Agricultural and Forest Meteorology 168 (2013) 47–58

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

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

Linking water vapor and CO_2 exchange from a perennial bioenergy crop on a drained organic soil in eastern Finland

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ARTICLE INFO

Article history:
Received 23 August 2011
Received in revised form 10 August 2012
Accepted 11 August 2012

Keywords:
Evapotranspiration
Gross ecosystem productivity
Energy balance
Radiation balance
Boreal environment
Peatland drainage

ABSTRACT

With the aim of addressing the broader issues of land use, climate change and energy crisis, eddy covariance measurements of energy and CO_2 exchange from a bioenergy crop (reed canary grass, *Phalaris arundinaceae*, L.) cultivated on a drained organic soil (a cutover peatland) in eastern Finland were initiated in the spring of 2004. Based on the climatically diverse dataset from the 2004 to 2010 period, the objectives of the work presented here are to characterize the interannual variability in water vapor exchange and to understand the linkage between energy and CO_2 exchange from this perennial crop during two extreme growing seasons. Correcting the measured soil heat flux by accounting for the change in heat storage above the heat flux plates helped close the energy balance at this site. Interannual variability in ecosystem processes of energy and CO_2 exchange were attributed primarily to marked differences in the amount and distribution of seasonal precipitation. Differences in the phonological development of the crop during seasons with contrasting climatic conditions were reflected in the normalized difference vegetation index (NDVI) estimated from the radiation instruments installed on the tower. Wet years were characterized by an even distribution of seasonal precipitation, low to moderate air and soil temperatures, lower solar and net radiation intensities (owing to reduced number of bright sunshine hours and therefore, higher amount of diffuse sky radiation), moderate to saturated soil moisture conditions and lower vapor pressure deficit. These climatic conditions resulted in high bulk surface conductance (g_s), high evapotranspiration (ET) and low sensible heat flux with a peak seasonal Bowen ratio ($\beta = 0.1$). These conditions were favourable for a high uptake of atmospheric CO_2. Dry years, on the contrary, were marked by long dry spells during important phases of crop growth, climatic and soil moisture stress leading to high evaporative demand, low g_s values, reduced evapotranspiration and high sensible heat flux ($\beta = 0.3$–0.4). On a seasonal basis, the ET losses during a dry year were 13% lower compared to those during a wet year. The corresponding reduction in gross ecosystem productivity (GEP), however, was to the extent of 21%. Owing to the ability of this perennial crop to sequester large amounts of atmospheric carbon into its above- and below-ground biomass, the water use efficiency (defined as the slope of the linear regression of monthly values of GEP against ET) of this cultivation system was found to be 9.1 g CO_2 per kg of H_2O lost as ET. The results stemming from this work further support our earlier conclusions that this bioenergy system is a suitable land use option on drained and abandoned cutover peatlands with a high potential for offsetting CO_2 load to the atmosphere.

1. Introduction

More than 50% of the natural peatlands in Finland were drained for forestry, agriculture and peat extraction for energy in the mid to late 20th century (Lappalainen, 1996). These organic soils cover about 30% of the Finnish land area and contain 5500 Tg of C (Turunen, 2008). They are extremely vulnerable upon drainage to significant losses of CO_2 to the atmosphere (Alm et al., 2007). Several after-use options to mitigate CO_2 emissions from drained organic soils have yielded little success (Maljanen et al., 2010). Since the mid 1990s, cultivation of reed canary grass (RCG, *Phalaris arundinaceae*, L.), a perennial bioenergy crop especially on peatlands drained and left abandoned after peat extraction has been considered as a suitable option in the Fenno-Scandinavian region with a potential for offsetting the CO_2 load to the atmosphere (Lewandowski et al., 2003). Although the aerial extent of peat extraction sites is less than 1% of the original peatland area in Finland, CO_2 emissions from these areas is estimated to be about 5.2 Tg (Turunen, 2008).

Since the mid 1990s, cultivation of perennial bioenergy crops on abandoned peat extraction areas has been thought of as an after-use

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http://dx.doi.org/10.1016/j.agrformet.2012.08.006

option on these drained organic soils. With a view to understanding the performance of RCG cultivation on a cutover peatland, eddy covariance measurements of net ecosystem CO_2 exchange (NEE), chamber soil GHG emissions were initiated in the spring 2004. RCG NEE, GHG emissions and their regulating factors have been published in Shurpali et al. (2008, 2009, 2010) and Hyvönen et al. (2009). Glasshouse based RCG leaf photosynthetic responses to light, temperature and water table level on soil microcosms from this study site are reported in Zhou et al. (2011). All these individual studies converge to a common conclusion that the site water balance plays a crucial role in how the soil, plant and atmosphere interactions are brought about in this ecosystem in regulating CO_2 dynamics in response to the prevailing climatic conditions. The net biome productivity, the single most important factor in the life cycle assessment of the atmospheric impact of RCG as a bioenergy crop at this site, was negative in wet years (implying net carbon uptake) and positive (a net source to the atmosphere) in dry years (Shurpali et al., 2010).

