Using 'snapshot' measurements of CH_4 fluxes from an ombrotrophic peatland to estimate annual budgets: interpolation *versus* modelling

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SUMMARY

Flux-chamber measurements of greenhouse gas exchanges between the soil and the atmosphere represent a snapshot of the conditions on a particular site and need to be combined or used in some way to provide integrated fluxes for the longer time periods that are often of interest. In contrast to carbon dioxide (CO_2), most studies that have estimated the time-integrated flux of CH_4 on ombrotrophic peatlands have not used models. Typically, linear interpolation is used to estimate CH_4 fluxes during the time periods between flux-chamber measurements. CH_4 fluxes generally show a rise followed by a fall through the growing season that may be captured reasonably well by interpolation, provided there are sufficiently frequent measurements. However, day-to-day and week-to-week variability is also often evident in CH_4 flux data, and will not necessarily be properly represented by interpolation. Using flux chamber data from a UK blanket peatland, we compared annualised CH_4 fluxes estimated by interpolation with those estimated using linear models and found that the former tended to be higher than the latter. We consider the implications of these results for the calculation of the radiative forcing effect of ombrotrophic peatlands.

KEY WORDS: blanket peatland, flux chamber, methane, time-integrated fluxes

INTRODUCTION

There is growing interest in the annual carbon dioxide (CO_2) and methane (CH_4) budgets of peatlands (e.g. Olson *et al*. 2013, Meng *et al*. 2016). Such budgeting is required for estimating the radiative forcing effect of peatlands on climate. The radiative forcing of different greenhouse gases (GHG) can be calculated using the concept of global warming potential (GWP) as defined by the Intergovernmental Panel on Climate Change (IPCC) (Myhre *et al*. 2013), and is usually expressed in terms of carbon dioxide equivalents (CO_2-e). CH_4 is a much more potent greenhouse gas than CO_2 and correspondingly has a higher GWP. It is currently estimated that CH_4 is 28 times more potent than CO_2 (excluding climate feedbacks) over a 100-year timeframe (Myhre *et al*. 2013). Therefore, in CO_2-e terms, CH_4 assumes equal importance to CO_2 when the CH_4 flux in mass terms is just 3.6 % of the net CO_2 flux (e.g. Baird *et al*. 2009). Consequently, any systematic under- or over-estimation of the annual flux of CH_4 may have a disproportionate effect on calculations of the radiative forcing effects of peatlands, with implications for policy and land management.

CH_4 fluxes from ombrotrophic peatlands, i.e. raised bogs and blanket bogs, are commonly measured using flux chambers at intervals typically no less than weekly, but often fortnightly or even monthly (e.g. Waddington & Roulet 1996, Dinsmore *et al*. 2009, Baird *et al*. 2010, Moore *et al*. 2011). It is common to use models based on flux chamber data to estimate annual fluxes of CO_2 from bogs (Waddington & Roulet 1996, Bubier *et al*. 1998, Tuittila *et al*. 1999, Strack & Zuback 2013, Vanselow-Algan *et al*. 2015). On the other hand, linear interpolation between measurements (see below) is usually used when estimating annual CH_4 fluxes (e.g. Waddington & Roulet 1996, Dise *et al*. 1993, Roulet *et al*. 2007), although there are cases where models have been used (e.g. Laine *et al*. 2007). CH_4 fluxes generally show a rise followed by a fall through the growing season that may be captured reasonably well by simple interpolation. However, day-to-day and week-to-week variability is also often evident in CH_4 flux data (e.g. Moore & Knowles 1990, Laine *et al*. 2007, Baird *et al*. 2010, Lai *et al*. 2014), and will not be properly represented using interpolation, in which case a modelling approach may be preferred (see INTEGRATION APPROACHES below). To our knowledge, interpolated and modelled estimates of time-integrated fluxes of CH_4 from bogs have not been compared, and it is not clear how they differ (both in terms of direction—does one type of estimate

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consistently give higher values than the other?—and magnitude). To partly address this knowledge gap, we used a large flux-chamber dataset from a UK blanket peatland.

