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Carbon dioxide exchange of a perennial bioenergy crop cultivation on a mineral soil

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Abstract

One of the strategies to reduce carbon dioxide (CO_2) emissions from the energy sector is to increase the use of renewable energy sources such as bioenergy crops. Bioenergy is not necessarily carbon neutral because of greenhouse gas (GHG) emissions during biomass production, field management and transportation. The present study focuses on the cultivation of reed canary grass (RCG, *Phalaris arundinaceae* L.), a perennial bioenergy crop, on a mineral soil. To quantify the CO_2 exchange of this RCG cultivation system, and to understand the key factors controlling its CO_2 exchange, the net ecosystem CO_2 exchange (NEE) was measured during three years using the eddy covariance (EC) method. The RCG cultivation thrived well producing yields of 6200 and 6700 kg DW ha^{-1} in 2010 and 2011, respectively. Gross photosynthesis (GPP) was controlled mainly by radiation from June to September. Vapour pressure deficit (VPD), air temperature or soil moisture did not limit photosynthesis during the growing season. Total ecosystem respiration (TER) increased with soil temperature, green area index and GPP. Annual NEE was −262 and −256 g C m^{-2} in 2010 and 2011, respectively. Throughout the studied period, cumulative NEE was −575 g C m^{-2}. When compared to the published data for RCG on an organic soil, the cultivation of this crop on a mineral soil had higher capacity to take up CO_2 from the atmosphere.

1 Introduction

Anthropogenic increase in the atmospheric concentration of greenhouse gases (GHG) has been considered as the major reason for the global climate warming (IPCC, 2013). The carbon dioxide (CO_2) concentration in the atmosphere has increased from 278 to 391 ppm between 1750 and 2011 and is still increasing (IPCC, 2013). Carbon dioxide emitted to the atmosphere originates mainly from respiration and fossil fuel combustion with the main sinks being photosynthesis and oceans (IPCC, 2013). In Finland the en-

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ergy sector and agriculture are the most important in the total national GHG emissions (Statistics Finland, 2014).

One of the strategies to reduce CO_2 emissions from the energy sector is to increase the use of renewable energy sources, e.g. using biomass. Bioenergy produced from biomass is not necessarily carbon neutral because of GHG emissions during biomass production, field management and transportation. Life-cycle assessment (LCA) results have been recently reported for reed canary grass (RCG, *Phalaris arundinaceae* L.) cultivation on cut-away peatlands in Finland (Shurpali et al., 2010) and Estonia (Järveoja et al., 2013). In these studies, the RCG sites were net sinks for CO_2 and hence, RCG is suggested to be a good after use option for such marginal soils which are known to release large amount of CO_2 as a result of decomposition of residual peat, when left abandoned (Kasimir-Klemedtsson et al., 1997).

RCG is a perennial crop well adapted to the northern climatic conditions. It has a rotation time of up to 15 years. The annual harvestable above-ground RCG biomass ranges from 6 to 12 tons dry matter ha^{-1} (Saijonkari-Pahkala, 2001; Lewandowski et al., 2003). As a perennial crop, it has many benefits when compared with the annual cropping systems. The growth starts earlier as the re-establishment of the crop in the spring is not needed. There is no annual tilling which reduces the CO_2 emissions from soil (e.g. Chatskikh and Olesen, 2007). Additionally, the continuous plant cover on the soil reduces leaching of nutrients (Saarijärvi et al., 2004).

While continuous and long-term measurements of GHG balance from bioenergy crops are needed to evaluate the atmospheric impact of the whole production chain, there are no GHG flux measurements from RCG cultivation on mineral soils. With this in view, we measured the CO_2 balance of RCG crop cultivation (2009–2011) on a mineral soil by the eddy covariance (EC) technique. Our objectives in this paper are to quantity and characterise the NEE of a perennial crop cultivated on a mineral soil and to investigate the factors controlling its CO_2 balance.

2 Materials and methods

2.1 Study site and agricultural practices

The study site is located in Maaninka (63°09′49″ N, 27°14′3″ E, 89 m above the mean sea level) in eastern Finland. Long-term (30 years, reference period 1981–2010; Pirinen et al., 2012) annual air temperature in the region is 3.2 °C with February being the coldest (−9.4 °C) and July the warmest (17.0 °C) month. The annual precipitation in the region is 612 mm. The amount of precipitation during the May–September period is 322 mm.

The experimental site is a 6.3 ha (280m × 220 m) agricultural field cultivated with RCG (cv. “Palaton”). During the last ten years prior to planting of RCG, the field was cultivated with grass (*Phleum pratense* L.; *Festuca pratensis* Huds), barley (*Hordeum vulgare* L.) or oat (*Avena sativa* L.). The soil is classified as a Haplic Cambisol/Regosol (Hypereutric, Siltic) (IUSS Working Group WRB, 2007) and the texture of the topsoil (0–28 cm) varied from clay loam to loam (clay 22–34 %, silt 46–64 % and sand 14–30 %) based on the US Department of Agriculture (USDA) textural classification system. In the topsoil, pH (H_2O) varied from 5.4 to 6.1, electrical conductivity from 960 to 3060 $\mu S\,cm^{-1}$ and soil organic matter content from 3 to 11 %. The average C : N ratio of the topsoil was 14.9. The exchangeable K and easily soluble P concentrations (Vuorinen and Mäkitie, 1955) ranged from 67.3 to 153 $mg\,L^{-1}$ soil and from 3.3 to 12.9 $mg\,L^{-1}$ soil, respectively. Particle density (0–18 cm) varied from 2.6 to 2.7 $g\,cm^{-3}$. Based on the soil moisture retention curve (0–18 cm), mean (± standard error) field capacity was 39.7 ± 1.2 % (soil moisture (v/v)) and wilting point was 21.6 ± 0.8 % (soil moisture (v/v)). The soil bulk density (0–7 cm) was calculated as a ratio of the dry weight of the soil and the sampling volume in August 2010 (0.76 $g\,cm^{-3}$) and October 2011 (0.89 $g\,cm^{-3}$). For this, six soil samples were collected from the field and oven dried (+60 °C) after which the weight of the soil was measured.

In the beginning of June 2009, the sowing of RCG was done with a seed rate of 10.5 $kg\,ha^{-1}$ together with the application of a mineral fertilizer (60 $kg\,N\,ha^{-1}$, 30 kg P ha^{-1} and 45 kg K ha^{-1}). The field was rolled prior to and after sowing. Additional sowing was done to fill the seedling gaps in June and July. Herbicide (mixture of MPCA 200 g L^{-1}, clopyralid 20 g L^{-1} and fluroxypyr 40 g L^{-1}, 2 L in 200 L of water ha^{-1}) was applied by the end of July 2009 to control the weeds. Mineral fertilizer was applied as surface application in spring 2010 (70 kg N ha^{-1}, 11 kg P ha^{-1} and 18 kg K ha^{-1}) and spring 2011 (76 kg N ha^{-1}, 11 kg P ha^{-1} and 19 kg K ha^{-1}). In order to enhance the quality of the biomass for burning, the crop was kept at the site over winter (Burvall, 1997) and was harvested in the following spring (28 April in 2011 and 9 May in 2012).

2.2 Micrometeorological measurements

Measurements of CO_2, latent heat (LE) and sensible heat (H) fluxes were carried out from July 2009 until the end of 2011 using the closed-path eddy covariance (EC) method (Baldocchi, 2003). Measurement mast was installed approximately in the middle of the field and the instrument cabin was located about 10 m east of the EC mast. Except for the wind sector from 85 to 130° downwind of the instrument cabin, all wind directions were acceptable. The prevailing wind direction was northerly with a 24 % occurrence during the study period. The EC instrumentation consisted of an infra-red gas analyser (IRGA) for CO_2 and water vapour (H_2O) concentrations (model: Li-7000 (primary) or Li-6262 (backup), LiCor) and a sonic anemometer (model: R3-50, Gill Instruments Ltd., UK) for wind velocity components and sonic temperature. The mast height was 2, 2.4 or 2.5 m, adjusted according to the vegetation height.

