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Biophysical drivers of the carbon dioxide, water vapor, and energy exchanges of a short-rotation poplar coppice

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ABSTRACT

We used the eddy-covariance technique to measure the temporal dynamics and the relationships between leaf area index (LAI) and exchanges of carbon dioxide (CO_2), latent heat (LE) and sensible heat (H) in a multi-genotype short-rotation poplar coppice (SRC) located in East-Flanders (Belgium). The study was carried out over four years (2010–2013) corresponding to the first two rotations of the plantation. The net carbon (C) balance during the first two-year rotation was 75.2 (±4.4) g C m^{-2} in the establishment year 2010 and −95.6 (±5.9) g C m^{-2} in 2011. After the harvest (second two-year rotation) the coppice was a net source of carbon, 151.0 (±10.5) g C m^{-2} in 2012, but a sink of −274.6 (±18.8) g C m^{-2} in 2013. Overall, at the end of the second rotation this SRC, was a net CO_2 sink with a cumulative uptake of −144.0 (±22.8) g C m^{-2}. The temporal dynamics and the magnitude of the ratio between gross primary production (GPP) and ecosystem respiration (R_{eco}) were similar to a deciduous forest. The evolution of LAI showed values ranging from 0.96 (±0.4) to 2.0 (±1.2) and from 5.1 (±1.5) to 4.5 (±0.84) during the first and the second rotation, respectively. The GPP (measured close to light saturation) was significantly related to LAI (r^2 of 0.76, $p < 0.001$). The cumulative evapotranspiration (ET) measured during the first rotation was 241.7 mm and 349.9 mm for 2010 and 2011, respectively, and 464.6 mm and 372.1 mm for 2012 and 2013. The average value of surface conductance (G_s) was 0.35 mol m^{-2} s^{-1} and 0.24 mol m^{-2} s^{-1} for the foliated and unfoliated periods, respectively. The mean decoupling factors (Ω) were 0.35 and 0.23 for the foliated and unfoliated periods, respectively, indicating that ET was primarily controlled by vapor pressure deficit (VPD) and G_s (a well-coupled system). The mean Priestley–Taylor coefficient (α) was 0.77 and 0.53 for the foliated and the unfoliated periods, respectively. Such low values indicate that ET was significantly lower than the equilibrium evaporation and thus also lower than the ET of a hypothetical reference crop. During the whole experiment only two short episodes of drought were identified when in May–June 2011 and June 2013 the evaporative fraction dropped below 0.4. The analysis of G_s showed a rather low stomatal control (anisohydric stomatal response) that put the poplar SRC at greater risk during severe drought conditions. All the three mentioned parameters related to ET and GPP (G_s, Ω and α) were significantly and positively correlated to LAI (r^2 from 0.14 to 0.2, $p < 0.0001$), suggesting that LAI was the main biophysical driver controlling the carbon and water balances in this bioenergy production system.

1. Introduction

The European Union has set the target of increasing the use of renewable energy sources to at least 20% of total consumption by the year 2020 (EU, 2009). The objective is to reduce the consumption of fossil fuels and thereby reduce CO_2 emissions (Zetterberg and Chen, 2014). Within the context of the search for renewable energy sources dedicated lignocellulosic crops, as short-rotation coppice (SRC), have a high potential. Indeed, one might expect a

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considerable increase in the area of these SRC if they are to be used as conventional biofuel for bioenergy production, or for the production of second-generation biofuels (Eisentraut, 2010). Poplar (*Populus* spp.) is one of the genera that currently receives a lot of attention as a very suitable crop for the production of biofuel (Kauter et al., 2003; Aylott et al., 2008; AEBIOM, 2012). The carbon (C) uptake by crops is primarily determined by the biology of the vegetation – e.g., leaf area index (LAI), physiological activity, length of the growing season – as well as by the meteorological conditions (Schmid et al., 2000). The gross primary productivity (GPP) is primarily dependent on the photosynthetically active radiation (PAR), in combination with LAI, while ecosystem respiration (R_{eco}) strongly responds to air and soil temperature (Carrara et al., 2004; Baldocchi, 1997; Reichstein et al., 2002). Carbon uptake in SRC is considered to be very sensitive to low water availability (Broeckx et al., 2013), and to high temperatures by stomatal (increase of vapor pressure deficit) and non-stomatal control (influencing R_{eco}) (Migliavacca et al., 2009). This suggests that SRC plantations could be vulnerable to climate change in regions where water is in short supply (King et al., 2013). Moreover, a poplar SRC might be more sensitive to drought than other deciduous and coniferous forests because poplar is a fast-growing species with rather low stomatal control (Pita et al., 2013).

Monitoring the net ecosystem exchange (NEE) of CO_2 (and its partitioning into GPP and R_{eco}) in combination with the fluxes of sensible heat (H) and latent heat (LE) is essential for quantifying the carbon sequestration potential and water use of SRC plantations, as well as for identifying the main environmental and/or biophysical drivers. Several studies on the physiology of SRC and of longer-rotation poplar plantations have already tried to elucidate the environmental controls (e.g., Neumann et al., 1996; Calfapietra et al., 2003, 2005; Zona et al., 2013). Heatwaves can induce a considerable reduction of the net C uptake in longer rotation (twelve-year) poplar plantations, even in the absence of pronounced soil water stress (Migliavacca et al., 2009). On the other hand in a two-year-old SRC plantation, soil water shortage limited the NEE when the water table progressively decreased and vapor pressure deficit (VPD) became an important control on CO_2 fluxes. By removing the influence of solar radiation on NEE, VPD explained up to 16% of the variability, and water limitation on CO_2 uptake mostly occurred when VPD was >1 kPa (Zona et al., 2013).