INTEGRATION APPROACHES

The integrated flux (F_g; e.g. mg m^{-2}) of CH_4 between Time 1 and Time 2 (t_1, t_2) may be estimated by interpolation using:

$$F_{g,1-2} = \frac{1}{2}\left(f_{g,1} + f_{g,2}\right)\left(t_2 - t_1\right) \quad [1]$$

where f_g is the instantaneous flux (e.g. mg m^{-2} day^{-1}). The F_g values for each time pair may then be summed to give an annual total. Alternatively, f_g may be modelled using environmental and ecological variables such as water-table depth, soil temperature, air temperature, and the abundance of different plant functional types. If some of these variables are measured at a higher frequency than flux chamber tests, models in which they are used can, in turn, be run or applied to simulate f_g at those higher frequencies. The high-frequency estimates of f_g can then be summed to give an estimate of annual F_g. In this study, we modelled f_g using ordinary multiple linear models of the following form:

$$f_g = a + b_1 X_1 + b_2 X_2 + ... + b_n X_n \pm \varepsilon \quad [2]$$

where a and b_1, b_2, ...b_n are fitting parameters, X_1, X_2,...X_n are the independent (environmental and ecological) variables, and ε is the model error. Multiplicative models can also be used but we found these performed less well than models based on Equation 2. Likewise, it is possible to use biophysical models in which the processes involved in CH_4 production, consumption and transport are described in considerable depth (e.g. Grant & Roulet 2002), but very few studies are detailed enough to provide the data needed for the parameterisation and application of such models. In this study we used air temperature, soil temperature, a temperature sum index and the abundance of plant functional type as our candidate independent variables in Equation 2 (see below).

COMPARISON OF ANNUAL CH_4 BUDGET APPROACHES

Study site and methods

The study was carried out on part of the Migneint blanket bog complex in the upper Conwy catchment in North Wales (latitude 52.97 °N, longitude 3.84 °W). Site vegetation comprised a typical blanket mire assemblage including *Calluna vulgaris* (L.) Hull (common heather), *Eriophorum vaginatum* L. (hare's tail cottongrass) and various species of *Sphagnum* (bog mosses; e.g. *S. capillifolium* (Ehrh.) Hedw., *S. papillosum* Lindb. and *S. cuspidatum* Ehrh. ex Hoffm.). The peat across the sampling area was 0.54–2.39 m deep, with a pH (H_2O) of 3.62–3.80, bulk density of 0.08–0.11 g cm^{-3}, loss on ignition of 98.8–99.7 % and a C/N quotient of 30.0–36.6 (depending on depth) (Table 1). The wider purpose of the project was to investigate the effects of different methods of ditch blocking (for peatland restoration) on GHG uptake and emissions. GHG exchanges were measured across the site, both within and between ditches, using flux chambers (Denmead 2008, Green *et al*. 2016a). These comprised cylindrical acrylic chambers with an outside diameter

Table 1. Physical and chemical properties of the peat at the study site (n = 12). Parentheses contain standard deviation.

Depth (cm)	Dry bulk density (g cm^{-3})	Volumetric water content (cm cm^{-3})	Loss on ignition (%)	pH (H_2O)	pH ($CaCl_2$)	Conductivity (H_2O μS cm^{-1})	C/N
0 – 10	0.08 (0.02)	0.77 (0.18)	98.8 (2.74)	3.80 (0.15)	2.98 (0.05)	61.6 (18.8)	36.6 (10.9)
15 – 25	0.10 (0.03)	0.96 (0.12)	99.6 (0.32)	3.62 (0.11)	2.97 (0.05)	81.2 (13.6)	30.0 (5.33)
30 – 40	0.11 (0.03)	0.91 (0.12)	99.7 (0.10)	3.63 (0.18)	2.95 (0.05)	79.2 (16.5)	34.8 (7.54)

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(o.d.) of 300 mm, a wall thickness of 3 mm and a height of 333 mm (Figure 1) that were placed on polyvinyl chloride (PVC) collars during tests. The collars had an o.d. of 315 mm and wall thickness of 8 mm, enclosing an area of 0.07 m^2. The collars were 200 mm long with half that length inserted below the ground surface. The upper rim of each collar was fitted with a gutter into which water was poured and the chamber placed to form a gas-tight seal during flux tests.