A heated gas sampling line (i.d. 4 mm, 8 m PTFE + 0.5 m metal) with 2 filters (pore size 1.0 µm, PTFE, Gelman® or Millipore®) was used to draw air with a flow rate of initially 6 L min^{-1} (until 31 March 2011). Subsequently, a flow rate of 9 L min^{-1} was used. The IRGA was housed in a climate controlled cabin. Reference gas flow, created using sodalime and anhydrone, also fitted with a Gelman® filter, was 0.3 L min^{-1}. The IRGA was calibrated approximately every second week with a two point calibration (0 and 399 µL L^{-1} of CO_2, AGA Oy, Finland) and additionally with a dew point generator (model: LI-610, LiCor) for H_2O mixing ratio during conditions when air temperature was above + 5 °C.

Data collection was done at 10 Hz using the Edisol program (Moncrieff et al., 1997). The 30 min EC flux values were calculated from the covariance of the scalars and vertical wind velocity (e.g. Aubinet et al., 2000). Data processing was done using EddyUH post-processing software (www.atm.helsinki.fi/Eddy_Covariance/index.php). Despiking was done by defining a limit for the difference in subsequent data points for CO_2 ($15\,\mu L\,L^{-1}$) and H_2O ($20\,mmol\,mol^{-1}$) concentrations. A data point defined as a spike was replaced with the adjacent value. Two dimensional-coordinate rotation (mean lateral and vertical wind equal to zero) was done on the sonic anemometer wind components. Angle of attack correction was not applied. Detrending was done using block-averaging. Lag time due to the gas sampling line was calculated by maximizing the covariance. Low frequency spectral corrections were implemented according to Rannik and Vesala (1999). For high frequency spectral corrections, empirical transfer function calculations were done based on the procedure introduced by Aubinet et al. (2000). Humidity effects on sonic heat fluxes were corrected according to Schotanus et al. (1983). Point by point dilution correction was applied after the spectral corrections. From the processed data, flux values measured when winds were from behind the instrument cabin (between 85 and 130°) and those during rain events were removed. The available flux data was further quality controlled using filters as follows. The night-time NEE did not correlate with $u*$, nevertheless, a $u*$ filter of $0.1\,m\,s^{-1}$ was used. Flux was considered non-stationary and rejected when stationarity (according to Foken and Wichura, 1996) was higher than 0.4. Both skewness and kurtosis of the data were checked and the acceptable skewness range was set from −3 to 3 and kurtosis from 1 to 14. Overall flags (according to Foken et al., 2004) higher than 7 were removed. Finally, the data was visually inspected. From the available data, approximately 30 % of the CO_2 and H flux data and 40 % of the LE flux data were rejected. Based on a footprint analysis, 80 % of the flux was found to originate from within 130 m radius from the mast.

The data gap filling and flux partitioning was done using the online tool (www.bgc-jena.mpg.de/~MDIwork/eddyproc/index.php). This gap filling method considers both the co-variation of the fluxes with global radiation, temperature and vapour pressure deficit (VPD) and temporal auto-correlation of the fluxes (Reichstein et al., 2005). Flux partitioning was done using only the measured data points. Total ecosystem respiration (TER) was defined as the night-time measured net ecosystem CO_2 exchange (NEE). The regression between night-time NEE and air temperature (T) was calculated using an exponential regression model (Lloyd and Taylor, 1994) of the form:

$$R(T) = R_{\mathrm{ref}}\, e^{E_0 \left(\frac{1}{T_{\mathrm{ref}} - T_0} - \frac{1}{T - T_0}\right)} \tag{1}$$

where $T_0 = -46.021\,^\circ\mathrm{C}$, $T_{\mathrm{ref}} = 10\,^\circ\mathrm{C}$ and fitted parameters were R_{ref} (the temperature independent respiration rate) and E_0 (temperature sensitivity). Using the model outputs for R_{ref} and E_0, the half-hour TER was estimated using the measured air temperature. Finally, gross photosynthesis (GPP) was calculated as a difference between NEE and TER. In this paper, CO_2 released to the atmosphere is defined as a positive value and uptake from the atmosphere as negative.

As a final step, the EC measurements were validated using the energy balance closure (EBC) determined as the slope of the regression between net radiation (R_n) and latent heat (LE), sensible heat (H) and the ground heat flux (G). The EBC is expressed in the following formulation;

$$R_n = \mathrm{LE} + H + G \tag{2}$$

The EBC was determined using data from only those 30 min time periods when all of the energy components were available. The slope of the regression was 0.70 in May–September period 2010 and 2011. Incomplete closure is a common as part of the available energy is also stored in different parts on the ecosystem (Foken, 2008). Different storage terms were included, i.e. heat in soil, canopy, photosynthesis, sensible and latent heat below the EC mast (following Meyers and Hollinger, 2004; Lindroth et al., 2010), and the slope increased to 0.75.

2.3 Supporting measurements

A weather station was set up close to the EC mast. Height of the weather station mast was adjusted according to the EC mast height. Supporting climatic variables, i.e., net radiation (model: CNR1, Kipp & Zonen B.V.), air temperature and relative humidity (model: HMP45C, Vaisala Inc.), photosynthetically active radiation (PAR, model: SKP215, Skye instruments Ltd.), amount of rainfall at 1 m height (model: 52203, R.M. Young Company), soil temperature at 2.5, 10 and 30 cm depths (model: 107, Campbell Scientific Inc.), soil moisture at depths of 2.5, 10 and 30 cm (model: CS616, Campbell Scientific Inc.), soil heat flux at 7.5 cm depth (model: HPF01SC, Hukseflux) and air pressure (model: CS106 Vaisala PTB110 Barometer) were measured. Data was collected using a datalogger (model: CR 3000, Campbell Scientific Inc.). All meteorological data were collected as 30 min mean values (precipitation as 30 min sum), except air pressure which was recorded as an hourly mean. Supporting data collection began since 14 August 2009. Short gaps in the data were filled using linear interpolation. If air temperature, relative humidity, pressure or rainfall data were missing for long periods, data from Maaninka weather station, located about 6 km to South-East from the site and operated by the Finnish Meteorological Institute (FMI), was used. At the end of the study period, the measured shortwave radiation data when compared with the radiation data available from FMI were found to be approximately 35 % higher. Based on this analysis, the overestimation in the measurements of the available energy was corrected before the EBC calculations were made.

The RCG green area index (GA) was estimated following Wilson et al. (2007). Measurements were done approximately on a weekly basis during the main growing period and less frequently in the autumn. Three locations (1 m × 1 m) were selected and within those, three spots (8 cm × 8 cm) were used to count the number of green stems (Sn) and leaves (Ln) per unit area. Three plants adjacent to small spots were selected for measurements of green area of leaves (La) and stems (Sa). Following equation was used to calculate GA ($m^2\,m^{-2}$);

$$GA = (Sn \times Sa) + (Ln \times La) \tag{3}$$

Leaf area index (LAI) was measured using plant canopy analyser (model: LAI-2000, LiCor) with an 180° view cap. The LAI was measured close to GA plots at the same interval and at the same day as GA was estimated. A measurement was accepted when the standard error of LAI was less than 0.3 and the number of above and below ground observation pairs was more than three.

Above-ground biomass samples were collected approximately on a monthly basis from three locations in the field during the snow-free season in 2009, 2010 and 2011 and root samples in 2009 and 2010. Above-ground biomass was collected from a 20 cm × 20 cm area. After drying (+65 °C) for 24 h, dry weight (DW) was measured. In 2011, the fresh weight (FW) was also recorded. Root biomass (0–25 cm) was sampled from the same areas as the above-ground biomass using a soil corer (diameter 7 cm). Living roots (fine and coarse roots) were picked and washed. After drying (+65 °C) for 24 h, DW was measured.