Here, we present and discuss measurements of CO_2 and H_2O fluxes in combination with measurements of LAI of a poplar SRC over a four-year period. We hypothesize that LAI explains most of the variability of the eco-physiological parameters that drive the CO_2 and water vapor exchanges. The knowledge of LAI is therefore useful to determine carbon uptake and water use of poplar SRC under various environmental conditions. In terms of water consumption of the SRC crop we hypothesized that the ET of the poplar plantation was lower than the ET of an hypothetical reference crop. The objectives of the present study were: (i) to quantify the magnitude and the seasonal dynamics of CO_2, water vapor and energy exchanges during two two-year rotations for a poplar SRC; (ii) to investigate the role of LAI in controlling GPP and ET; (iii) to quantify and analyze the seasonal variation of surface conductance (G_s), decoupling factor (Ω), and Priestley–Taylor coefficient (α). These latter variables represent important bulk parameters that treat the soil and the vegetation as one single layer, in relation to LAI.

2. Material and methods

2.1. Site description

The research site was an operational multi-genotype SRC plantation of poplars located in Lochristi, East-Flanders (Belgium; 51°06′44″N, 3°51′02″E) at an elevation of 6.25 m above sea level. The SRC culture was planted on 7–10 April 2010 with 12 selected genotypes of *Populus deltoides*, *Picea maximowiczii*, *Phyllostachys nigra*, and *Populus trichocarpa*, and their interspecific hybrids in a double-row design with a planting density of 8000 plants ha^{-1}. No fertilizers and no irrigation were applied during the four years of the study. The aboveground biomass was harvested in January–February 2012 (end of the first rotation) and in February 2014 (end of the second rotation). The first rotation was characterized by single-stem plants, while the second rotation consisted a multiple-stem coppice. More details on the planting materials, and on the plantation lay-out and management are provided by Broeckx et al. (2012) and Verlinden et al. (2013).

The present contribution and the SRC plantation are part of the larger POPFULL project (http://uahost.uantwerpen.be/popfull) where the full balances of greenhouse gases, of energy and the economics are being evaluated. The 30-year average annual temperature and precipitation (collected by a nearby station of the Royal Meteorological Institute of Belgium; www.meteo.be) at the site are 9.5 °C and 726 mm, respectively. The precipitation is equally distributed across the year. The site is characterized by two different former land-use types: extensively grazed pasture, and agricultural cropland (ryegrass, wheat, potato, beet, and most recently monoculture maize with regular nitrogen (N) fertilization at a rate of 200–300 kg ha^{-1} yr^{-1} as liquid animal manure and as chemical fertilizer).

Prior to planting a soil survey (described in detail by Broeckx et al., 2012) revealed that the soil has a sandy texture with a clay-enriched deeper soil layer and poor natural drainage. The carbon (C) and N mass fractions were significantly different in the upper 0–15 cm soil layer (p = 0.0001) and were lower in previous cropland (1.48% ± 0.32 and 0.12% ± 0.03, respectively) as compared to previous pasture (1.95% ± 0.36 and 0.18% ± 0.03, respectively). The C and N contents – in the upper 90 cm – were not significantly different between the two different former land-use types (Broeckx et al., 2012).

2.2. Flux and meteorological measurements

The eddy-covariance (EC) system – used to measure gas and energy fluxes between the SRC plantation and the atmosphere – has been extensively described previously (Zona et al., 2013). Briefly, the EC system included a three-dimensional sonic anemometer (Model CSAT3, Campbell Scientific, Logan, UT, USA) to measure the wind speed component fluctuations, and a closed-path differential infrared gas analyzer (LI-7000, LI-COR, Lincoln, NE, USA) for the measurements of the CO_2 and H_2O mole fractions in air. Both instruments sampled variables continuously with a frequency of 10 Hz. The sonic anemometer and the inlets of the sampling lines were situated at 5.8 m above the soil surface during a first period (from 1st June 2010 to 30th August 2011), and were raised to 6.6 m thereafter (from 31 August 2011 to 31 December 2013) to match the rapid growth of the plantation. A vacuum pump positioned at the outlet of the LI-7000 gas analyzer, generated a flow rate of about 20–22 l min^{-1}. This maintained a turbulent flow regime in the sampling line – as required by standard EC methodology – to avoid concentration dilution in the air samples between the sampling line inlet and the gas analyzer, and the consequent, high-frequency fluctuation dampening (Munger et al., 2012). To eliminate the fluctuations caused by the pump two buffers (volume of 0.5 l each) were positioned between the pump and the outlet of the analyzer. The sampling tubes were heated and thermally insulated from the environment to prevent condensation and deliquescence of the air samples in the inlet tubes. These phenomena can cause dampening of the water vapor high frequency fluctuations possibly leading to large underestimates of the LE fluxes (Fratini et al., 2012).