Within-chamber CH_4 concentrations during tests were measured either (a) by taking syringe samples of the gas (25 mL) and later analysing these in the laboratory (see below) or (b) in-field using an on-line Los Gatos Research Ultra-portable GHG Analyzer (UGHGA; Model 915-0011; Los Gatos Research, Mountain View, California). Method (a) was used at the beginning of the project but was replaced by Method (b) in 2013 because it allowed tests to be carried out more quickly and because the UGHGA was more accurate than the laboratory method of measuring CH_4 concentrations (see below). For the syringe-sample tests (i.e. Method (a)), gas samples were taken at intervals of 1, 6, 11, 16 and 21 minutes after chamber closure. The gas samples were analysed for CH_4 content using either a Perkin Elmer Clarus 500 gas chromatograph (GC) system fitted with a flame ionisation detector (FID), or an Agilent Varian 450 GC system, also fitted with a FID. Standard analytical grade reference span gases (Cryoservice, Worcester, UK) were used to calibrate the GCs, and were inserted at regular intervals during sample runs to check for instrument drift. When using the Los Gatos UGHGA, CH_4 concentration readings were taken over a period of 3–5 minutes after chamber closure at a frequency of 0.5 Hz. We varied the closure time according to disturbance effects (abrupt variations in CH_4 concentrations within the chamber) associated with placing a chamber on a collar. Sometimes these effects were minimal, so we ran the test for three minutes. However, sometimes they affected readings in the first 50–100 s, in which case we ran the test for up to five minutes. Inspection of our data had shown that at least three minutes' worth of readings were required to provide a reliable flux estimate.

Changes in CH_4 concentration during a chamber test can be used to estimate the flux between the peatland and the atmosphere using (Denmead 2008):

$$f_g = \frac{V}{A}\frac{d\rho_g}{dt} \quad [3]$$

where f_g is the gas flux density at the peatland surface (mg m^{-2} day^{-1}), V is the combined volume of the flux chamber and the collar above the peatland surface, A is the inside area of the collar (m^2), ρ_g is the mass concentration of the gas in the chamber (mg m^{-3}), and t is time (days). Equation 3 may also be written in slightly modified form, as:

$$f_g = \frac{1}{A}\frac{dg_m}{dt} \quad [4]$$

Figure 1. An example collar (left), and demonstration (right) of the use of the on-line Los Gatos Research Ultra-portable GHG Analyzer (UGHGA; Model 915-0011; Los Gatos Research, Mountain View, California) for CH_4 flux measurement using a shrouded chamber.

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where g_m is the mass of the gas in the chamber (mg) ($g_m = V \times \rho_g$).

We applied Equation 4 to our chamber data by first converting ppm gas concentrations into masses using the Ideal Gas Equation. Ordinary least squares regression (using the LINEST function in Excel 2010) was used to estimate dg_m/dt by fitting a line through the gas *versus* time data. The regression fit was only accepted if $r^2 \geq 0.7$ and $p < 0.05$. Fluxes for datasets that did not meet these criteria were rejected with one exception: if variations in gas concentration during a test were within a threshold error range of the instrument being used to measure the concentrations, the flux was assumed to be zero. This range was 0.3 ppm for the GC-FID determinations (Method (a)) and 0.03 ppm for the UGHGA (Method (b)). If this additional criterion had not been used, the flux estimates would be biased to higher fluxes because all zero and close-to-zero fluxes would have failed the regression criteria and been excluded (this additional criterion applied to ~4 % of our measurements).

In addition to measuring gas fluxes at the study site we measured the following variables, which were candidates for inclusion in the linear models based on Equation 2 (see above).