To analyse the performance of the crop, water use efficiency (WUE) was determined following Law et al. (2002). For this purpose, evapotranspiration (ET) was determined by dividing LE with the latent heat of vaporization ($L = 2500\,\mathrm{kJ\,kg^{-1}}$). Monthly sums of GPP and ET from May to September period were obtained and WUE was determined as the slope of the linear regression between monthly GPP and ET. Bowen ratio was calculated from daytime ($\mathrm{PAR} > 20\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$) measured H and LE fluxes.

2.4 Analysis of environmental factors governing CO_2 exchange

The relationship between GPP and PAR was examined on a monthly basis from mid-May to September separately for 2010 and 2011. Prior to the analysis, PAR data were binned at an interval of $10\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$. The bin averaged values of GPP were plotted against PAR and the data were fitted with a rectangular hyperbolic model of the form;

$$\mathrm{GPP} = \frac{\mathrm{GP_{max}} \times \mathrm{PAR} \times \alpha}{\mathrm{GP_{max}} + \mathrm{PAR} \times \alpha} \tag{4}$$

where $\mathrm{GP_{max}}$ ($\mu\mathrm{mol\,m^{-2}\,s^{-1}}$) is the theoretical maximum rate of photosynthesis at infinite PAR and α is the apparent quantum yield. Additionally, data with PAR levels greater than 1000 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ were used to study the relationship between GPP and air temperature, VPD and soil moisture. To analyse the relationship between GPP and GA and also LAI, a weekly averaged GPP was constructed for those weeks when the plant variables were available. These data were fitted with a linear regression.

To be able to compare the results in detail with the earlier findings on RCG on organic soil site in Finland (Shurpali et al., 2010) another regression model was used to assess the relationship between TER and soil temperature, night-time measured NEE ($\mathrm{PAR} < 5\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$) from May to September separately for 2010 and 2011 was used. Prior to the analysis, the data were binned with soil temperature at 2.5 cm depth (from 0 to 21.5 °C with a 0.5 °C interval). The bin averaged values of TER were plotted against soil temperature and the data were fitted with an exponential regression model of the form;

$$\mathrm{TER} = R_{10} \times Q_{10}^{\left(\frac{T_\mathrm{s}}{T_{10}}\right)} \tag{5}$$

where T_s is the measured soil temperature (°C) at 2.5 cm depth, $T_{10} = 10\,^\circ\mathrm{C}$ and the fitted parameters are R_{10} (base respiration, $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$, at 10 °C) and Q_{10} (the temperature sensitivity coefficient). To analyse the relationship between TER and vegetation, we constructed weekly means from daily TER values for the weeks during which GA was estimated for 2010 and 2011. To assess the relationship between GPP and TER, daily sums of TER and GPP from May to September separately for 2010 and 2011 were used in the linear regression analysis.

3 Results

3.1 Seasonal climate and crop growth

The mean annual air temperature at the study site was 3.5, 2.2 and 4.5 °C in 2009, 2010 and 2011, respectively, with the daily means varying from −30.0 to +27.1 °C (Fig. 1a). Annual precipitation was 421, 521 and 670 mm in 2009, 2010 and 2011, respectively. In May–September period the precipitation was 40 and 28 % lower in 2009 (192 mm) and 2010 (228 mm). Precipitation was about the same as the long-term mean in 2011 (327 mm, Fig. 1b). The growing season is defined to have commenced when the mean daily air temperature exceeds 5 °C for five consecutive days with no snow and ended when the mean daily air temperature is below 5 °C five consecutive days. Growing season commenced on 1 May in 2009, 9 May in 2010 and 23 April in 2011 and lasted 152, 156 and 182 days in the three consecutive years.

The daily averaged VWC ranged from 0.12 to 0.54, from 0.09 to 0.37 and from 0.11 to 0.45 $m^3 m^{-3}$ in 2009, 2010 and 2011, respectively (Fig. 1c). The maximums in soil temperatures were recorded at 2.5 cm depth in July 2010 (20.9 °C) and 2011 (19.1 °C) (Fig. 1d). During the winter 2009–2010 and 2010–2011 the soil temperatures were close to zero. The lowest soil temperatures were recorded at 2.5 cm depth in December 2009 (−7.5 °C) and November 2010 (−3.4 °C).

The estimated evapotranspiration (ET), was 110, 330 and 370 mm in August – September 2009, May–September 2010 and May–September 2011, respectively. During those time periods, ecosystem used more water than was received through rainfall as the corresponding precipitation amounts were 80, 220 and 320 mm in 2009, 2010 and 2011, respectively. Clear linear relationship was found between GPP and ET (adjusted $R^2 = 0.73$, $p < 0.01$, $n = 12$) during May-September period in 2010 and 2011. The water use efficiency (WUE) of the RCG cultivation determined from this relationship was 12 $g\,CO_2\,kg^{-1}\,H_2O$. Averaged daytime Bowen ratio was 0.18 and 0.28 during the May-September period in 2010 and 2011, respectively.

During the first growing season (2009), the vegetation development was slow and the maximum plant height was low when compared to the subsequent years (0.6, 1.7 and 1.8 m in 2009, 2010 and 2011, respectively). In the following years, the initial sprouting in early spring was followed by vigorous plant growth which lasted about 9. The rapid plant growth resulted in a steep increase in green area (GA) and leaf area indices (LAI) in 2010 and 2011 (Fig. 2b and c). Both GA and LAI levelled off in the beginning of June. The maximum above-ground biomass was recorded at the end of the season (560, 1100 and 1600 g DW m^{-2} in 2009, 2010 and 2011, respectively) (Fig. 2a–c). The maximum root biomass was 480 g DW m^{-2} in 2010 (Fig. 2b). Depending on the sampling occasion, 70 to 80 % of the roots were distributed within the 0–10 cm depth. The crop yield was 6200 kg DW ha^{-1} and 6700 kg DW ha^{-1} in for 2010 and 2011, respectively.

3.2 CO_2 exchange patterns

3.2.1 Measured net ecosystem CO_2 and energy exchange

Measured 30 min values of NEE, H and LE during 2009, 2010 and 2011 are shown in Fig. 3. In 2009, the NEE measurements began 45 days after the sowing in mid-June. The maximum amplitude of the diurnal NEE cycle varied from −26 to 20 µmol m^{-2} s^{-1} during the growing season in 2009. The amplitude of the diurnal NEE cycle was noticeable around mid-May onwards until November in 2010 and 2011. The maximum amplitude of diurnal NEE cycle varied from −31 to 18 µmol m^{-2} s^{-1} and from −37 to 20 µmol m^{-2} s^{-1} during the growing seasons in 2010 and 2011, respectively (Fig. 3a). Outside the growing seasons, respiratory losses dominated the net CO_2 balance. The ecosystem CO_2 loss was 0.62 µmol m^{-2} s^{-1} from October 2009 to mid-May 2010, 0.76 µmol m^{-2} s^{-1} during a similar period in 2010–2011 and 1.1 µmol m^{-2} s^{-1} for a shorter time period in 2011 (November and December).The diurnal LE cycle had the maximum amplitude during the summer months and ranged from −30 to 400, from 0 to 400 and from 0 to 600 W m^{-2} in 2009, 2010 and 2011, respectively. LE was close to zero during the non-growing season. The amplitude of diurnal H cycle was at the maximum during the summer months and ranged from −50 to 130, from −100 to 210 and from −100 to 190 $\mathrm{W\,m^{-2}}$ in 2009, 2010 and 2011, respectively. H ranged from −60 to 20 $\mathrm{W\,m^{-2}}$ during the non-growing seasons.

