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ABSTRACT

Fluxes of methane (CH_4) and carbon dioxide (CO_2) estimated by empirical models based on small-scale chamber measurements were compared to large-scale eddy covariance (EC) measurements for CH_4 and to a combination of EC measurements and EC-based models for CO_2. The experimental area was a flat peat meadow in the Netherlands with heterogeneous source strengths for both greenhouse gases. Two scenarios were used to assess the importance of stratifying the landscape into landscape elements before up-scaling the fluxes measured by chambers to landscape scale: one took the main landscape elements into account (field, ditch edge ditch), the other took only the field into account. Non-linear regression models were used to up-scale the chamber measurements to field emission estimates. EC CO_2 respiration consisted of measured night time EC fluxes and modeled day time fluxes using the Arrhenius model. EC CH_4 flux estimate was based on daily averages and the remaining data gaps were filled by linear interpolation. The EC and chamber-based estimates agreed well when the three landscape elements were taken into account with 16.5% and 13.0% difference for CO_2 respiration and CH_4, respectively. However, both methods differed 31.0% and 55.1% for CO_2 respiration and CH_4 when only field emissions were taken into account when up-scaling chamber measurements to landscape scale. This emphasizes the importance of stratifying the landscape into landscape elements. The conclusion is that small-scale chamber measurements can be used to estimate fluxes of CO_2 and CH_4 at landscape scale if fluxes are scaled by different landscape elements.

1. Introduction

Net emission of greenhouse gases in an ecosystem is a result of uptake and emission and will change depending on variables such as temperature, moisture conditions, soil physics, topography, management practices and vegetation cover (e.g. Riutta et al., 2007). The greenhouse gases carbon dioxide (CO_2) and methane (CH_4) have a significant impact on the greenhouse gas balance and account for over 60% and 20% of global warming, respectively (IPCC, 2007a). Variables that define greenhouse gas production and consumption in ecosystems vary spatially and temporally. In order to determine the origin of fluxes, to properly extrapolate fluxes to the ecosystem scale and to ascertain possible management interventions in heterogeneous landscapes, it is necessary to combine small-scale gas measurement techniques and large-scale measurement techniques. Comparison of the different scale techniques can also give independent information about the reliability of the methods. Three widely used and totally independent methods for determining fluxes at different spatial scales are chamber-based methods, micrometeorological towers (e.g. eddy covariance systems), and calculations based on equations for diffusion at the soil/air and water/air interfaces (Denmead, 2008).

In this study, the first two methods are compared for CO_2 respiration and CH_4 emissions in a peat meadow and estimates of cumulative emissions are given over one year and three months, respectively. With the chamber-based method, the emissions are up-scaled to field scale using a temperature regression model which takes into account the heterogeneity of the ecosystem. Three regression models are determined for the three main landscape elements (field, ditch edges and ditches) based on chamber flux measurements. The up-scaled chamber fluxes are compared to EC CO_2 respiration and CH_4 fluxes which were measured at the same site. CO_2 respiration fluxes are based on measured night time fluxes and modeled day time fluxes using the Arrhenius model. EC CH_4 fluxes are based on daily averages and the remaining data gaps are filled by linear interpolation.

Chamber-based methods are often used to determine source and sink distributions in non-uniform landscapes and are used to quantify small-scale spatial differences in CO_2 and CH_4 fluxes (e.g.

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Christensen et al., 1995; Hutchinson and Livingston, 2002; Kutzbach et al., 2004; Hendriks et al., 2007; Schrier-Uijl et al., 2009). Because of the large increase in gas concentration in the headspace, chamber-based methods are highly sensitive (Denmead, 2008). However, this methodology is often criticised because of uncertainties due to pressure artefacts, temperature effects (e.g. Hutchinson and Livingston, 2002; Rochette and Eriksen-Hamel, 2008), discontinuity of measurements and lack of spatial integration (Flechard et al., 2007a). Although in recent set-ups most of the direct chamber effects have been eliminated, the problem of neglecting the influence of wind remains (Denmead, 2008). In this study closed static chambers were used, in which the air is circulated between the headspace of a dark chamber and a gas analyzer. Measures were taken to minimize pressure artefacts, cross-interference and mixing artefacts.

