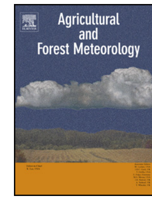
Agricultural and Forest Meteorology 228–229 (2016) 120–129

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Carbon and water exchange over a temperate semi-arid shrubland during three years of contrasting precipitation and soil moisture patterns

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ARTICLE INFO

Article history:
Received 15 January 2016
Received in revised form 7 July 2016
Accepted 9 July 2016
Available online 16 July 2016

Keywords:
Carbon balance
Carry-over
Eddy-covariance
Inter-annual variability
Soil water availability
Water use efficiency

ABSTRACT

Water is considered a key factor affecting ecosystem carbon exchange in dryland regions. However, the relationship between inter-annual variations in precipitation and ecosystem productivity remains to be clarified for arid and semi-arid areas. Based on eddy-covariance measurements, we examined how ecosystem production in a shrubland of northern China varied over three years (2012–2014) with contrasting precipitation and soil moisture patterns. Net ecosystem production (*NEP*) was 77 ± 10 (± standard deviation), −4 ± 10 and −22 ± 5 g C m^{-2} in 2012–2014, respectively, indicating a rapid shift from an annual sink to a source of carbon. Gross ecosystem production (*GEP*), total ecosystem respiration (*TER*) and evapotranspiration (*ET*) also declined over the three years. Annual carbon and water fluxes appeared to be suppressed in years with low spring soil moisture, which declined dramatically from 2012 to 2014. *GEP* declined more than *TER* and *ET*, leading to reduced carbon sequestration capacity and water use efficiency (*WUE* = *GEP*/*ET*). Neither annual nor growing-season precipitation could explain the year-to-year variations in carbon fluxes, whereas at our site *ET* was a better proxy for water available to ecosystem carbon exchange on an annual basis. Autumn soil moisture levels were carried over winter to the following spring, and, thus, may affect the rates of leafout, plant growth and carbon uptake in the early- to mid-growing season. Our conclusions were drawn from only three years of measurements and are therefore preliminary. Longer timeseries encompassing a wider range of precipitation and soil moisture conditions are needed to confirm or refine these conclusions. Our findings highlight the importance of precipitation timing and soil moisture carry-over in controlling ecosystem productivity. Winter warming and decreases in autumn and winter precipitation may induce spring drought and thus impair the carbon sequestration potential of shrubland and steppe ecosystems in semi-arid and arid Eurasia.

1. Introduction

Global climate models project larger climatic variability and more frequent extreme events (*e.g.*, drought, storm and heat wave) in the future (Dong et al., 2011). Increases in both the severity and frequency of drought are expected to profoundly impact ecosystem structure and functioning (Jongen et al., 2011; Biederman et al., 2016). Arid and semi-arid ecosystems play an essential role in the global carbon (C) cycle, and are highly sensitive to year-to-year climatic variations (Poulter et al., 2014; Ahlström et al., 2015). Therefore, knowledge on the key factors affecting annual ecosystem production and water use efficiency in dryland areas is crucial to the projection of global C balance under changing climate.

Previous studies showed that semi-arid grasslands and steppes have larger inter-annual variability in C exchange than forest and grassland ecosystems in mesic areas, and that semi-arid ecosystems could switch from a net C sink in wet or normal years to a C source in dry years (Aires et al., 2008; Jongen et al., 2011; Scott et al., 2015; Liu et al., 2016). Although water is considered a key factor affecting ecosystem C exchange in dryland regions, the response of ecosystem production to year-to-year fluctuations in precipitation (*PPT*) often varies among sites (Sala et al., 2012; Scott et al., 2015). Despite many findings that annual *PPT* amount is a good