Air temperature

This was measured at a height above the ground surface of 1.3 m using a Davis Instruments Vantage Pro 2 (Davis Instruments Corp., Hayward, California, USA) automatic weather station (AWS) situated within 100 m of the experimental area. Hourly averages of air temperature (°C) were available for use in the linear models.

Soil temperature

Soil temperature (°C) was measured by the AWS (see above) at a depth of 5 cm, and hourly averages recorded.

Temperature sum index

The temperature sum index (*ETI*) is the ratio of the cumulative air temperature sum to the number of temperature sum days. A threshold temperature has to be reached before the *ETI* is calculated. Alm *et al*. (1997) and Tuittila *et al*. (1999) estimated *ETI* only for that part of the year (for sites in eastern and southern Finland, respectively) when the five-day moving average air temperature was above 5 °C. Here, we also used a temperature of 5 °C. Mathematically, the *ETI* is given by:

$$ETI_j = \left(\sum_{i=1}^{j} T_{air,i} \right) \Big/ j \qquad [5]$$

where j is the day of interest (counted from the first day when the five-day moving average air temperature exceeds the threshold temperature), T_{air} is daily-average air temperature (°C) and i is day number.

Abundance of plant functional types

The abundance of sedges (mainly *Eriophorum* spp.), *Sphagnum* spp. and ericoid shrubs was measured in each collar from digital photographs. Photographs were taken during every flux test and a subset of these were analysed for nested frequency. This measurement comprised placing a 100-cell grid over the photograph and recording the presence/absence of all sedges, *Sphagnum* spp. and ericoid shrubs in each cell. While this method has limitations—for example, it cannot account for layering of species—it does provide a quantitative measure of plant abundance that can be used as a predictor of CH_4 exchanges between a peatland and the atmosphere.

Meteorological conditions over the study period

Meteorological conditions, especially rainfall, varied quite strongly over the study period (Figure 2), which ran from March 2012 to March 2015. Each project year ran from March to February; however, henceforth we abbreviate the project years according to the calendar year in which the majority of the project year fell. For each project year, the site had an annual mean air temperature of 6.5 °C (2012), 6.9 °C (2013) and 7.6 °C (2014). In the same period, the rainfall for each successive year was 2409, 1786 and 1936 mm.

Comparison of approaches to estimating time-integrated fluxes

For our comparison of integration approaches we considered CH_4 fluxes from 24 of the flux chambers deployed at the site, situated in the areas between the ditches (i.e. not within the ditch channels). Measurements were made every three to six weeks in 2012 ($n = 10$ readings per chamber), 2013 ($n = 11$) and 2014 ($n = 11$) (768 flux chamber tests in total). We use the convention that positive fluxes represent emissions and negative fluxes indicate uptake. We compared estimates of annual peatland–atmosphere CH_4 emissions calculated using interpolation (Equation 1) and an ordinary multiple linear model (Equation 2). Estimates were made separately for each flux-chamber collar; i.e., a separate version of Equation 2 was developed for each collar. Models were fitted by minimising the sum of the squared differences between the model and the training data. Model fit (i.e. prediction error) was described using the standard error of the estimate (SEE). Although