Eddy covariance (EC) techniques have been used for continuous quantification of landscape-scale temporal variability of CO_2 and CH_4 (e.g. Baldocchi et al., 2001; Aubinet et al., 2000; Veenendaal et al., 2007; Hendriks et al., 2007; Kroon et al., 2007). This technique has been used to measure CO_2 fluxes, and many studies have been published in which CO_2 EC fluxes are discussed; however, only a few instruments are available for EC measurements of CH_4 and until recently only a few studies have tested the appropriateness of EC measurements of CH_4 (e.g. Kroon et al., 2007, 2009a; Hendriks et al., 2008). The EC method is based on sensing turbulent wind fields, temperature, and gas concentrations at high frequency at a certain measurement point (e.g. Baldocchi, 2003). The advantage of this method is that it does not disturb the soil/air environment, and integrates over larger areas and has continuous time coverage. EC fluxes represent the integrated net fluxes from the landscape upwind from the measurement point. The extent of the upwind area from which the flux originates, the footprint area, depends on atmospheric stability and surface roughness (e.g. Grelle and Lindroth, 1996; Kormann and Meixner, 2001; Neftel et al., 2007). However, EC measurements are based on assumptions, such as horizontal homogeneity, flat terrain and negligible mean vertical wind velocities over the averaging period. Furthermore, they are beset by uncertainties, among others due to one-point sampling and the lack of low and high frequency responses (e.g. Moore, 1986; Aubinet et al., 2000; Kroon et al., 2009a, b).

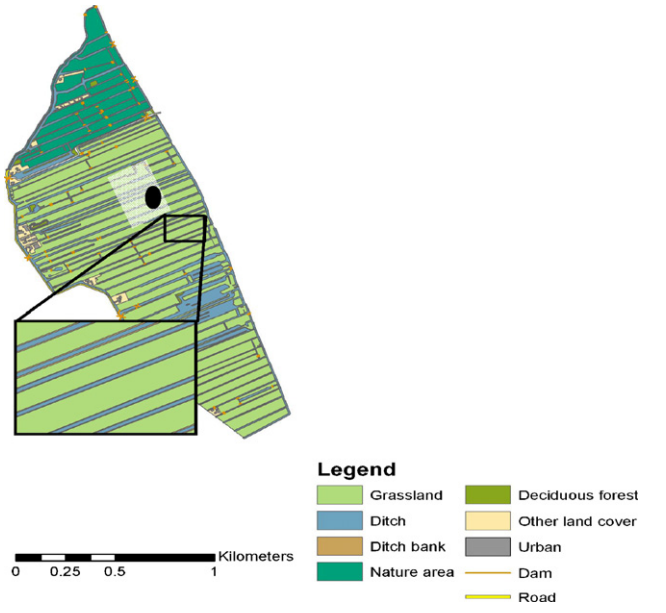

Fig. 1. The Oukoop experimental site. The inset is a close-up of the managed peat area around the measurement set-ups, showing the characteristic field pattern of the polder landscape (Nol et al., 2008). The black dot is the location of the EC systems and the white area around the EC systems is the area where chamber measurements were performed.

In this study, the cumulative CO_2 respiration and CH_4 emissions are estimated over one year (2006) and three months (August–November 2006), respectively. The experimental area is a flat peat meadow in the Netherlands with heterogeneous CO_2 and CH_4 source strengths. The objective is to compare the cumulative field emissions derived based on chamber measurements with the cumulative emissions based on EC flux measurements. Two emission scenarios are compared: the first scenario took only fields into account, the second scenario took the three main landscape elements (fields, ditches, ditch edges) into account when up-scaling the chamber measurements to landscape scale.

2. Experimental site and climatic conditions

The experimental site Oukoop, is an intensively managed dairy farm area in a polder in the west of the Netherlands (52°02′11.22″N/04°46′49.53″E/). The site is divided into three landscape elements according to micro topography and soil moisture condition: permanently water-filled ditches, almost saturated ditch edges and the relatively dry field area with fluctuating water table (Fig. 1). Ditches, ditch edges and fields account for 16%, 5% and 79% of the average footprint area of the EC system, as estimated from areal photographs.

The soil consists of a clayey peat layer of 0.5 m overlying 12 m eutrophic peat deposits. Table 1 gives more details on the site properties.