Given that the stomates act as a common pathway for water vapor and CO_2 exchange in vegetated ecosystems, evapotranspiration (ET) and NEE should be responsive to soil water balance. Ecosystem parameters such as soil moisture content, vegetation productivity, ecosystem nutrient and water balance are all affected by ET. Many previous studies on water vapor exchange from forests and grasslands in tropical, temperate and boreal environments have characterized the interannual variation in ET and highlighted the importance of soil water balance on surface energy exchange from these various ecosystems (Baldocchi et al., 2004; Beer et al., 2009; Eugster et al., 2000; Wilson et al., 2002). However, very few studies have addressed the variation in ET on drained boreal organic soils (e.g., Petrone et al., 2004) and not much is known about the water use efficiency of perennial grasses on these soil types. The soil water balance, radiation balance, surface energy and carbon exchange are all interrelated. These phenomena in turn provide a feedback to the regional climate. Therefore, our objectives in this paper are twofold. Firstly, we characterize the water vapor exchange during seven climatically diverse growing seasons from 2004 to 2010 from a drained peatland site cultivated with a bioenergy crop. Secondly, we investigate how the two important ecosystem process–water vapor and CO_2 exchange are interlinked at this study site. We aim to illustrate the linkage between the two exchange processes using NEE and ET data from two climatically extreme years: 2004 – a wet year and 2005 – a dry year. The overarching goal of this work is to compare the water use efficiency of this perennial bioenergy system on a drained organic soil with other ecosystems.

2. Materials and methods

2.1. The site

The study site (62°30′N, 30°30′E) is located in the rural area of the city of Joensuu in eastern Finland. It lies on the border of southern and mid boreal climatic zones. Based on the 30-year normal (1971–2000) climatic data, the mean annual temperature and precipitation in the region are 2.1 °C and 669 mm, respectively (Drebs et al., 2002). The daily maximum and minimum temperatures of −10.6 and 16.0 °C occur in January and July, respectively. July and August are the wettest months with 80–90 mm of rainfall, while February, March and April, on an average, receive the lowest amount of precipitation mostly in the form of snow with about 35 mm (water equivalent) during each month. The site was a minerotrophic fen until the late 1970s (Tolonen, 1967) when it was drained for peat extraction. It was taken out of peat extraction in 2001 and cultivated with RCG, a perennial bioenergy crop. The general RCG cultivation practice in the Fenno-Scandinavian region is to harvest the crop in the spring of the following year starting from the third year of the 10–15 year rotation cycle. The site was fertilized with a surface application of 59.5 kg N, 14.0 kg P and 45.5 kg K ha^{-1} $year^{-1}$. The soil is not tilled, except at the time of land preparation in the beginning of the rotation cycle. Whether the soil needs additional lime is decided depending upon the soil pH and crop performance in the preceding year.

2.2. Eddy covariance measurements

Surface energy and net ecosystem CO_2 exchange (NEE) measurements were initiated during March 2004 using the eddy covariance (EC) technique (Shurpali et al., 2009) and are continuing. The eddy covariance system consists of a 3-D sonic anemometer (Model CSAT-3: Campbell Scientific, Logan, UT, USA) and an open path infrared CO_2/H_2O analyser (Model LI-7500: LI-Cor Inc., Lincoln, NE, USA) installed on an instrument tower at 3.7 m above the ground and aligned at an angle of 225°. The eddy covariance signals are measured at a frequency of 10 Hz using a datalogger (Model CR5000: Campbell Scientific, Logan, UT, USA) and the raw data are stored in a binary format on 1 GB PCMCA cards. The EC data were post-processed using “Edire” program developed at the University of Edinburgh (Mauder et al., 2007). Various corrections to account for the coordinate rotation, instrument frequency response (Moore, 1986) and density variations due to simultaneous transfer of water vapor (Webb et al., 1980) were applied. Quality checked NEE data were gap filled and partitioned into gross primary productivity (GPP) and total ecosystem respiration (TER) employing the marginal distribution sampling method described in Reichstein et al. (2005). Further details are available in Shurpali et al. (2009).

2.3. Supporting measurements

Other supporting meteorological measurements made at the RCG cultivation site included air temperature and relative humidity (Model MP101A: Rotronic Instruments UK Ltd., West Sussex, UK), net radiation and its components (Model CNR1: Campbell Scientific, Leicestershire, UK), global (Model LI-200SA: LI-Cor Inc., Lincoln, NE, USA) and photosynthetically active radiation (Model LI-190SA: Li-Cor Inc., Lincoln, NE, USA), wind speed and direction (Model QMV101: Väisälä Oyj, Vantaa, Finland) at 3.7 m height above the soil surface, soil heat flux (at 0.08 m below soil surface, Model HFP01SC, Campbell Scientific, Leicestershire, UK), soil temperature profile (at 0.02, 0.04, 0.06, 0.08, 0.16, 0.32 and 0.64 m below the soil surface, Model 107: Campbell Scientific, Leicestershire, UK), precipitation (MODEL 52202/52203: Campbell Scientific, Leicestershire, UK), soil moisture profile (at 0.025, 0.10 and 0.30 m below the soil surface, Model CS616: Campbell Scientific, Leicestershire, UK) and snow depth (at 2.5 m above the surface, Model SR 50A: Campbell Scientific, Leicestershire, UK) (see Shurpali et al., 2009 for details).

2.4. Plant biomass and leaf area index (LAI)

For plant biomass estimation, the plants were harvested from 25 cm × 25 cm plots ($n = 9$) by clipping at the stem base, and separated into living, green biomass and dead standing biomass. From six out of the nine plots a soil core was additionally taken for below-ground root biomass determination. The soil core was sampled to a depth of 15 cm depth, thus up to the maximum rooting depth of the plants (in general, roots from the 10–15 cm deep layer contributed less than 2% to the total (0–15 cm depth) root biomass), by using a metal soil corer (of 7 cm diameter). In the laboratory, roots were collected and carefully washed over a 0.2 mm sieve. Only the white,