3.2.2 Diurnal trends

To examine the diurnal trends, the data on air temperature, VPD, PAR and NEE in June 2010 and 2011 were averaged to generate half-hour diurnal means (Fig. 4). In both years, June represented a period with both high CO_2 uptake and loss from the RCG cultivation system. Air temperature was lower in 2010 than in 2011 but both years showed typical diurnal patterns with minimum values during early morning hours and maximum values late in the afternoon (Fig. 4a). Similarly, the VPD was lower in 2010 than 2011 (Fig. 4b). The maximum in VPD (0.96 kPa) occurred late afternoon in 2010 whereas in 2011 the maximum (0.89 kPa) occurred around noon. In both years, the amplitude of diurnal mean of temperature and VPD was moderate. The mean diurnal pattern of NEE was similar between 2010 and 2011 and the patterns were fairly symmetrical (Fig. 4d). During the night time, from 22:00 to about 02:00 UTC+02:00, CO_2 exchange between the ecosystem and atmosphere was constant and dominated by respiration. Mean NEE during this time was 4.5 $\mathrm{\mu mol\,m^{-2}\,s^{-1}}$ in 2010 and 6.6 $\mathrm{\mu mol\,m^{-2}\,s^{-1}}$ in 2011. In the morning hours, with increasing PAR (Fig. 4c), NEE began to decline and the light compensation point occurred at a PAR level of about 200 $\mathrm{\mu mol\,m^{-2}\,s^{-1}}$ at around 05:00 UTC+02:00. After this, the uptake dominated the CO_2 balance. The peaks in mean NEE occurred around 12:00 UTC+02:00 at the same time as the peaks in the mean PAR. The maximum mean NEE in June was −21 and −23 $\mathrm{\mu mol\,m^{-2}\,s^{-1}}$ 2010 and 2011, respectively. With declining PAR levels, the plant CO_2 uptake also declined. The secondary light compensation point occurred at around 20:00 UTC+02:00.

3.2.3 Daily patterns

Seasonal patterns of daily sums of GPP, TER and NEE are shown in Fig. 5. From the start of NEE measurements in late July to mid-August in 2009, the site was a net source of CO_2 to the atmosphere. By mid-August, GPP began to overwhelm TER turning the site into a CO_2 sink. During the growing season, the maximum daily values of NEE, TER and GPP were −5.8, 9.7 and −10.5 $\mathrm{g\,C\,m^{-2}\,d^{-1}}$, respectively. The uptake of CO_2 ended by late October. Respiration levelled off by mid-December. From mid-December 2009 until May 2010, TER remained low at an average rate of 0.46 $\mathrm{g\,C\,m^{-2}\,d^{-1}}$. In May 2010 and 2011, the daily GPP and TER were clearly distinguishable. During the growing season, the maximum daily values of NEE, TER and GPP were −9.4, 11.5 and −18.0 $\mathrm{g\,C\,m^{-2}\,d^{-1}}$, respectively Respiration levelled off at the end of November and TER remained low during the winter time until beginning of May in 2011. Winter time TER averaged to 0.51 $\mathrm{g\,C\,m^{-2}\,d^{-1}}$. During the growing season in 2011, the maximum daily values of NEE, TER and GPP were similar to that in 2010. Respiration levelled off by the beginning of December, with an average value of 0.76 $\mathrm{g\,C\,m^{-2}\,d^{-1}}$ for December 2011.

3.3 Factors controlling CO_2 exchange

3.3.1 Gross photosynthesis

The strong relationships between bin-averaged GPP and PAR from May to September in 2010 and 2011 can be seen in Fig. 6a–e. The rectangular hyperbolic model provided good fits to the data (adjusted $R^2 > 0.90$, Table 1) except in May 2010 and 2011 (adjusted R^2 0.52 and 0.76, respectively) and all relationships were statistically significant ($p < 0.01$). There was no clear indication of GPP saturation even at PAR levels close to 1800 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ during June and July (Fig. 6a–e). The estimated monthly GP_{max} values are shown in Table 1. There were no differences in the GP_{max} values for May, June and July during 2010 and 2011, whereas in August and especially in September, the monthly average GP_{max} was higher in 2011 than in 2010. The seasonal variation in monthly GP_{max} values was clear (Table 1) and in May, September and August, the monthly averaged GP_{max} were low while the maximum values were observed in June and July. The range of the monthly α values (quantum yield) varied from −0.04 to −0.06 in 2010 and from −0.05 to −0.07 in 2011. Further analysis under conditions with PAR level greater than 1000 $\mu mol\, m^{-2}\, s^{-1}$ revealed that effect of other climatic variables such as air temperature, VPD and soil moisture on GPP was masked by the dominant role of PAR.

We studied the relationships between weekly averaged GPP, GA and LAI. GPP increased with an increasing GA implying a positive linear relationship between these variables, the adjusted R^2 value of the regression was 0.28 in 2010 ($p = 0.011$) and 0.45 in 2011 ($p < 0.01$). Relationship between GPP and LAI was not evident in 2010; however, they were better correlated in 2011 with an adjusted R^2 value of 0.42 ($p < 0.01$).

3.3.2 Ecosystem respiration

There was a clear relationship between bin-averaged night-time TER and soil temperature from May to September in 2010 and 2011 (Fig. 7a). The exponential regression model provided good fits to the data (adjusted R^2 0.71 and 0.69 for 2010 and 2011, respectively) and the relationships were statistically significant ($p < 0.01$). The Q_{10} values were similar between the two years (2.17 and 2.35). The R_{10} values were 1.75 and 1.66 $\mu mol\, m^{-2}\, s^{-1}$ in 2010 and 2011, respectively. Additionally, TER increased with the increasing GA in 2010 (Fig. 7b), however, the linear correlation was not statistically significant (adjusted $R^2 = 0.16$, $p = 0.053$). TER and GA were better correlated in 2011 (adjusted $R^2 = 0.51$, $p < 0.01$). There was a strong positive linear relationship between TER and GPP ($p < 0.01$) in both years (Fig. 7c). GPP explained 82 and 75 % of the variation in the TER in 2010 and 2011, respectively.

3.4 Annual balance

The estimated annual balances of TER, GPP and NEE are given in Table 2. The site acted as a CO_2 sink during the studied years and the annual NEE was −56.7, −262 and $-256\,g\,C\,m^{-2}$ in 2009 (23 July–31 December), 2010 and 2011, respectively. The pattern in NEE accumulation is show in Fig. 8. During the three week time period from late July to mid-August 2009, the site acted as a source of atmospheric CO_2. After the transition from a source to a sink in mid-August 2009, the site sequestered atmosphere CO_2 for about 60 days leading to a negative cumulative NEE of $-160\,g\,C\,m^{-2}$. During the winter dormancy period (from late October 2009 to May 2010) the site lost $183\,g\,C\,m^{-2}$ and the cumulative NEE was $23\,g\,C\,m^{-2}$. After this, the site was an annual CO_2 sink, since the summer time uptake was higher than the winter time CO_2 loss. In 2010, CO_2 uptake period lasted approximately 120 days (May to mid-September) and in mid-September the cumulative NEE was $-403\,g\,C\,m^{-2}$. During the second winter dormancy, from Mid-September 2010 to mid-May 2011, the site lost approximately $168\,g\,C\,m^{-2}$. In 2011, the CO_2 uptake period lasted about 135 days (from mid-May to early October) with a cumulative NEE of $-679\,g\,C\,m^{-2}$ by the end of this season. By the end of 2011, the cumulative NEE was $-575\,g\,C\,m^{-2}$. This final cumulative value of CO_2-C represents the amount of carbon the site accumulated from the start of the measurements in July 2009 until the end of 2011.

4 Discussion

The use of renewable energy sources such as perennial bioenergy crops has been suggested as one of the options for mitigating CO_2 emissions. Cultivation of RCG, a perennial bioenergy crop, has been shown to be a promising after-use option on a cutaway peatland (a drained organic soil) in Finland (Shurpali et al., 2009). In the present study we explore further if the benefits of RCG cultivation were limited to the organic soils only. For the purpose, we measured CO_2 exchange during three years from the start of the crop rotation cycle on a mineral soil from the same variety of RCG crop as was used on a drained organic soil, in eastern Finland. Generating such knowledge from different soil types is useful in developing scientifically based bioenergy policies.