The climate is temperate and humid, with an annual mean precipitation of 807 mm and an annual mean temperature of 11.2 °C in 2006. The elevation of the polder is between 1.6 and 1.8 m below sea level. The depth of the groundwater varies from 0.70 to 0.15 m below field level and perched water tables occur after heavy rain, when the soil impedes water infiltration. Manure and artificial fertiliser are applied about five times a year from February to September. The application rates in 2006 were 55 m^3 ha^{-1} (253 kg N ha^{-1} $year^{-1}$) for cow manure and 320 kg ha^{-1} (84 kg N ha^{-1} $year^{-1}$) for artificial fertiliser. The ecosystem is eutrophic and in terms of vegetation the area is very homogeneous, with Rye grass (*Lolium perenne*) the dominant grass species, and Blue grass (*Poa trivialis*) the co-dominant species (Veenendaal et al., 2007). The grass height ranged from 0.05 to 0.35 m and is harvested about four times a year. Based on farmers' data and field measurements, the yield is estimated at 6.5×10^3 kg dry matter ha^{-1} $year^{-1}$. Grazing removed an additional $2–3 \times 10^3$ kg dry matter ha^{-1} $year^{-1}$ giving a total dry matter offtake in the order of 9×10^3 kg dry matter ha^{-1} $year^{-1}$ (Veenendaal et al., 2007). The area is a source of CO_2 and CH_4 (Veenendaal et al., 2007; Kroon et al., 2007; Schrier-Uijl et al., 2009). Spatial variability of CO_2 and CH_4 is known to be high (Schrier-Uijl et al., 2009).

3. Instrumentation and methodology

3.1. Chamber-based emission estimates methodology

3.1.1. Chamber measurements

CO_2 and CH_4 fluxes from the field, ditches and ditch edges were measured using a static chamber method. A Photo Acoustic Field Gas Monitor (INNOVA 1412 sn, LumaSenseTM Technologies, Ballerup, Denmark) was connected by Teflon tubes to a dark PVC chamber with a surface area of 0.072 m^2 and a height of 0.20 m. This methodology is often criticised because of uncertainties due to pressure and temperature effects (e.g. Hutchinson and Livingston, 2002; Rochette and Eriksen-Hamel, 2008), discontinuity of measurements and lack of spatial integration (Flechard

Table 1
Main characteristics of the Oukoop site in the Netherlands.

Soil class, topography and landscape element	Human influence	Parent material	Drainage
Fibric rheic eutric Histosol	0–23 cm anthropogenic topsoil Peat from ditches on edges	0–23 cm: anthropogenic 23–50 cm: clayey peat	Poorly drained Saturated for long periods during winter as a result of compaction
Flat (alluvial) plain	Application of fertiliser Application of cow manure	>50 cm: peat, 70% discernible remnants of wood and reed	Mean highest WT: ca. 35 cm Mean lowest WT: ca. 50 cm

et al., 2007a) and therefore measures are taken to avoid these artefacts. A small fan was installed in the chamber to homogenize the inside air; a small water lock on top of the chamber adapted inside pressure to air pressure. In the field and at the ditch edges the chamber was put into a water-filled groove on a 0.15 m high collar inserted into the soil to prevent leakage. At the ditches, floaters and a lever system were used to lower the chamber onto the water surface gently, to avoid the effect of pressure differences. Since the gas monitor software does not compensate fully for cross-interference of CO_2 and water vapour at high concentrations, air was lead through silica gel and soda lime filled glass tubes before it entered the gas analyzer. The soda lime filter was not applied in months with low CO_2 concentrations (fluxes ranging from 0 to 600 mg m^2 h^{-1}). The gas analyzer was annually calibrated and tested for drift at the NMI (Nederlands Meet Instituut: Delft, The Institution of Standards, the Netherlands). Detection limits of the gas analyzer were 1.5 ppm for CO_2 and 0.1 ppm for CH_4.

To estimate the quality of the measurement set-up we used the Rochette and Eriksen-Hamel (2008) method, which defines the quality of different chamber systems on a scale of 1 (very poor) to 4 (high), basing the overall confidence in the flux measurement on the weakest factors in each study. The quality of the measurement set-up used in this study was estimated to be 4.

To study the spatial variability of CO_2 and CH_4 emissions we measured the fluxes at 21 locations: 4 on the ditches, 4 on the ditch edges and 13 on the field. The measurements were performed between 9 am and 3 pm at bi-weekly intervals in spring and summer and four-weekly intervals in autumn and winter. For the regression analyses we used 300 measurements of CO_2 obtained in 2006 and 600 measurements of CH_4 obtained over the period 2005–2008.

