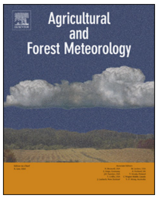
Agricultural and Forest Meteorology 263 (2018) 15–24

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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



Direct and carry-over effects of summer rainfall on ecosystem carbon uptake and water use efficiency in a semi-arid woodland

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ARTICLE INFO

Keywords:
Diurnal pattern
Drought legacy
Ecosystem carbon flux
Semi-arid woodland
Summer rainfall
Water use efficiency

ABSTRACT

Biological activity in semi-arid and arid ecosystems is strongly dependent on rainfall, particularly in summer. A period of favourable rainfall can alter ecosystem carbon balance and is likely influence inner-annual variability of the regional and global carbon cycle. The effect of rainfall variability on ecosystem carbon and water fluxes in semi-arid ecosystems, particularly in woody ecosystems has not been adequately investigated. In this study, we used eddy covariance data from four springs (September–November), four summers (December of that year–February of the following year) and three following autumns (March–May) between 2010 and 2013 in a semi-arid woodland of southern Australia to better understand the effect of pre-summer, summer and post-summer rainfall variability on diurnal pattern of carbon flux. In 2010/11 summer, La Niña conditions resulted in extensive rainfall, which marked an historic record over the last 100 years. The 2011/12 summer was also moist. In contrast, the two following summers (2012/13 and 2013/14) were dry. Cumulative net ecosystem productivity (NEP) was lower in dry summers than in moist summers, due to lower maximum carbon flux rate and total hours of net carbon uptake. Maximum NEP and gross primary productivity rates on a given day were reached earlier in dry summers, indicating that photosynthetic activity was not suppressed by high temperatures but by water availability. Ecosystem water use efficiency, calculated as the ratio of daily NEP to evapotranspiration, was higher in moist than dry summers. In addition, the effect of summer rain extended into the following autumn. Cumulative NEP and ecosystem water use efficiency in autumn following a dry summer were lower than when following a moist summer. We conclude that summer rainfall has a strong impact on the carbon cycle in semi-arid woodlands due to its direct and carry-over effect. Therefore seasonal rainfall variation is likely to determine inter-annual variability of annual net carbo uptake of this ecosystem.

1. Introduction

Rainfall is a key driver of biological activity in semi-arid and arid ecosystems (Huxman et al., 2004; Nielsen and Ball, 2015; Noy-Meir, 1973; Weltzin et al., 2003), which occupy more than a third of the world's land area and store large amounts of carbon (Lal, 2004). A period of high rainfall can trigger an increase in vegetation biomass and thus carbon stock (Haverd et al., 2017; Poulter et al., 2014; Smith et al., 2017). In dry conditions on the other hand, net primary productivity is reduced and microbial activity is limited (Frank et al., 2015; Murray-Tortarolo et al., 2016). Therefore rainfall distribution is highly likely to affect plant and ecosystem processes and thus carbon balance (Zscheischler et al., 2016). Indeed, it has been suggested that precipitation variability in semi-arid ecosystems plays a dominant role in the inner-annual variability of land CO_2 uptake (Ahlstrom et al., 2015).

In semi-arid ecosystems, dry periods are occasionally interrupted by rainfall events, particularly in summer. Climate models project that frequency and intensity of long-term drought, heat waves and variability of rainfall will be enhanced in semi-arid and arid regions of Australia (Hughes, 2003) and globally (Frank et al., 2015; IPCC, 2014). Therefore, understanding the response of carbon flux to different rainfall amounts in semi-arid ecosystems is essential for better predicting annual, regional and global carbon budgets. Such studies have been conducted on grasslands in semi-arid climates (e.g., Arredondo et al., 2016; Mueller et al., 2016), but information on woody ecosystems is limited. A recent study reported that in the 2012/2013 summer, net carbon uptake was reduced during an extreme heat wave in semi-arid woodlands of southern Australia (van Gorsel et al., 2016). The study described diurnal patterns of carbon flux during the heat wave. However, the duration of the study was short, using eddy covariance flux