The studied RCG site on mineral soil was an annual sink for atmospheric CO_2 with an average NEE of $-260\,\mathrm{g\,C\,m^{-2}}$ for 2010 and 2011 (Table 2). This net uptake rate of CO_2 is higher than what has been reported previously for RCG cultivation. Annual NEE ranging from -8.7 to $-210\,\mathrm{g\,C\,m^{-2}}$ has been reported for a cut-away peatland with RCG cultivation in Finland (Shurpali et al., 2009) and $+69\,\mathrm{g\,C\,m^{-2}}$ for an organic agricultural site in Denmark (Kandel et al., 2013). Measurements of CO_2 exchange have been carried out also on other bioenergy crops such as switchgrass (*Panicum virgatum* L.), miscanthus (*Miscanthus giganteus*), hybrid poplar (*Populus deltoides* × *Populus petrowskyana*) and willow (*Salix* spp) (Grelle et al., 2007; Skinner and Adler, 2010; Zeri et al., 2011; Jassal et al., 2013). Compared to these studies, the annual NEE of the present study is in the middle range. Annual NEE of switchgrass cultivation ranged from -150 to $-470\,\mathrm{g\,C\,m^{-2}}$ and for miscanthus cultivation in US, it was $-420\,\mathrm{g\,C\,m^{-2}}$ (Skinner and Adler, 2010; Zeri et al., 2011). Annual NEE of young hybrid poplar stand in Canada was $+37\,\mathrm{g\,C\,m^{-2}}$ (Jassal et al., 2013). Willow stands have been studied in Sweden with an annual NEE value of $-510\,\mathrm{g\,C\,m^{-2}}$ (Grelle et al., 2007). Forests are an important source of bioenergy in the boreal region and long-term CO_2 exchange studies have been carried out on Scots pine stands on mineral soils. Annual NEE of an approximately 40 year old stand in southern Finland was $-210\,\mathrm{g\,C\,m^{-2}}$ during the six year period (2002–2007, Kolari et al., 2009). Average NEE of a 50 year old stand measured during a 10 year period (1999–2008) in eastern Finland was estimated to be $-190\,\mathrm{g\,C\,m^{-2}}$ (Ge et al., 2011). So, RCG has a higher capacity for carbon uptake than Scots pine on mineral soils under boreal environmental conditions.

The mineral soil site in the present study had stronger capacity to withdraw atmospheric CO_2 than the same variety of RCG crop cultivated on a drained organic soil in Finland (Shurpali et al., 2009). In the following, we will compare the differences between the mineral soil site in the present study and the published results of a drained organic soil site (a reference site, Shurpali et al., 2008; Hyvönen et al., 2009; Shurpali et al., 2009, 2010, 2013; Gong et al., 2013). In brief, this reference site was originally an ombrotrophic pine bog (Biasi et al., 2008). It was drained for peat mining in 1976 and the cultivation of RCG started in 2001. Flux studies on RCG were carried out from 2004–2007.

The main differences between the two sites lie in the soil type, nutrient status and water retention characteristics of the soil. Mineral soil site studied here is an agricultural field with soil texture ranging from clay loam to loam. Also the soil was rich with nutrients indicated by the low C : N ratio. While the mineral soil site investigated here had a C : N ratio of 14.9, the reference site had a C : N ratio of 40.3 (Shurpali et al., 2008). The differences in the nutrient status of the soil types is further borne out by the fact that the mineral soil had a seasonal N_2O emission from this RCG cultivation system of the order of 2.4 $\mathrm{kg\,ha^{-1}}$ (Rannik et al., 2015), while the reference site had negligible emissions (Hyvönen et al., 2009). Higher N_2O emissions implying that the enhanced rates of soil N transformations in the mineral soil, support active soil C cycling and associated high release of soil nutrients for the plant roots to exploit so that a vigorous plant growth can be sustained. Additionally, the soil moisture conditions during the study period at the mineral site under investigation were conducive for prolific rates of below-ground and above-ground RCG biomass growth. Based on the results presented here, it seems that the soil water movement at the mineral site was coupled with the energy load on the surface. The daily variations in soil profile moisture content (Fig. 1c) reveal that soil moisture at 30 cm depth also varies in phase with the surface soil moisture content at this site hinting at a coupled soil hydrological system. The soil water and heat exchange monitored in this study is thus influenced by the surface energy exchange. This is contrary to what has been reported for the reference site. The organic soil moisture content at 30 cm depth was found to be rather constant and saturated throughout the growing seasons (Shurpali et al., 2009), while only the near surface soil layers exhibited variations in soil moisture content as affected by the radiation load on the soil surface and seasonal precipitation events. These observations hint at a decoupled hydrological system in the reference site (Gong et al., 2013). This is further supported by the shallow rooting pattern reported in Shurpali et al. (2009) where 95 % of the RCG roots were concentrated in the first 15 cm of the drained organic soil profile. Owing to a coupled soil hydrology, the rooting depth of RCG plants in the mineral soil, however, appears to be not constrained by hydrological limitations as opposed to the restrictions laid on the RCG root development in a cutover peatland.

Typical rotation cycle of the RCG cropping system grown for bioenergy in eastern Finland varies from 10–15 years. The RCG stand at the mineral site studied here was young, 0–3 year old stand. At the reference site the RCG stand was a matured, 4–7 year old stand. Compared to the published yield from RCG on the reference site, the crop yield from the study site was approximately 3.5 times higher (Shurpali et al., 2009). This difference in the above-ground biomass was visible also in the seasonal LAI with higher maximum values measured at the mineral soil site (5.4) than at the reference site (3.5, Shurpali et al., 2013). However, the timing of the peak LAI (Fig. 2) was similar between the sites. Despite the young age of the crop on the mineral soil, RCG has a capacity to produce more biomass than the same variety of the older RCG crop on the reference site. The average spring harvested RCG yield reported here, 6500 kg DW ha^{-1}, was not the highest yield reported for mineral soil sites in Finland. The RCG yield for mineral soils in Finland has ranged from 6400 to 7700 kg DW ha^{-1} (Pahkala and Pihala, 2000). However, we expect that the above- and belowground biomass of the crop at our mineral soil site will further increase with the crop age. RCG on mineral soil site had higher water use efficiency (12 g CO_2 kg^{-1} H_2O) when compared with published WUEs for RCG reference site or for grasslands and crops (Law et al., 2002; Shurpali et al., 2013). These results indicate that the RCG crop cultivated on a mineral soil is more efficient, in sequestering atmospheric CO_2 per unit amount of H_2O lost as ET and thus more effective in utilizing the available resources.

As NEE is the balance between the two major opposing fluxes of GPP and TER, it is important to evaluate these processes separately. Average annual GPP

($-1300\,\mathrm{g\,C\,m^{-2}}$) at the mineral soil site was in the range of what has been reported earlier for RCG cultivation on the reference site ($-590\,\mathrm{g\,C\,m^{-2}}$, Shurpali et al., 2009) and in organic agricultural field Denmark ($-1800\,\mathrm{g\,C\,m^{-2}}$, Kandel et al., 2013). Annual GPP of the present study is higher than what has been published earlier for switchgrass, hybrid poplar and Scots pine forests (Kolari et al., 2009; Skinner and Adler, 2010; Ge et al., 2011; Jassal et al., 2013). Annual GPP for switchgrass cultivation was $-930\,\mathrm{g\,C\,m^{-2}}$ in USA (Skinner and Adler, 2010), $-540\,\mathrm{g\,C\,m^{-2}}$ for hybrid poplar stand in Canada (Jassal et al., 2013), $-1100\,\mathrm{g\,C\,m^{-2}}$ for Scots pine stand in southern Finland (Kolari et al., 2009) and $-830\,\mathrm{g\,C\,m^{-2}}$ for Scots pine stand in eastern Finland (Ge et al., 2011). During the summer months, GPP at our study site was limited primarily by light levels. Especially early in the summer (June–July), plants were developing rigorously. The inherent ability of the crop to sequester maximum atmospheric CO_2 in this phase was seen in the high GP_{max} values (Table 1). Higher photosynthesis activity at the present study on the mineral soil than at the reference site can be explained by the higher plant productivity. Soil moisture conditions and nutrient status of the site were optimal for an optimal crop growth. Additionally, it is vital to realise that the crop water losses from the RCG crop at this site were higher than the water input to the ecosystem through precipitation events during summer periods. The CO_2 uptake rates, however, do not seem to be affected by climatic stress as the crop had the mechanism to cope with the stress by drawing the available soil moisture through capillary forces from deeper layers of the soil. This explains why the crop was limited primarily by light levels and other environmental variables had minimal role in regulating the RCG photosynthetic rates at this site.