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http://dx.doi.org/10.1016/j.agrformet.2016.07.007
0168-1923/

predictor of year-to-year variations in net primary productivity (*NPP*), net ecosystem productivity (*NEP*), or gross ecosystem production (*GEP*) (Huxman et al., 2004; Scott et al., 2015; Biederman et al., 2016), some studies showed weak or non-significant relationships between annual *PPT* and ecosystem production (Xu and Baldocchi, 2004; Gilmanov et al., 2006; Jongen et al., 2011; Sala et al., 2012). Clearly, the relationship between inter-annual variations in *PPT* and ecosystem production remains to be clarified for arid and semi-arid areas. Firstly, the seasonal pattern of *PPT* can be more important than its total amount in determining the annual C balance in semi-arid ecosystems (Jongen et al., 2011; Liu et al., 2016). Secondly, hydrologic losses through runoff and evaporation may render *PPT* amount inaccurate as a measure of water availability for eco-physiological processes (Scott et al., 2015; Biederman et al., 2016). Thirdly, carry-over effects may further complicate the responses of ecosystem production to *PPT* (Sala et al., 2012).

Water-use efficiency (*WUE*) is a critical link between C and water cycling (Niu et al., 2011). Ecosystem *WUE* tends to increase with increasing *MAP* at the regional scale (Bai et al., 2008; Xiao et al., 2013), although Huxman et al. (2004) reported an opposite trend in rain use efficiency (*RUE*) across a broader *MAP* gradient (*i.e.*, data from throughout North and South America). For a given site, there is a lack of consensus regarding the response of *WUE* to drought, with either increases (Huxman et al., 2004; Bai et al., 2008; Dong et al., 2011) or decreases (Liu et al., 2012; Scott et al., 2015) in *WUE* being observed in dry years. The organizational level considered (*e.g.*, leaf, canopy and ecosystem), the way *WUE* is computed (*e.g.*, *NPP*/*PPT*, *GEP*/*ET* or *NEP*/*ET*, where *ET* denotes evapotranspiration), or the scale of analysis (*e.g.*, seasonal, inter-annual and multi-decadal) may partially account for the inconsistent *WUE* responses to dry conditions (Bai et al., 2008; Niu et al., 2011; Scott et al., 2015). A better understanding is needed of the relationship between year-to-year variations in water availability and ecosystem *WUE*, which can help constrain predictions of coupled C and water cycling under changing climate. In addition, information on how key eco-physiological parameters (*e.g.*, maximum C uptake rate and surface conductance) respond to inter-annual variations in climatic factors can help improve the modeling of C and water cycles.

Despite the extent and potential for C sequestration of desert shrublands in Eurasia, they have been less studied than forests or grasslands (Jia et al., 2014). The arid and semi-arid regions of northern China are characterized by highly variable annual *PPT* and frequent drought periods (Liu et al., 2012). Recent studies in this region have reported diurnal and seasonal dynamics of C and water exchange over shrub-dominated ecosystems, and have revealed the importance of seasonal changes in soil moisture, vapor pressure deficit (*VPD*) and canopy characteristics in controlling C sequestration (Gao et al., 2012; Liu et al., 2012; Jia et al., 2014, 2016). However, mechanisms regulating C and water dynamics depend on the timescale considered (Bai et al., 2008; Jia et al., 2014), and inter-annual dynamics should be addressed as more multi-year datasets become available. The vast Eurasia arid and semi-arid areas are expected to undergo increases in temperature and altered *PPT* patterns (Gao et al., 2012; Liu et al., 2012). In this respect, the long-term uncertainty in regional C sequestration potential lies primarily in the sensitivity of shrublands to climate variability. Therefore, it is necessary to investigate the biophysical controls on inter-annual variations in *NEP*, *WUE* and their components in these shrubland ecosystems.