Each flux measurement consisted of five points taken at one-minute intervals to estimate the slope dC/dt at time $t = 0$. Concentration profiles were visually analyzed on linearity; the first or last measurement point was rejected if pressure artefacts were visible after the chamber had been positioned or when leveling occurred due to leakage. This left 85% of the CO_2 data and 65% of CH_4 data for analysis. The slope dC/dt of the gas concentration curve at time $t = 0$ s was estimated using linear regression and the slope intercept method (Kroon et al., 2008). The average flux values for CO_2 and CH_4 estimated by the slope intercept method were about 3.5% and 4.0% higher than those estimated by the linear method. This small difference between the two methods is a result of the short measurement period of 240 s, the rejection of the last point in the case of leveling, and by additional measures taken to prevent leakage, mixing and temperature artefacts (e.g. water seal around the chambers, small fan and water lock). Because the difference was not significant, the linear method was used to calculate the flux

$$F_{ch} = \frac{V}{A}\left[\frac{dC}{dt}\right]_{t=0} \quad (1)$$

where F_{ch} is the flux measured by the chamber, V is the volume of the chamber (m^3), A is the surface of the chamber (m^2), C is the gas concentration in the chamber at ambient temperature and pressure (mg m^{-3}) and t is the length of the measurement period (s). Since the output of the gas analyzer is in ppm, dC/dt is calculated by

$$\frac{dC}{dt} = 0.036\frac{PM}{RT}\frac{d\hat{C}}{dt} \quad (2)$$

where P is the air pressure (Pa), $\hat{C}$ is the gas concentration (ppm), R the universal gas constant (8.314 J mol^{-1} K^{-1}), T the absolute temperature during the measurement (K), M the molecule weight and 0.036 is a conversion factor for time.

3.1.2. Empirical models based on chamber data

The empirical model for CO_2 respiration was based on a modified Arrhenius equation which is given by (Lloyd and Taylor, 1994)

$$R_{Res} = R_{10}e^{E_0}\left(\frac{1}{283.15 - T_0} - \frac{1}{T - T_0}\right) \quad (3)$$

in which R_{Res} is the respiration measured by the chambers (μmol m^{-2} s^{-1}), E_0 is the activation energy (K), $T_0 = 227.13$ K, T is the soil or water temperature and R_{10} is the ecosystem respiration at 10 °C. The R_{10} and E_0 were determined for each landscape element using the measured CO_2 respiration and the measured soil and water temperatures during the respiration measurement (e.g. Reichstein et al., 2005).

Methane emission was found to be correlated with several parameters, with temperature being the most important driver (Schrier-Uijl et al., 2009). The dependence on temperature followed an exponential function which differed per landscape element; this finding was in line with earlier studies (e.g. Hargreaves et al., 2001; Hendriks et al., 2007). The effect of soil moisture or water table did not enhance the predictive power of the regression, probably because the water levels in the field (a polder) are controlled by the water board. We used an empirical model for CH_4, which was based on a non-linear regression with temperature as only explanatory variable

$$F_{CH_4} = e^{a+bT} \quad (4)$$

where F_{CH_4} is the CH_4 flux measured by the chamber, T is the temperature of soil or water and a and b are the coefficients which were derived for each landscape element using the measured temperatures and CH_4 fluxes. This resulted in three landform-dependent empirical relationships.

Half-hourly soil and water temperatures were used to calculate half-hourly emissions for CO_2 and CH_4 for each landscape element using Eqs. (3) and (4), respectively. Because soil and water temperatures were measured by different instruments, the temperatures were corrected for the offset between the average temperature derived from the manual sensor used at each chamber measurement and the sensors installed in the soil at 4 cm depth

and in the water. The final emission was calculated by the weight-factors for each landscape element within the average footprint of the EC systems. The uncertainties around the CO_2 and CH_4 lines were based on temperature-dependent uncertainties of the parameters in the regression analyses and were calculated for each day.

3.2. Eddy covariance emission estimates methodology

3.2.1. Eddy covariance measurements

EC fluxes of CO_2 and CH_4 were both measured at a height of 3.05 m in the middle of the field, 5 m apart from each other. The footprint is estimated each half hour by the model of Kormann and Meixner (2001) (Neftel et al., 2007). Monthly average length of the 1%-ellips varied between 300 and 500 m and monthly average half width of the 1%-ellips varied from 20 to 90 m in the period August–December 2006. The 1%-ellips is the area where the footprint function reaches 1% of its maximum value. Under the predominant wind direction (W/SW) the proportions of field, ditch and ditch edge within the footprint remained approximately 79%, 16% and 5%, respectively. When the wind shifted to N/NW, which occurred in 8.5% of the measurement moments in 2006, then the proportion of ditch in the footprint was 16–19%.

