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Prior rainfall pattern determines response of net ecosystem carbon exchange to a large rainfall event in a semi-arid woodland

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ABSTRACT

Semi-arid climate is characterized by long dry periods which are interrupted by rainfall events differing in magnitude. The effect of these rainfall events on ecosystem carbon fluxes has been studied in semi-arid grass and shrublands, but data for woodlands is lacking. In this study net ecosystem productivity (NEP), partitioned ecosystem respiration (Reco) and gross primary productivity (GPP) in a semi-arid eucalyptus woodland were measured using eddy covariance data. Four natural large rainfall events with similar magnitude (35–60 mm), but contrasting previous rainfall patterns (several moderate rainfall events vs. limited or no rainfall) were chosen. NEP, Reco and GPP rates 28 days prior to and 35 days after the three central rainfall events were used. Prior rainfall patterns influenced ecosystem carbon fluxes after the central rainfall event. GPP rates were not affected by the four rainfall events. After four weeks with several medium to large rainfall events, the central rainfall event had little effect on Reco. In contrast, a large rainfall event following four weeks with very little rainfall induced an increase in Reco for about three weeks and thus a decrease in NEP. The strong increase in Reco after the central rainfall event can, at least partly, be explained by an increase in soil respiration upon rewetting. A water addition experiment (30 mm rainfall simulation) conducted in the field following a long dry period (only 4.8 mm rainfall input in 45 days) showed that heterotrophic soil respiration usually decreases rapidly after rewetting. In the sandy soil of the study area, the top 0–5 cm dry within a few days after rainfall, but at 10 cm depth the soil remained moist for several weeks after the large rainfall event that followed a long dry period. Therefore, sustained higher Reco following the large rainfall event could be due to respiration of roots in the moist deeper soil layers. We conclude that the previous rainfall should be considered when interpreting the response of ecosystem C fluxes to rainfall events which could alter ecosystem carbon balance and may potentially affect seasonal or inter-annual variability of ecosystem carbon uptake.

1. Introduction

In arid and semi-arid ecosystems, rainfall constrains biological and physical processes (Noy-Meir, 1973; Weltzin et al., 2003; Beer et al., 2010). On the other hand, extensive and large rainfall across these ecosystems can have a global effect on the trend and inter-annual variability of terrestrial CO_2 uptake (Ahlstrom et al., 2015). Recent climate models project that large rainfall events and extended dry periods will become more frequent (Hughes, 2003; Fischer et al., 2013; IPCC, 2014). Hence there is increased interest in quantifying the C flux response of arid and semi-arid ecosystems.

Many studies suggest that both rainfall amount and frequency are important controllers of ecosystem processes in dry regions (e.g., Huxman et al., 2004) because a significant rainfall event after an extended dry period can lead to rapid nutrient mineralization and a pulse of CO_2 evolution (Austin et al., 2004; Collins et al., 2008; Kim et al., 2012; Nielsen and Ball, 2015). The magnitude of this pulse of CO_2 from soil respiration following rewetting of dry soil has been shown to be dependent on the frequency of previous dry-wet cycles (e.g., Fierer et al., 2003; Shi and Marschner, 2014). Pulses of CO_2 from soil respiration following large rainfall events are therefore commonly observed, but the following effect on ecosystem C fluxes is not clear. In grass- or shrub-lands, some studies showed that large rainfall events increase plant productivity and net ecosystem C uptake (e.g., Heisler-White et al., 2008; Thomey et al., 2011; Parton et al., 2012; Guo et al., 2015); while others reported a net ecosystem C release after rainfall events (e.g., Snyder et al., 2004; Wohlfahrt et al., 2008; Liu et al., 2013; Huang et al., 2015; López-Ballesteros et al., 2016). The C flux response of semi-arid woodlands has not been comprehensively studied (Zeppel et al., 2014) and it is therefore uncertain whether large rainfall events

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will induce net C uptake or net loss in these ecosystems.

Trees in semi-arid woodlands often have very deep roots (e.g., Nulsen et al., 1986) and use water conservatively (e.g., Meyer et al., 2015) compared to shallow-rooted, annual plants such as grasses and may therefore respond differently to sequences of long dry periods and large rainfall events. Understanding the response of semi-arid woodlands to drying and wetting is important in projecting ecosystem C flux change, particularly as climate is predicted to become drier in many regions of the world.

The aim of this study was to determine the effect of rainfall patterns preceding large rainfall events on ecosystem C fluxes in a semi-arid woodland. The first hypothesis is that irrespective of the background of rainfall history, gross primary productivity and ecosystem respiration rates will be enhanced by large rainfall events. This is based on the assumption that soil microbes and plants are strongly limited by water availability in this ecosystem. The second hypothesis is that the increase in gross primary productivity and ecosystem respiration rates after a rainfall event will last for only 1–7 days. It is based on previous studies in other semi-arid ecosystems (e.g. grass- and/or shrub-based), which showed that the responses of C fluxes to incident available water is immediate and short-lived.