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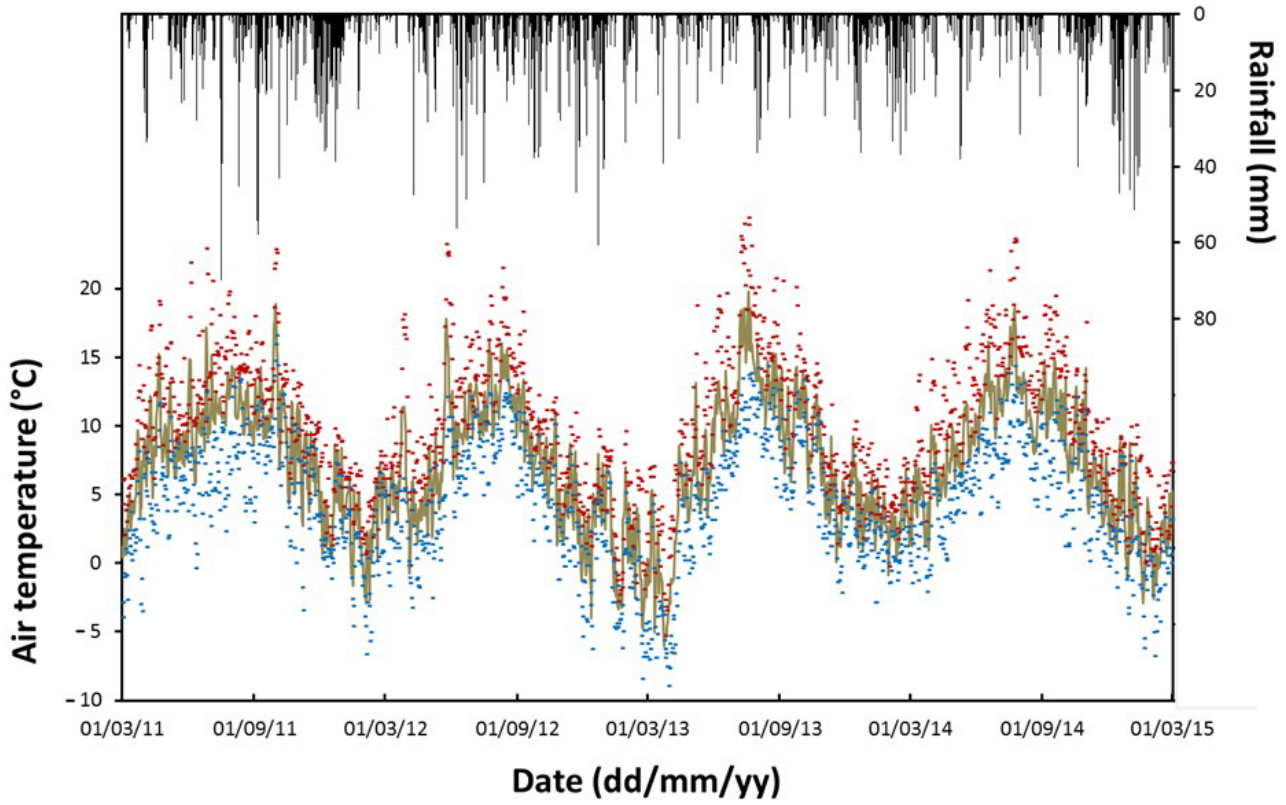

Figure 2. Meteorological conditions at the experimental site between 01 March 2012 and 01 March 2015. The black bars indicate daily rainfall (mm). Average daily air temperature (°C) is denoted by the green-brown line, daily maximum temperature by the red dashes and daily minimum by the blue dashes.

there were quite large variations in model fit (see below), all of the models were included in the comparison of modelled and interpolated fluxes so that the effect of model quality (as described by SEE) on differences between the flux estimation methods could be assessed.

The models were run at hourly time intervals and the hourly fluxes summed to give annualised fluxes. The plant abundance data were obviously not available at hourly intervals, but were entered for each hour and updated for every time at which abundance was re-measured (twice *per* year). The training (calibration) datasets used for each model were mostly sufficiently extensive to cover the range of conditions encountered over the period of model application (i.e. 2012–2014 inclusive). The *ETI* and plant functional type abundance training sets included the full range of conditions encountered during the period of model application. Twelve percent of the soil temperature values during the period of application were lower or higher than the range used in the training set, while for air temperature the figure was 8.7 percent. However, in all cases where the model was applied beyond the range of the training set, the modelled CH_4 fluxes were not extreme or unreasonable.