The terrain around both towers was flat and free of obstruction for at least 600 m in all directions, except for the container in which instruments were placed. The CO_2 mast consisted of a Campbell Csat C3 Sonic anemometer (Campbell Scientific, Logan, UT, USA) oriented towards the predominant wind direction and a Licor 7500 open path Infrared gas analyzer (LI-COR Lincoln, NE, USA). The CO_2 gas analyzer was calibrated annually using CO_2 concentrations of 370 and 400 ppm. Data were logged with a data logger (CR5000, Campbell Scientific, USA).

Night time EC fluxes of CO_2 were integrated as half-hourly means with the EDDYFLUX software (O. Kolle MPI-BGC Jena following Carbo-Europe protocols: Aubinet et al., 2000). Data were filtered for spikes and linear detrending was used. A Webb correction for density fluctuations was applied (Webb et al., 1980). Quality control criteria according to Foken and Wichura (1996) were used to reject bad data. In addition, we also removed bad quality data due to temporary frost and dew, or moisture formation on the open path gas analyzer sensor head and we removed the data for which respiration values were reduced below a certain friction velocity (u^*). From the remaining data set, which varied from 42% data coverage in July to 55% data coverage in December, storage fluxes were calculated from the CO_2 measurements and added to the EC flux for each 30 min period according to Hollinger et al. (1994). For a detailed description of the CO_2 meteorological system, see Veenendaal et al. (2007).

Up to recently, it was not possible to obtain EC flux measurements of CH_4. However, instrumentation that meets the requirements for continuous measurements of CH_4 is now becoming available (e.g. Laurila et al., 2005; Rinne et al., 2007). One of these systems is that of Kroon et al. (2007) which measured EC fluxes of CH_4 in the same field where chamber measurements of CH_4 were performed from August–September 2006. The system consisted of a three-dimensional sonic anemometer (model R3, Gill Instruments, Lymington, UK) and a quantum cascade laser (QCL) spectrometer (model QCL-TILDAS-76, Aerodyne Research Inc., Billerica MA, USA). The QCL spectrometer was calibrated at least once a week using mixtures in N_2/O_2 of CH_4 concentrations of 1700 and 5100 ppb (Scott Specialist Gases, the Netherlands). The sonic anemometer data and the QCL spectrometer output were logged and processed using a data acquisition program developed at ECN, following the procedures of McMillen (1988).

The CH_4 fluxes were measured according to Kroon et al. (2007) and were calculated according to Kroon et al. (2009a,b). The EC fluxes were corrected for changing calibration, frequency response losses and density fluctuations. The net CH_4 exchange was calculated by adding the storage change term to the EC flux term. The data was flagged using the instationarity tests of Foken and Wichura (1996) and was rejected when the flag was larger than 2. In addition, the fetch was checked by Kormann and Meixner footprint model (Kormann and Meixner, 2001) and the flux value was removed when less than 70% of the flux came from the dairy farm site. No u^*-filtering was applied on this data set since the CH_4 was probably partly stored in the soil during periods of low u^* and escaped to the atmosphere during periods of high u^*-values (i.e. pumping effects) (e.g. Flechard et al., 2007b; Kroon et al., accepted for publication). We used daily CH_4 fluxes to minimize the uncertainty in the used estimates. Daily values were derived when 12 min or more 30 min fluxes were available during a day (Kroon et al., accepted for publication) which occurred in 84% of the days and the remaining gaps were filled by an linear interpolation procedure.

The uncertainty in a single 30 min EC flux measurement consists of several uncertainties either linked to the correction algorithm of the systematic errors or linked to processes for which no corrections could be made. All uncertainties are random and decrease with increasing independent realizations (Kroon et al., 2009a). The uncertainty in a 30 min EC flux can be even larger than 100% and is mainly caused by the one-point uncertainty (e.g. Businger, 1986; Kroon et al., 2009a). However, the uncertainty in emission estimates over longer time spans, like a day, month or year, will be much smaller. Annual uncertainty in the CO_2 and CH_4 measurements are in the order of 15% for both instrumental set-ups (Veenendaal et al., 2007; Hendriks et al., 2007; Baldocchi et al., 2001).

