ fluxes were de-spiked following the procedures described in Papale et al. (2006).

We used the sign convention by which positive net ecosystem productivity (NEP) indicates $CO_2$ fluxes toward the surface (*i.e.*, an uptake of $CO_2$ by plants corresponds to NEP >0). The $CO_2$ storage term was not added in estimating NEE because of the relatively short canopy that usually makes the term negligible (Zhang et al., 2007). In addition, $CO_2$ storage term tends to be close to zero when summed over daily and annual timescales (Jia et al., 2014). Above-canopy meteorological variables are measured at 4.5 m above the ground and reported as half-hourly means. Air temperature ($T_a$, °C) and relative humidity (RH, %) are measured with HMP155 sensors (Vaisala Oyj, Helsinki, Finland). Photosynthetically active radiation (PAR, μmol $m^{-2}$ $s^{-1}$) is measured with LI-190SA sensors (LI-COR Biosciences, Lincoln, NE, USA) and net radiation