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Research paper

Strong radiative effect induced by clouds and smoke on forest net ecosystem productivity in central Siberia

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ABSTRACT

Aerosols produced by wildfires are a common phenomenon in boreal regions. For the Siberian taiga, it is still an open question if the effects of aerosols on atmospheric conditions increase net CO_2 uptake or photosynthesis. We investigated the factors controlling forest net ecosystem productivity (NEP) and explored how clouds and smoke modulate radiation as a major factor controlling NEP during fire events in the years 2012 and 2013. To characterize the underlying mechanisms of the NEP response to environmental drivers, Artificial Neural Networks (ANNs) were trained by eddy covariance flux measurements nearby the Zotino Tall Tower Observatory (ZOTTO). Total photosynthetically active radiation, vapour pressure deficit, and diffuse fraction explain at about 54–58% of NEP variability. NEP shows a strong negative sensitivity to VPD, and a small positive to f_{dif}. A strong diffuse radiation fertilization effect does not exist at ZOTTO forest due to the combined effects of low light intensity, sparse canopy and low leaf area index. Results suggests that light intensity and canopy structure are important factors of the overall diffuse radiation fertilization effect.

1. Introduction

The high northern latitudes (> 55°N) are one of the largest carbon sink regions and have become warmer and drier due in recent decades to rising temperatures (Forkel et al., 2016). Moreover, boreal forests in Russia, so-called “taiga”, comprise about 21% of the world’s forest area (Tishkov, 2002). Despite its importance to the terrestrial carbon cycle, this area is one of the most data-deficient regions because of its remoteness. One of the critical disturbance factors in the taiga are large wildfires induced by a combination of human activity and climate change (Achard et al., 2008; Vasileva et al., 2011; Tautenhahn et al., 2016; Tchebakova et al., 2009; Furyaev et al., 2001). Since 1996 a significant increase in the number and frequency of wildfires, as well as burned areas, has been observed (Ponomarev et al., 2016; Antamoshkina and Korets, 2015). For instance, heavy smoke from wildfires covered central Siberia in the summers of 2012 and 2013 (Ponomarev, 2013). This heavy smoke resulted in reduced incoming solar radiation and caused changes in the surface radiation balance (Schafer et al., 2002a,b).

Solar radiation, in particular photosynthetically active radiation (PAR: 400–700 nm), controls canopy processes related to photosynthesis such as gross primary productivity (GPP), net ecosystem exchange of CO_2 (NEE), and light use efficiency (LUE). Determining the biophysical and physiological mechanisms influencing canopy photosynthesis under cloudy and smoky conditions has been difficult due to the interaction among multiple environmental factors such as incoming radiation, diffuse radiation or diffuse fraction, leaf temperature, air humidity, and/or surface wetness (Dengel and Grace, 2010; Doughty et al., 2010; Gu et al., 2002, 1999; Hollinger et al., 1994; Knohl and Baldocchi, 2008; Misson et al., 2005; Rocha et al., 2004). Under cloudy, overcast or high fire-related aerosol load conditions, the total radiation reaching the canopy is reduced, typically resulting in a reduction in

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photosynthesis (Cirino et al., 2014; Yamasoe et al., 2006).

The diffuse radiation fertilization (DRF) effect is an increase in photosynthesis that results from a trade-off between decreased solar radiation and increased light scattering, both caused by clouds or smoke (Mercado et al., 2009; Rap et al., 2015; Roderick et al., 2001). Diffuse radiation enhances photosynthesis because diffuse light can more effectively penetrate the canopy (Dengel et al., 2015; Doughty et al., 2010; Knohl and Baldocchi, 2008; Urban et al., 2007; Yamasoe et al., 2006). This effect, however, depends on properties of vegetation structure properties, such as canopy architecture, leaf area index (LAI), and plant functional type (PFT) (Alton et al., 2007; Kanniah et al., 2012; Knohl and Baldocchi, 2008; Niyogi et al., 2004). Under diffuse light conditions, the efficiency of canopy photosynthesis increased substantially for both crops and forests (Choudhury, 2001; Gu et al., 2002; Niyogi et al., 2004), but not in wetlands due to their low canopy height and low LAI (Letts et al., 2005). Synthetic and data-based modelling studies have also shown that results differ significantly for the same PFT, which may be explained by differing model assumptions, treatment of radiation, and the complexity level of each model (Alton, 2008; Alton et al., 2007; Knohl and Baldocchi, 2008; Matsui et al., 2008; Mercado et al., 2009; Rap et al., 2015; Still et al., 2009). Therefore, it is still an open question how forest ecosystems respond to various light regimes (Cheng et al., 2015; Dengel and Grace, 2010; Kanniah et al., 2012; Misson et al., 2005; Oliphant et al., 2011; Strada et al., 2015).

Aerosol particles have a significant influence on photosynthesis by increasing diffuse radiation, exhibiting favorable conditions for photosynthesis similar to those created by cloudy conditions (Gu et al., 2003; Niyogi et al., 2004; Rap et al., 2015). The aerosol scattering effect may increase the amount of diffuse light, enhancing the CO_2 uptake of forests at midday by up to 8%, without reducing incoming solar radiation (Misson et al., 2005). This effect is more pronounced in forests and croplands than in grasslands (Jing et al., 2010; Niyogi et al., 2004). Another study in grassland did not find significant increases of CO_2 uptake due to aerosol loading (Kanniah et al., 2010). In tropical forests, an increase of aerosol optical depth (AOD) results in an increase of CO_2 uptake, particularly in the sub-canopy (Doughty et al., 2010; Yamasoe et al., 2006). However, if AOD is very high (>2) or cloud cover is thick, CO_2 uptake decreases due to the reduction of incoming radiation (Cirino et al., 2014; Oliveira et al., 2007; Yamasoe et al., 2006). This suggests that moderate aerosol concentrations increase CO_2 uptake at ecosystem scales because of the DRF effect, whereas high levels of aerosols reduce CO_2 uptake by blocking solar radiation (Kanniah et al., 2012; Strada and Unger, 2016).