3.2.2. Model based on eddy covariance data

Net ecosystem exchange of CO_2 (NEE) was determined directly from the eddy covariance flux measurements and is considered to be the sum of the gross ecosystem production (GEP) and ecosystem respiration (R_{eco}). The respiration was determined using nightly NEE values, when photosynthetic active radiation (PAR) = 0, assuming that photosynthesis is absent and the NEE consists only of R_{eco}. Next, the soil respiration is described as a function of the half-hourly soil temperatures ($N = 2710$) by using the Arrhenius relation (Eq. (3)) (e.g. Béziat et al., 2009) and parameters were estimated from the one-year dataset (2006). In some months there was insufficient data available for calculating monthly R_{10} and E_0 values and therefore yearly parameters were estimated. The missing night- and day time CO_2 respiration data (PAR > 0) were estimated with this model (e.g. Béziat et al., 2009; Veenendaal et al., 2007; Hendriks et al., 2007; Reichstein et al., 2005). The data gaps in CH_4 flux measurements were filled using a linear interpolation.

3.3. Additional measurements

Soil temperature, water temperature, air temperature and soil moisture content were recorded during each chamber measurement and grass height was determined every month. The mast was equipped with micrometeorological sensors to measure short and long wave radiation (CRN1 Kipp & zonen, Delft, the Netherlands), photosynthetic photon flux density (Parlite, Kipp & zonen, the Netherlands), air temperature and humidity (HMP 45a, Vaisala, Finland) and air pressure (Druck CS115, Campbell Scientific, USA). Soil heat flux plates (HPF01, Campbell Scientific, USA) were installed in the field to estimate the soil heat flux at depths of 0.02, 0.04, 0.08, 0.16, and 0.32 m. Soil temperature sensors were installed at depths of 0.02, 0.04, 0.08, 0.16, and 0.32 m (Campbell Scientific, USA). Precipitation rates were measured with a tipping

Table 2
The three landscape elements with their proportional coverage within the footprint, average R_{10}, a and b values and uncertainties (u) or 95% confidence intervals.

	Coverage	CO_2 respiration				CH_4 emission			
		R_{10}	95% CI (R_{10})	E_0	95% CI (E_0)	a	u (a)	b	u (b)
Ditch	0.16	0.56	0.4–0.7	269	142–356	−0.75	0.48	0.19	0.03
Edge	0.05	4.66	3.9–6.1	306	208–421	0.37	0.38	0.12	0.03
Field	0.79	6.26	6.0–7.1	335	300–375	−1.03	0.19	0.07	0.02

bucket rain gauge (Young, Traverse City, MI, USA). Water level was measured with pressure transducers (Eijkelkamp, Giesbeek, the Netherlands).

4. Results and discussion

4.1. Parameter estimation

Night time CO_2 respiration measurements by EC were performed over 2006. Fluxes were found to be reduced below u^* of 0.16 m s^{-1} and therefore those fluxes were eliminated from the dataset. To accurately calculate ecosystem respiration at 10 °C and the activation energy in Eq. (3) (R_{10} and E_0), night time fluxes over 2006 were analyzed and non-linear regression was applied. Yearly parameters were used, which were estimated at 4.1 μmol CO_2 m^{-2} s^{-1} (95% confidence interval 3.9–4.3 (mol CO_2 m^{-2} s^{-1}) and 306 K (95% confidence interval 277–335 K), respectively. Monthly estimated parameters would improve the temporal variation component of the models, but there was insufficient data available for some months.

Empirical models derived from the chamber data were based on measured respiration and the corresponding soil temperature and water temperature. They were different for the three landscape elements within the average footprint area of the masts: CO_2 respiration rates were highest in the field and lowest in the ditches.

The parameters R_{10} and E_0 for each landscape element and their uncertainties were determined by non-linear regression using Eq. (3), see Table 2.

Large-scale CH_4 flux measurements by EC were performed over a three-month period in 2006; they are described in Kroon et al. (2007). We used this data set to compare large-scale measurements with up-scaled small-scale measurements.

At the small scale, CH_4 fluxes were based on the chamber measurements of 2005–2008. Temperature was found to be significantly related to emission of CH_4 and was used to fit an exponential function using equation 4. The parameters a and b and their uncertainties are given in Table 2. The magnitude of the fluxes depended on the landscape element: CH_4 emissions were highest from the ditches and lowest from the fields.