On an annual basis, the average TER ($+1000\,\mathrm{g\,C\,m^{-2}}$) for our study was within the range of what has been reported earlier for RCG cultivations at reference site ($+480\,\mathrm{g\,C\,m^{-2}}$, Shurpali et al., 2009), in cut-away peatland Estonia ($+600\,\mathrm{g\,C\,m^{-2}}$, Mander et al., 2012) and in organic agricultural field Denmark ($+1900\,\mathrm{g\,C\,m^{-2}}$, Kandel et al., 2013). When compared to annual TER values for switchgrass, hybrid poplar and Scots pine forest (Skinner and Adler, 2010; Jassal et al., 2013; Kolari et al., 2009), the annual

TER of the present study is higher. Average annual TER for switchgrass cultivation was $+780\,\mathrm{g\,C\,m^{-2}}$ in USA (Skinner and Adler, 2010), $+580\,\mathrm{g\,C\,m^{-2}}$ for hybrid poplar stand in Canada (Jassal et al., 2013) and $+790\,\mathrm{g\,C\,m^{-2}}$ for 40 year old Scots pine stand in southern Finland (Kolari et al., 2009). Difference in the annual respiration rates between our mineral soil site and the reference site can be explained with differences in the biomass as higher biomass increases also autotrophic and heterotrophic respiration. TER was mainly controlled by soil temperature during the summer months at this site with plant biomass, LAI and GPP also explaining a part of the variation in TER rates. The base respiration (R_{10}) rate (1.75 and 1.66 $\mathrm{\mu mol\,m^{-2}\,s^{-1}}$) and Q_{10} (2.17 and 2.35) values were estimated in this study with a nonlinear regression of observed TER on soil temperature (Fig. 6). Both R_{10} and Q_{10} in the present study are in the range of what has been reported by other authors. Earlier papers have reported R_{10} values for the reference site ranging from 0.24 to 1.39 $\mathrm{\mu mol\,m^{-2}\,s^{-1}}$ (Shurpali et al., 2009) and for grassland in Canada ranging from 0.2 to 3.6 $\mathrm{\mu mol\,m^{-2}\,s^{-1}}$ (Flanagan and Johnson, 2005). For Q_{10}, the earlier reported values range from 2.0 to 5.4 for the reference site (Shurpali et al., 2009) and from 1.2 to 2.7 grassland in Canada (Flanagan and Johnson, 2005). The R_{10} was higher and Q_{10} was lower for RCG on mineral soil, an opposite trend has been reported for the RCG reference site (Shurpali et al., 2009). Higher base respiration rate observed in this study reflects of the active cycling of soil C in this ecosystem.

In this paper we showed that the RCG was environmentally friendly from the CO_2 balance point of view when cultivated on a mineral soil. When compared to the earlier findings on the same crop on organic soil site, the capacity of the crop to withdraw atmospheric CO_2 was even stronger on mineral soil site than that on the organic soil site. For full estimation of the climatic impacts of RCG on mineral soil site, other greenhouse gas (N_2O and CH_4) emissions during the crop production phase have to be included in addition to all energy inputs and outputs associated with the crop management. Only then a complete life cycle assessment can be done needed to understand the sustainability of a bioenergy system.

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Table 1. Monthly fit results of a rectangular hyperbolic model together with average climatic conditions. The fit results between gross primary production (GPP, $\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$) binned with photosynthetically active radiation (PAR, $\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$, bins from 0 to 1800 $\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ with an interval of 10 $\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$) from mid-May to September in 2010 and 2011. A rectangular hyperbolic model of the form $\text{GPP} = (\text{GP}_{\text{max}} \times \text{PAR} \times \alpha)/(\text{GP}_{\text{max}} + \text{PAR} \times \alpha)$, where GP_{max} (± SE, $\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$) is the theoretical maximum rate of photosynthesis at infinite PAR and α (± SE) is the apparent quantum yield, i.e., the initial slope of the light response curve, was used. Adjusted R^2 of regression and number of PAR bins (n) are shown. Also monthly average (± SD) of air temperature (T, °C), volumetric water content (VWC, $\text{m}^3\,\text{m}^{-3}$) at 2.5 cm depth and vapour pressure deficit (VPD, kPa) are shown together with number of rain event days (when precipitation > 0.2 mm) in month, precipitation sum (prec., $\text{mm}\,\text{mo}^{-1}$) and monthly averaged green area (GA, $\text{m}^2\,\text{m}^{-2}$) and leaf area (LAI, $\text{m}^2\,\text{m}^{-2}$) indices.

Month	GPmax ($\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$)	α	R^2	n	T (°C)	VWC ($\text{m}^3\,\text{m}^{-3}$)	VPD (kPa)	Prec. events	sum	GA	LAI
2010											
May	−21.5 ±1.7	−0.057 ±0.009	0.52	133	14.3 ±5.3	0.26 ±0.05	0.65 ±0.6	7	23	8.7	1.8
Jun	−44.5 ±1.7	−0.047 ±0.002	0.93	158	13.0 ±4.6	0.26 ±0.05	0.54 ±0.4	9	72	19.0	4.3
Jul	−40.1 ±1.1	−0.053 ±0.002	0.95	163	21.0 ±4.7	0.14 ±0.03	0.85 ±0. 7	7	34	17.2	4.0
Aug	−25.2 ±0.7	−0.057 ±0.003	0.91	148	15.8 ±6.2	0.14 ±0.05	0.53 ±0.5	14	42	14.0	3.9
Sep	−18.1 ±2.2	−0.040 ±0.007	0.93	19	9.8 ±3.9	0.21 ±0.04	0.14 ±0.2	16	53	14.1	4.0
2011											
May	−21.2 ±1.0	−0.056 ±0.005	0.76	134	11.2 ±4.0	0.30 ±0.03	0.45 ±0.4	11	38	5.7	1.8
Jun	−45.8 ±1.4	−0.060 ±0.002	0.94	163	16.1 ±4.9	0.21 ±0.05	0.73 ±0.6	11	41	16.2	4.6
Jul	−40.4 ±1.5	−0.050 ±0.002	0.92	154	19.1 ±4.4	0.20 ±0.06	0.65 ±0.5	11	91	15.5	5.3
Aug	−29.9 ±1.0	−0.069 ±0.004	0.90	141	15.0 ±3.5	0.25 ±0.05	0.38 ±0.4	10	80	12.5	3.7
Sep	−24.2 ±0.7	−0.074 ±0.004	0.94	103	11.1 ±3.3	0.31 ±0.04	0.20 ±0.2	13	70	8.0	4.3

Table 2. The estimated annual CO_2 balances of the reed canary grass cultivation. Annual values of net ecosystem CO_2 exchange (NEE), total ecosystem respiration (TER) and gross primary production (GPP) are shown in two units: $g\,C\,m^{-2}$ and $g\,CO_2\,m^{-2}$. Negative values stand for uptake and positive for emission to the atmosphere. Note that 2009 is not a full year (23 July–31 December).