In this study, we use flux measurements obtained by the eddy covariance (EC) technique at the ZOtino Tall Tower Observatory (ZOTTO) site in central Siberia (Heimann et al., 2014; Kozlova et al., 2008; Winderlich et al., 2010) to understand the underlying processes of the DRF effect in a boreal forest during wildfire events. To our knowledge, no other study has investigated the effect of smoke and clouds on NEP at an ecosystem scale in central Siberia.

The objectives of this study are: (1) to characterize the environmental controls of Net Ecosystem Productivity (NEP) and (2) to examine the impact of clouds and smoke on radiation partitioning and its influence on NEP. To address these objectives we first identified the environmental drivers of NEP using an Artificial Neural Networks (ANNs) model (Moffat et al., 2010). We then tested the hypothesis that different levels of smoke particles influence NEP, enhancing it at intermediate levels and decreasing it at higher smoke levels.

2. Materials and methods

2.1. Study site

The research area is situated on the western side of the Yenisei river basin in the middle taiga subzone (Heimann et al., 2014; Kozlova et al., 2008; Winderlich et al., 2010; Fig. 1 bottom). Long-term energy and mass exchange measurements based on the EC technique in this region were performed quasi-continuously from 1998 to 2000 and 2002 to 2005 (Arneth et al., 2006; Kelliher et al., 1999; Lloyd et al., 2002; Schulze et al., 2002; Tchebakova et al., 2015). A new flux tower (60°48′25″N, 89°21′27″E, 180 m a.s.l.) was erected at a distance of 900 m from the tall tower site in mid-June 2012 (Winderlich et al., 2014; Fig. 1 top). This station is located in a homogeneous Scots pine (*Pinus sylvestrisis* L.) forest, with an average canopy height of 20 m, similar to the former site. However, the average tree age is estimated to be more than 100 years younger compared to the old site (82–107 and 230 years, respectively). The forest around Zotino is an open stand with sparse understory and a lichen-dominated ground cover (Wirth et al., 1999). The estimated stand density is 448 ± 88 trees ha^{-1} (mean ± standard deviation). The LAI value was not available during the measurement period, however, it may be the value in the range reported at the old station (1.3 $m^2\,m^{-2}$ for minimum and 3.5 $m^2\,m^{-2}$ for maximum) due to the sparse canopy structure (Alton et al., 2005; Los et al., 2000; Shibistova et al., 2002; Wirth et al., 1999). The forest is located on alluvial sandy mineral soil with no underlying permafrost (Kelliher et al., 1999; Lloyd et al., 2002).

2.2. Measurement systems

2.2.1. Eddy covariance flux measurements

The EC system consists of a three-axis ultrasonic anemometer USA-1 (METEK GmbH, Elmshorn, Germany) to measure three wind components as well as sonic temperature, and a closed-path infrared gas analyzer LI-7200 (LI-COR Biosciences, Lincoln, NE, USA) to measure CO_2 and H_2O concentrations. The sampling intake line consists of a 1 m stainless steel tube with an inner diameter of 7.7 mm (a 3/8″ tube). The flow rate inside the sampling line was 15 L min^{-1}, which should provide turbulent airflow inside the tubing to minimize frequency losses. The horizontal and vertical sensor separations were 25 cm and 5 cm, respectively. The voltage signals for CO_2 and H_2O concentrations (dry mole fractions) of the gas analyzer were connected to the analog input channels of the sonic anemometer. After the analog-to-digital conversion by the converter inside the anemometer, these signals were added to the digital data stream sent from the sonic anemometer to the computer via serial data transmission at a sampling rate of 20 Hz. Storage of the raw data was managed by the program EddyMeas as part of the EddySoft package (Kolle and Rebmann, 2007). Additionally the LI-7200 was directly connected to the computer via RS-232 and the program LI7200Log collected all status information and measured data from the gas analyzer at a rate of 1 Hz and stored them as 30 min averages.

In order to determine the CO_2 storage flux below the EC measurement height, ambient CO_2 concentrations were measured at nine heights (0.1, 0.3, 1, 2, 5, 9, 15, 22, 29.2 m) with a GMP343 probe (Vaisala, Helsinki, Finland). A CR10X data logger (Campbell Scientific, Logan, UT, USA) was used to control the gas-switching unit and to collect the data from the probe. Air was drawn through equal length tubes at a rate of 7 L min^{-1}, with each height being sampled for 1 min (the lowest level was sampled for 2 min). Readings were taken at a rate of 1 Hz over the last 50 s (110 s for lowest level) of sampling at each height and then averaged for each 10 min cycle before being stored. Storage fluxes of CO_2 below the flux measurement level were determined as the time change of an integrated spline function through the CO_2 profile measurements. Manual calibration of the LI-7200 and replacement of new filters were performed periodically (April, June, and September) in each measurement year.

2.2.2. Auxiliary measurements

Along with the flux measurements, meteorological data were collected. Air temperature (T_a) and relative humidity (RH) were measured