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https://doi.org/10.1016/j.agrformet.2018.07.027
Received 4 January 2018; Received in revised form 17 June 2018; Accepted 25 July 2018

data collected one week prior to and post the event, not for the entire season. Longer term studies are required to understand the response of daily carbon and water fluxes to seasonal rainfall in semi-arid woodlands. This is because deep rooted vegetation may respond to rainfall differently to shallow rooted plants. The deeper roots could allow trees to extract water from greater soil depth than grasses (Kulmatiski and Beard, 2013). The effect of low rainfall on carbon fluxes may therefore be delayed or smaller in woodlands than grasslands.

In the 2010/11 summer, La Niña conditions caused extensive rainfall across the study region. The total amount of rainfall in the 2010/11 summer was an historic high for the last 100 years. The 2011/12 summer was also moist. In contrast, the two following summers (2012/13 and 2013/14) were dry. In the 2012/13 summer, the woodland only received 7.8 mm rainfall. These marked differences in rainfall provided an opportunity to investigate carbon flux response to rainfall in this woodland. Therefore, the aims of this study were to determine (i) the effect of summer rainfall on diurnal patterns of carbon fluxes and ecosystem water use efficiency in a semi-arid woodland, (ii) the relationship between net ecosystem productivity (NEP) and summer rainfall, (iii) whether the difference in diurnal patterns of carbon flux in dry and moist summers is related to antecedent (spring) rainfall, and (iv) whether carbon flux rates and water use efficiency in autumn are influenced by rainfall in the preceding summer. We used eddy covariance data during four springs, four summers, and three autumns between 2010 and 2013. Autumn rain amount was similar in the four years of this study. This allowed us to investigate the legacy effect of summer rainfall on carbon flux rates and water use efficiencies in the following autumn. According to recent studies, the 2010–2011 net CO_2 uptake due to high rainfall was transient with rapid dissipation in a following drought, lasting between a few months to a year in Australian semi-arid to arid ecosystems (Cleverly et al., 2016b; Ma et al., 2016). Therefore carry-over effects of the previous summer rainfall to the next summer are unlikely.

We hypothesised that: (i) net ecosystem productivity (NEP), gross primary productivity (GPP) and ecosystem respiration (Reco) are lower in dry summers than in moist summers, (ii) NEP increases with summer rainfall, and (iii) water use efficiency is greater in moist than in dry summers. These three hypotheses were because plant and microbial activities are predominantly limited by water availability in semi-arid ecosystems. The fourth hypothesis was that the previous summer rainfall does not affect carbon flux rates and water use efficiencies in the following autumn. We assume that the woodland is well adapted to dry conditions and therefore recovers quickly when autumn rains commence.

2. Methods and materials

2.1. Site description

The study was conducted at Calperum Station (34.04 °S, 140.71 °E), adjacent to the Chowilla floodplain of the River Murray in South Australia. The site is part of the Terrestrial Ecosystem Research Network's (TERN) OzFlux and Australian Supersite Network (ASN) programs (Karan et al., 2013) and the global FLUXNET (http://fluxnet.ornl.gov/). It is equipped with an eddy covariance monitoring system mounted on a 20 m high tower and described below.

Details of the study site are given in Sun et al. (2016). Briefly, the area is classified as semi-arid and has an annual median rainfall of 242 mm and an annual average of 41 rain days. The mean maximum and minimum air temperatures are 24.9 and 9.6 °C respectively (data recorded from 1996 to 2014, from http://www.bom.gov.au/). Historical rainfall data between 1930 and 2010 recorded at a nearby meteorology station (ID: 24048, Renmark, South Australia) is shown in Fig. 1.