The south edge of the Mu Us Desert, an ecotone between arid and semi-arid climates in northern China, is vulnerable to anthropogenic disturbances and land use changes (Jia et al., 2014, 2016). Regional conservation practices in the past two decades have resulted in a dramatic expansion of shrubland distribution, which is considered a sign of desertification reversal (Jia et al., 2016). Jia et al. (2014, 2016) reported diel and seasonal dynamics of eddy-covariance (EC) C, water and energy fluxes in a typical shrubland of the southern Mu Us Desert, showing that the ecosystem acted as a C sink of 77 g C m^{-2} in 2012. Here we focus on how C sequestration and *WUE* vary inter-annually in the shrub-dominated ecosystem. The three years (2012–2014) reported here were characterized by contrasting seasonal patterns of *PPT* and soil moisture, offering an opportunity to examine ecosystem responses to inter-annual variations in water availability. We hypothesized that decreases in water availability, which is determined by the amount and seasonal pattern of *PPT*, reduce *GEP* more than *TER* and *ET*, leading to lowered *NEP* and ecosystem *WUE*.

2. Materials and methods

2.1. Study site

This study was conducted at the Yanchi Research Station (37°42′31″N, 107°13′37″E, 1530 m a.s.l.), Ningxia, Northwest China. The site is situated at the southern edge of the Mu Us Desert, an area of mid-temperate semi-arid continental climate. The mean annual air-temperature (1954–2004) is 8.1 °C, with mean monthly temperature ranging from −8.7 °C in January to 22.4 °C in July (Jia et al., 2014). The *MAP* of 287 mm is much lower than pan-evaporation (2024 mm). In addition, *PPT* shows large seasonal (~80% falling during June–September) and inter-annual variations (145–587 mm for the period 1954–2004) (Jia et al., 2016). The growing season (May–October) coincides with the warm and wet period. The soil is sandy with a bulk density of 1.54 ± 0.08 g cm^{-3} (mean ± SD, $n = 16$) in the upper 10 cm of the soil profile. The studied shrubland has a total vegetation cover of ~70%. It is dominated by a mixture of xerophytic shrub species, including *Artemisia ordosica* (35% relative cover), *Hedysarum mongolicum* (30%), *H. scoparium* and *Salix psammophila* (20%), with a minor component (15%) of grass species such as *Stipa capillata* and *Agropyron cristatum*. The shrub canopy is about 1–1.5 m tall. Shrub roots are distributed mainly in the 20–50 cm soil layer. Soil water availability depends entirely on *PPT* as the water table lies 8–10 m below the ground surface. Seasonal water deficit constrains photosynthesis, *ET* and soil respiration of the studied shrub ecosystem (Jia et al., 2014, 2016).

2.2. EC and meteorological measurements

Net ecosystem CO_2 exchange (here defined as *NEE* = −*NEP*) and *ET* were measured with a EC system, which consisted of a 3D sonic anemometer-thermometer (CSAT-3, Campbell Scientific Inc., USA) and a closed-path infrared gas analyzer (LI-7200, LI-COR Inc., USA), mounted on a tower at 6.2 m height. Air was drawn from an inlet 20 cm away from the center of the sonic anemometer sensor volume. The sampled air was then pumped through a tube of 1 m in length and 9 mm in diameter to the LI-7200 at a flow rate of 15 L min^{-1}. On-site maintenance and sensor calibration were performed every three months. Raw signals were recorded at 10 Hz using a data logger (LI-7550, LI-COR Inc., USA). The CO_2 and water vapor (H_2O) storage terms were not estimated due to the short-statured canopy (1–1.5 m) and low sensor height, which usually render storage terms negligible. In addition, the cumulative storage terms should get close to zero as the timescale of flux integration increases (*e.g.*, daily, seasonal and annual) (Burba, 2013).

Meteorological variables were measured with sensors installed at 6 m height on the EC tower, and included incident and reflected photosynthetically active radiation (*PAR*, PAR-LITE, Kipp and Zonen, the Netherlands), wind speed (u) and direction (034B, Met One Instruments Inc., USA), net radiation (R_n, CNR-4, Kipp & Zonen, The Netherlands), and air temperature (T_a) and relative humidity (HMP155A, Vaisala, Finland). Soil heat flux (G) was calculated as