4.2. Comparison of EC and empirical models over larger temporal scales

The CO_2 respiration model and the CH_4 model were compared using two different scenarios. The first scenario is based on the model that considers the field only and in the second scenario fluxes are weighted with fixed coverage fractions for the three main landscape elements within the average footprint area of the masts (Table 2). The CO_2 respiration rates and estimates of CH_4 fluxes from the peat meadow obtained using the weighted non-linear models based on chamber data (second scenario) agreed well with the EC fluxes (Figs. 2 and 3, respectively) over one year and three months, respectively, while respiration rate estimates based on the model that considers the field (first scenario) did not. This emphasizes the importance of stratifying the landscape into landscape elements that contribute differently to the greenhouse gas emission.

In the first scenario the difference between cumulative values for CO_2 respiration measured by EC and chamber-based values was 31.0%, and in the second scenario the model for CO_2 respiration estimated 16.5% higher cumulative emissions compared to EC measurements: 188×10^{-3} mmol m^{-2} CO_2 versus 157×10^{-3} mmol m^{-2} CO_2, respectively (Fig. 4). In the second scenario, the largest differences occurred in August, September and October 2006: 20.8%, 24.4%, 21.9%, respectively, with lower fluxes measured by EC (Fig. 2), while the respiration rates in spring, early summer and winter months agreed well (within 10%).

In the first scenario, cumulative CH_4 fluxes over the three-month period estimated by the model were 55.1% lower compared to the EC fluxes and in the second scenario fluxes were 13.0% lower measured by EC: the estimates were 247.6 and 205.2 mg m^2 for chambers and EC, respectively (Fig. 4).

Higher emission rates for CO_2 based on chamber data compared with emissions measured by EC have been reported earlier in the literature (e.g. Norman et al., 1997; Jansen et al., 2001; Davidson et al., 2002; Reth et al., 2005). For example: Kabwe et al. (2005) found 12% higher fluxes measured by chambers in the summer. Twine et al. (2000) tested 9 EC systems for CO_2 and showed that surface fluxes measured by EC tend to be underestimated for a number of reasons, including mismatched sources of latent heat fluxes (LE) and sensible heat fluxes (H), inhomogeneous surface cover and soil characteristics, flux divergence or dispersion,

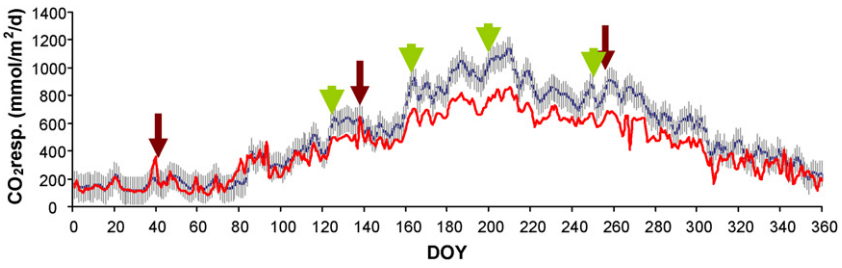

Fig. 2. Comparison of a model based on chamber measurements (blue dashed line) including the different landscape elements and respiration rates derived by EC (red, solid line) for 2006. The uncertainty band around the dotted line represents plus and minus one standard error for mean prediction, based on the regression analysis, and calculated for each day. Arrows indicate manure events (brown, large) and mowing events (green, small). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

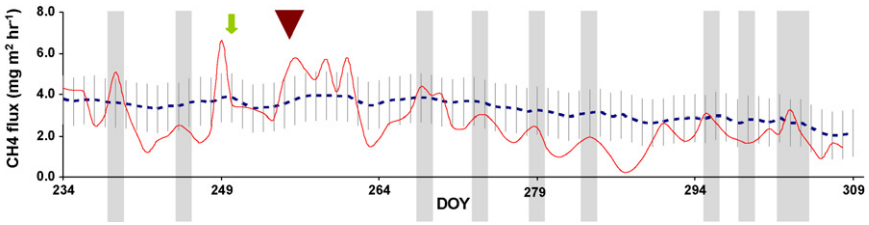

Fig. 3. Time series of measured (red solid line) and modeled (scenario 2, blue dashed line) daily averaged CH_4 fluxes during the period 21 August to 5 November, 2006. The uncertainty band around the dotted line represents plus and minus one standard error for mean prediction, based on the regression analyses, and calculated for each day. The bars represent days on which wind velocity exceeded 5 m s^{-1}; the brown large arrow represents a manure application event and the green small arrow represents a mowing event. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