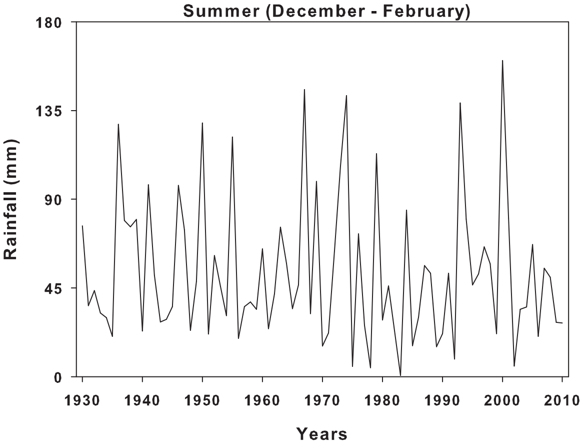

Fig. 1. Historical summer rainfall (December–February) between 1930 and 2010 recorded at a nearby meteorology station (ID: 24048, Renmark, South Australia). Average summer rainfall from 1930–2010: 53.1 mm.

The mallee woodland is a eucalypt-shrub association. The area around Calperum and surrounding properties cover over one million hectares of mallee habitat. The tree vegetation is dominated by four multi-stemmed eucalypt species (*Eucalyptus dumosa*, *E. incrassata*, *E. oleosa* and *E. socialis*) with sparse leaf canopies between 3–5 metres aboveground. The understory, often in the space between trees, is mainly spinifex (*Triodia basedowii*) that grows in spreading clumps to a height of ca. 0.7 m. The rest of the ground surface is largely bare, with occasional low coverage by ephemeral grasses.

The alkaline sandy soil in this woodland is classified as a Tenosol in the Australian Soil Classification (Isbell, 2002), and as an Aridisol in the US Soil Taxonomy (Soil Survey Staff, 1996), which consists of 94% sand, 4% silt and 2% clay. Soil properties in 0–30 cm depth are bulk density 1.6 g cm^{-3}, $EC_{1:5} < 0.4$ dS m^{-1}, $pH_{1:5}$ of 8.3, carbonate 0.2–0.3%, total organic C and total nitrogen from 0.35% to 1.02% and from 0.03% to 0.07%, respectively (Sun et al., 2016).

2.2. Eddy covariance measurement and data processing

The 20 m high eddy covariance (EC) tower was erected in June 2010 to measure fluxes of CO_2, H_2O and energy. The footprint of the EC tower covers ca. 34 ha. A detailed description of the instrumentation can be found in Meyer et al. (2015) (see https://calperumchowilla.wordpress.com/ for more information). Briefly, measurements of three-dimensional wind speed (CSAT3 sonic anemometer, Campbell Scientific Inc., Logan, UT, USA), virtual temperature (CSAT3), as well as air water vapour density and CO_2 density using an open-path infra-red gas analyser (Licor LI7500, LiCor Biosciences, Lincoln, NE, USA), were recorded at a frequency of 10 Hz. The latent energy flux (LE, W m^{-2}) and hence evapotranspiration (ET) was estimated by using the output from the LI7500. The half-hour LE was subject to the correction procedures which were mentioned in Meyer et al. (2015) and then divided by the latent heat of vaporization ($\lambda \sim 2.45$ MJ m^{-2} mm^{-1}) to obtain system evapotranspiration in mm $(0.5\ h)^{-1}$.

Auxiliary observations of solar irradiance, air temperature, vapour pressure deficit and rainfall, soil temperature and soil water content were also concurrently collected. Incident solar irradiance was recorded by a four-component radiometer that was positioned at a height of 20 m (CNR4, Kipp and Zonen, Delft, the Netherlands). Vapour pressure deficit was determined as the difference between atmospheric vapour pressure (kPa) and saturation vapour pressure at air temperature (HMP45C, Vaisala, Helsinki, Finland) at a height of 2 m. An additional pyranometer (Licor LI2003S, LiCor Biosciences, Lincoln, NE, USA) was mounted at 20 m and cup anemometers and wind direction sensors (RM Young, Traverse City MI, USA) at 2 and 8.6 m. Onsite rainfall was measured with the tipping bucket gauge (CS7000, Hydrologic services, Warwick, NSW, Australia) (0.2 mm resolution) mounted on a stand at