	2009	2010	2011
NEE ($g\,m^{-2}$)			
C	−56.8	−262	−256
CO_2	−208	−959	−940
TER ($g\,m^{-2}$)			
C	434	969	1043
CO_2	1592	3550	3821
GPP ($g\,m^{-2}$)			
C	−491	−1231	−1299
CO_2	−1800	−4509	−4760

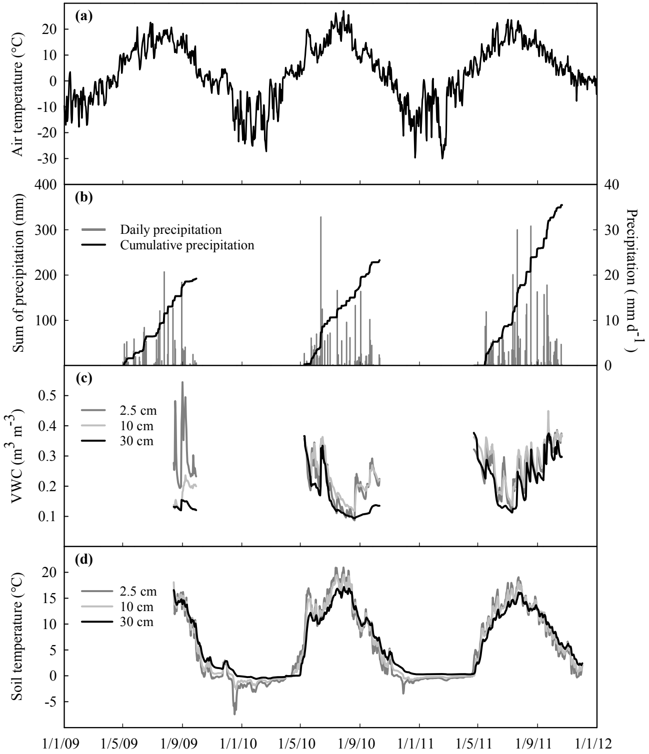

Figure 1. Climatic conditions at the study site during the measurement years. **(a)** Daily averaged air temperature (°C) during 2009–2011, **(b)** daily precipitation (mm d^{-1}, grey line) and its cumulative sum (mm, black line) during the growing seasons. **(c)** Daily averaged volumetric water content (VWC, $\text{m}^3\,\text{m}^{-3}$) at 2.5 cm (dark grey line), 10 cm (light grey line) and 30 cm (black line) during the growing seasons, from 14 August 2009 onwards. **(d)** Soil temperatures (°C) at the 2.5 cm (dark grey line), 10 cm (light grey line) and 30 cm (black line) depths as daily means from 14 August 2009 until 2 December 2011.

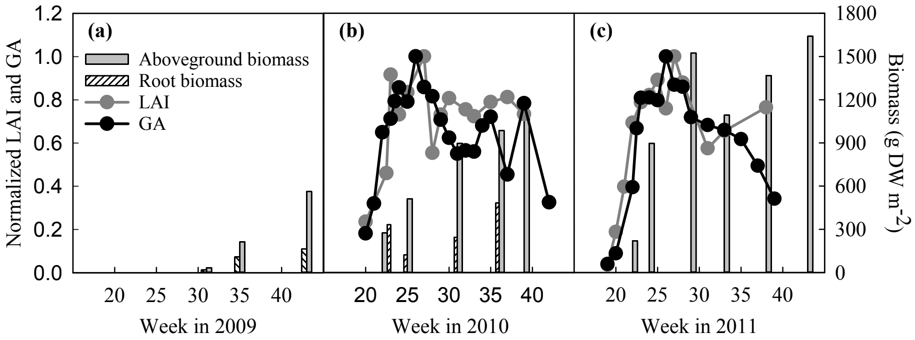

Figure 2. Vegetation parameters determined on the reed canary grass (RCG) cultivation. Approximately monthly determined above-ground (grey bars) and root biomass (hatched bars) in g dry weight (DW) m^{-2} between week 15 and 45 in **(a)** 2009, **(b)** 2010 and **(c)** 2011. Also approximately weekly determined normalized green area index (GA, black dots) and leaf area index (LAI, grey dots) for **(b)** 2010 and **(c)** 2011 is shown.

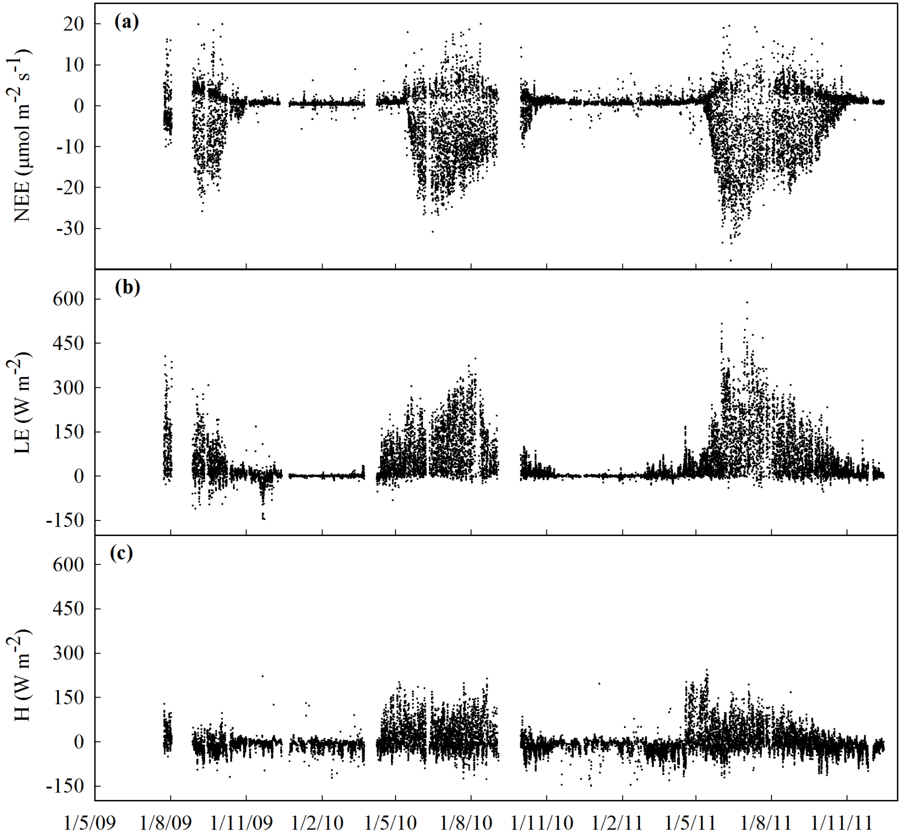

Figure 3. Measured CO_2 and energy fluxes from July 2009 to December 2011. **(a)** Net ecosystem CO_2 exchange (NEE, µmol m^{-2} s^{-1}). **(b)** Latent heat flux (LE, W m^{-2}). **(c)** Sensible heat flux (H, W m^{-2}).

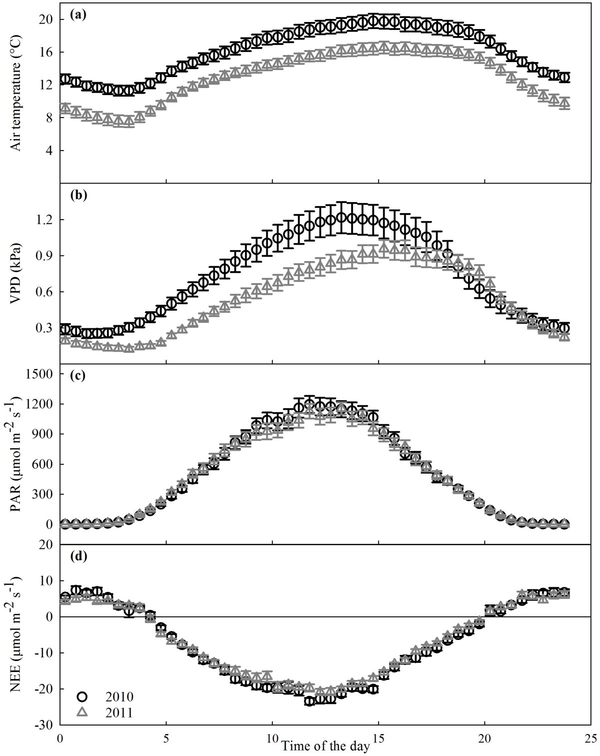

Figure 4. Mean diurnal variations in June 2010 (open grey triangles) and 2011 (open black circles). **(a)** Air temperature (°C). **(b)** Vapour pressure deficit (VPD, kPa). **(c)** Photosynthetically active radiation (PAR, µmol m^{-2} s^{-1}). **(d)** Net ecosystem CO$_2$ exchange (NEE, µmol m^{-2} s^{-1}). Data are half-hour means with standard error.