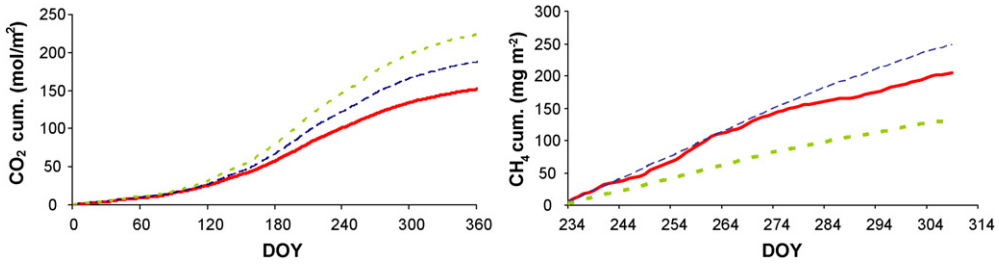

Fig. 4. Cumulative CO_2 respiration (left) and CH_4 emission (right) over one year and three months, respectively. The blue dashed line is the model based on chamber measurements and weighted for the landscape elements (scenario 2), the red solid line shows the EC results and the green dotted lines show the cumulative values based on up-scaling from field measurements (scenario 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

non-stationarity of the flow, lack of a fully developed turbulent surface layer, flow distortion, sensor separation, topography and instrument error. In our case, the energy balance was not fully closed (Veenendaal et al., 2007). This discrepancy is not unusual for EC measurements (e.g. Corradi et al., 2005; Nieveen et al., 2005) and might lead to underestimation of the actual fluxes (Twine et al., 2000). Further inter-comparison studies at different sites are needed.

4.3. Comparison of EC and empirical models on a daily basis

The daily averaged EC fluxes were compared with the daily averaged fluxes estimated by the empirical model, to validate the response to meteorological conditions and management. The temporal variation of the EC averaged daily fluxes was large, whereas the emission rates as estimated by the empirical model were smoothed. The difference in fluxes between the two methods was especially marked in periods of manure application: the chamber method did not follow the variation in CO_2 and CH_4 as measured by the EC systems (see also, e.g. Reth et al., 2005). Neither did the chamber method capture the change in CO_2 respiration rates after mowing, whereas the EC system did.

Furthermore, the EC system sometimes measured increased CH_4 (Fig. 3) and CO_2 emissions at high wind velocity followed by a short period of reduced emissions. We corrected the EC fluxes for temperature and we found a significant positive correlation between these EC emission values of both gases and wind velocity at three meters ($P < 0.01$). Other researchers (Sachs et al., 2008; Wille et al., 2008) have recently also reported a correlation between horizontal wind speed and CH_4 fluxes and they suggested a possible underestimation by chambers. They stated that higher CH_4 fluxes from water bodies at high wind velocity may be due to turbulence induced ebullition and indicate a possible threshold of wind speed for the triggering of this process. Ebullition in water could also be triggered by changes of air pressure (Frolking and Crill, 1994). Besides, increased turbulence could flush out the CH_4 stored in the surface layer at non-turbulent periods at night (Hargreaves et al., 2001), but the total effect could perhaps be neglected over longer time spans because flushing and storage of gases in the vegetation layer or in the upper water layer could be in balance. More research is needed, especially in water bodies, to capture this flux variability and to also determine the influence of u^* on CH_4 fluxes from water bodies and soil.

4.4. Conclusion

Two independent methods for measuring CH_4 and CO_2 at large-scale (EC) and small-scale (chambers) have been tested at different temporal scales in a heterogeneous landscape of fields and ditches. When only the field emissions are included, the difference between EC and up-scaled chamber-based cumulative emissions is 31.0% for CO_2 and 55.1% for CH_4. However, when the representative landscape elements within the ecosystem are taken into account and a regression model is created for the different components, the EC and up-scaled chamber-based cumulative emissions agree well with 16.5% difference for CO_2 and 13.0% difference for CH_4. This difference can become even smaller if the regression models will be refined by, e.g. management influences. To conclude, small-scale chamber measurements can thus certainly be used to estimate fluxes of CO_2 and CH_4 at landscape scale when all different landscape elements are taken into account.

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