2. Methods and materials

2.1. Site description

The field site was at Calperum Station (34.04° S, 140.71° E), adjacent to the Chowilla floodplain of the River Murray in South Australia. The area is classified as semi-arid with 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 (data recorded from 1996 to 2014, from http://www.bom.gov.au/). 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. Onsite rainfall was measured with the tipping bucket gauge (CS7000, Hydrologic services, Warwick, NSW, Australia) (0.2 mm resolution) mounted on a stand at 0.65 m in a tree-free area. In the 1249 days from tower establishment to the end of 2013, 264 days had rainfall greater than 0.2 mm. The average daily rainfall (considering only rainfall > 1 mm) was 8.0 mm. Daily rainfall > 35 mm was considered a large event.

The mallee woodland is a eucalypt-shrub association. The area around Calperum and surrounding properties contain over one million hectares of mallee habitat, that is the largest continuous remnant of this vegetation association in Australia (Nulsen et al., 1986). 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 m 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 and low coverage by ephemeral grasses.

The alkaline sandy soil (94% sand, 4% silt and 2% clay) at the study site 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). At 0–30 cm depth the soil had a bulk density of 1.6 g cm^{-3} (Sun et al., 2015), was non-saline ($EC_{1:5} < 0.4$ dS m^{-1}) and a $pH_{1:5}$ of 8.3. Soil carbonate content was 0.2–0.3%, soil total organic C and total nitrogen varied 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). 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 (IRGA, Licor LI7500, LiCor Biosciences, Lincoln, NE, USA), were recorded at a frequency of 10 Hz.

Concurrently with carbon flux, solar irradiance, air temperature, vapour pressure deficit and rainfall, soil temperature and soil water content were collected. Incident solar irradiance was recorded by a four component radiometer that was positioned at 20 m height (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. A set of soil water content sensors (CS650, Campbell Scientific, Townsville, Australia) were placed 10 m away from the tower base in bare soil, beneath a eucalypt canopy and beneath a shrub canopy at depths of 0.1, 0.25, 0.50, 1.0 and 1.8 m in March 2012. To estimate soil water content before operation of the sensors, we used the Random Forest model, fitted in the 'randomForest' package (Liaw and Wiener, 2002) in R, to simulate soil water content at 10 cm depth at a daily scale with field measured data (March 2012–March 2017). The following environmental drivers were considered as potential explanatory variables to simulate daily soil water content: daily rainfall, evapotranspiration, air temperature, relative humidity, vapour deficient pressure and wind speed. First, we produced a frequency distribution table of all field measured soil water content data and divided the whole database into four categories according to range of the data (i.e. 0.02–0.03, 0.03–0.04 v/v). We kept all categories with equal amount of soil water content data. Once the selection procedure was complete, we again randomly divided the dataset into a training group (70%) and a test group (30%) (Baccini et al., 2012). The random selection was carried out using the 'RAND()' function in Microsoft Excel. The test dataset was used to independently validate and compute the root mean squared error (RMSE). Then a stepwise forward regression approach was applied to the training dataset. The validation of modelled compared to measured data is shown in Fig. A.1 in the Supplementary material ($r^2 = 0.48$). The developed model was used to estimate soil water content at 10 cm depth from the start of the flux tower operation (Fig. 1).

Covariances were computed every 30 min to generate fluxes following standard OzFlux QA/QC correction procedures (Calperum Tech, 2013; Cleverly et al., 2013; Eamus et al., 2013; Isaac et al., 2016) and cross-checked with methods described in Thomas et al. (2011). Removal of latent energy flux and sensible heat flux spikes, gap filling, night-time flux filtering (where solar radiation < 20 W m^{-2}) and friction coefficient threshold determination were carried out in the OzFluxQC program. A friction coefficient threshold was then calculated and set to 0.26 m s^{-1}, 0.21 m s^{-1}, 0.23 m s^{-1}, 0.25 m s^{-1}, 0.26 m s^{-1} and 0.26 m s^{-1} for the years 2010, 2011, 2012, 2013, 2014 and 2015 respectively.

The tower measures of CO_2 flux give net ecosystem exchange (NEE) which is partitioned into ecosystem respiration (Reco) using night time exchange to estimate full day respiration and gross primary productivity (GPP).

NEE = GPP + Reco

Net ecosystem productivity (NEP) was calculated by subtracting partitioned Reco from GPP. NEP = GPP − Reco

Thus positive NEP values indicate net C uptake (sequestration) by the vegetation; while negative NEP values indicate a net C loss from the ecosystem. Daily average measurements of NEP, GPP and Reco were calculated.

Four large rainfall events (35–60 mm) with contrasting previous rainfall patterns (several moderate rainfall events vs. limited or no rainfall) between 2010 and 2015 were chosen. The selection was based on two criteria. Firstly, we considered the size of rainfall event. Each of