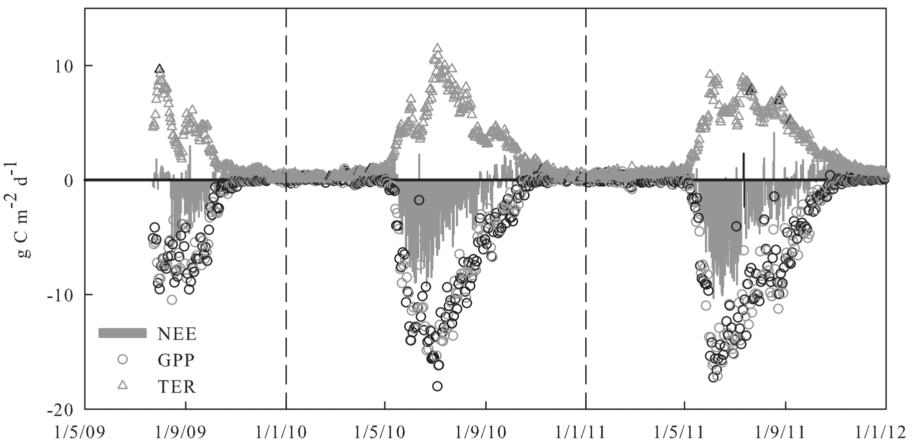

Figure 5. The components of daily CO_2 exchange over the measurement period. Daily sum of net ecosystem CO_2 exchange (NEE, grey bars), gross primary production (GPP, open black circles) and total ecosystem respiration (TER, open grey triangles) as g C m^{-2} d^{-1}. Horizontal solid black lines show the zero level and vertical dashed black lines mark beginning of the year.

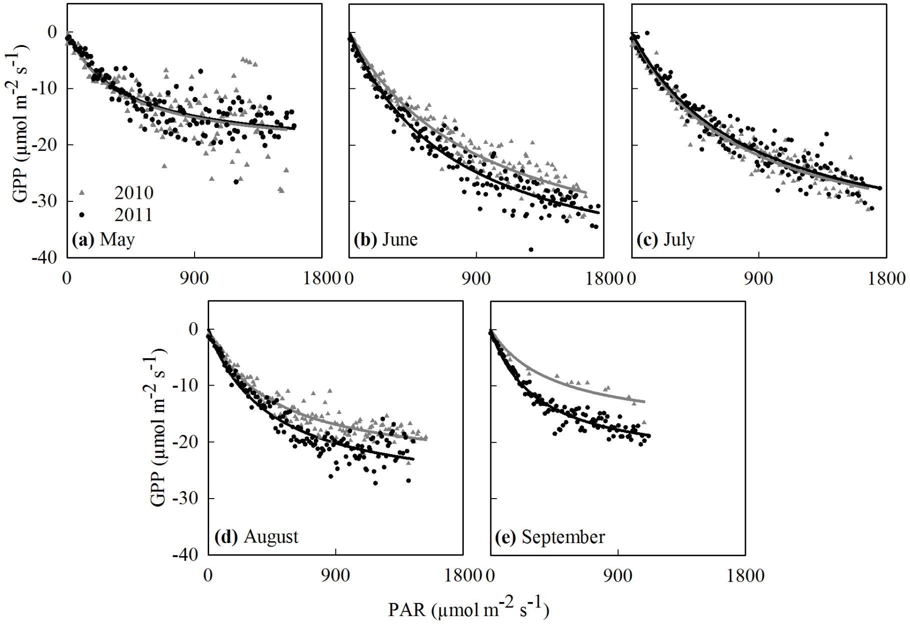

Figure 6. Relationship of gross primary production (GPP) to incident photosynthetically active radiation (PAR). Measured monthly (mid-May–September) GPP (µmol m^{-2} s^{-1}) averaged with binned (steps of 10 µmol m^{-2} s^{-1}) PAR (µmol m^{-2} s^{-1}) for 2010 (closed grey triangles) and 2011 (closed black circles). Data are fitted with nonlinear regression ($\mathrm{GPP} = (\mathrm{GP}_{\max} \times \mathrm{PAR} \times \alpha)/(\mathrm{GP}_{\max} + \mathrm{PAR} \times \alpha)$) between GPP and PAR (fit results in Table 1). Only measured data were used in the analysis.

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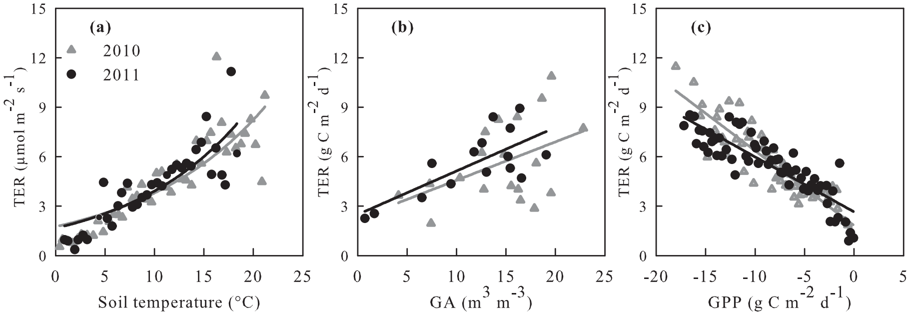

Figure 7. Relationships between total ecosystem respiration (TER) and environmental variables. **(a)** TER (μmol m^{-2} s^{-1}) and soil temperature (°C) at 2.5 cm depth (binned with steps of 0.5 °C) in May-September period fitted with an exponential nonlinear regression ($\text{TER} = R_{10} \times Q_{10}^{(T_s/T_{10})}$, where R_{10} and Q_{10} are fitted parameters). **(b)** Weekly averaged TER (g C m^{-2} d^{-1}) and green area index (GA, m^3 m^{-3}) in May–October period fitted with linear regression. **(c)** Daily values of TER (g C m^{-2} d^{-1}) and gross primary production (GPP, g C m^{-2} d^{-1}, binned with steps of 0.25 g C m^{-2} d^{-1}) in May-September period fitted with linear regression. Closed grey triangles are data for 2010 and closed black circles for 2011. Fit results are given in the text.

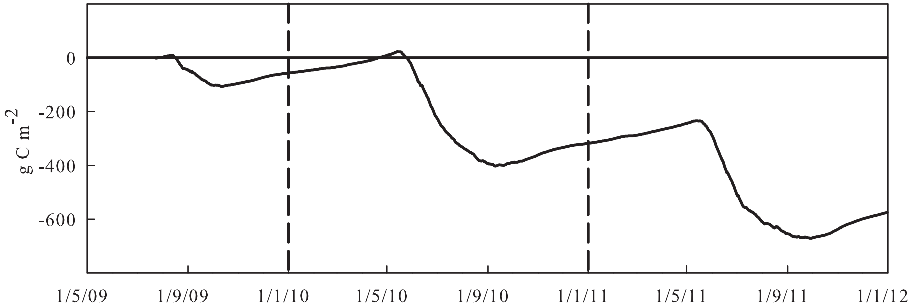

Figure 8. Cumulative NEE over the study period. Negative values indicate uptake of CO_2 and positive values emission to the atmosphere. Horizontal solid black lines show the zero level and vertical dashed black lines mark beginning of the year.