Comparison of annualised CH_4 fluxes estimated by interpolation and modelling (Figure 3) revealed a moderate correlation ($r = 0.73$, $p < 0.0001$) but a significant difference between the two datasets ($p = 0.001$) (IBM SPSS version 23: paired *t*-test). Interpolated fluxes were on average 29 % higher than those estimated through the modelling approach. In some cases, even the sign of the flux differs (Figure 3). The difference between the methods seems also to be related to the size of the flux, with greater differences (and scatter) at the higher end (i.e. greater than 20 g CH_4 m^{-2} y^{-1}). Modest-sized fluxes (5–15 g CH_4 m^{-2} y^{-1}) are scattered closer to the 1:1 line (Figure 3). There was no correlation between the SEE of the individual flux models and the ratio of interpolated to modelled annual CH_4 flux ($r = -0.143$, $p = 0.232$) (Figure 4). This suggests that model quality is of less importance than the inclusion of short-term changes in environmental variables in this instance. Because the modelling approach includes variables based on hourly measurements it can reflect short-term changes in fluxes, which are not accounted for in the interpolation approach. The accuracy of interpolation depends on the frequency

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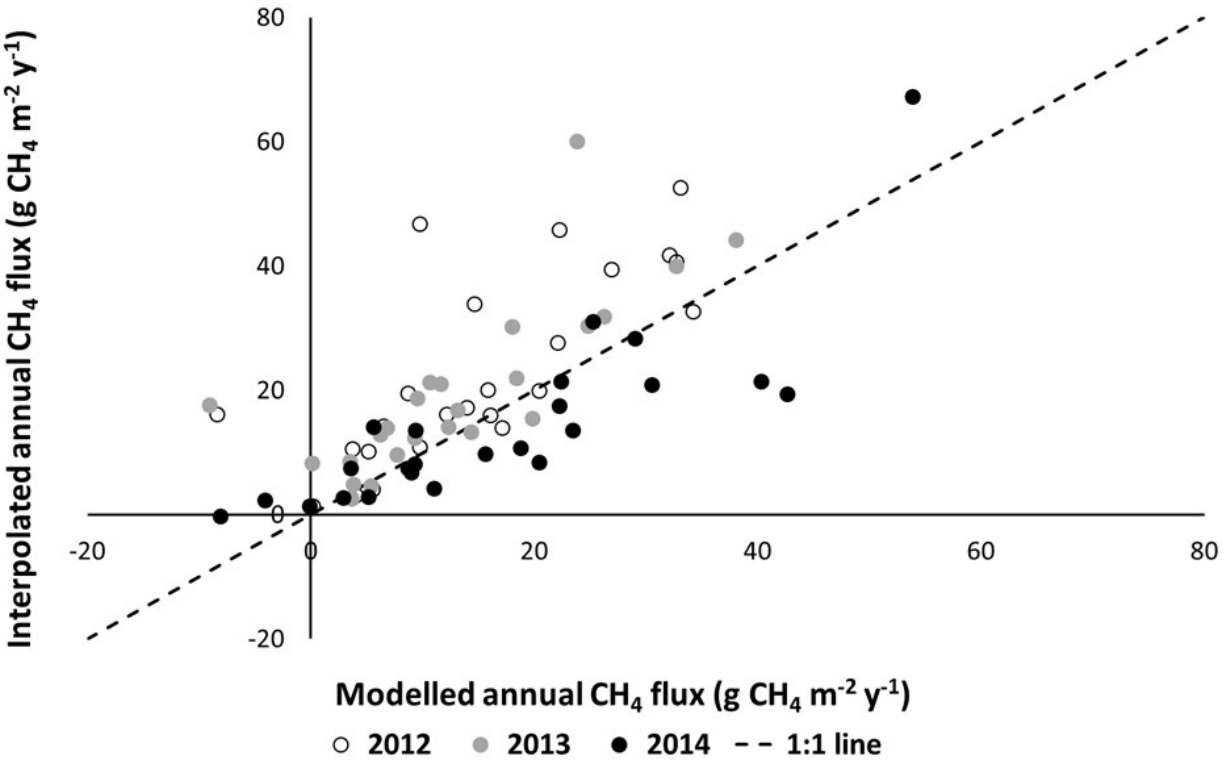

Figure 3. Interpolated *versus* modelled annual methane (CH_4) flux. A positive CH_4 flux indicates emission and a negative flux uptake.

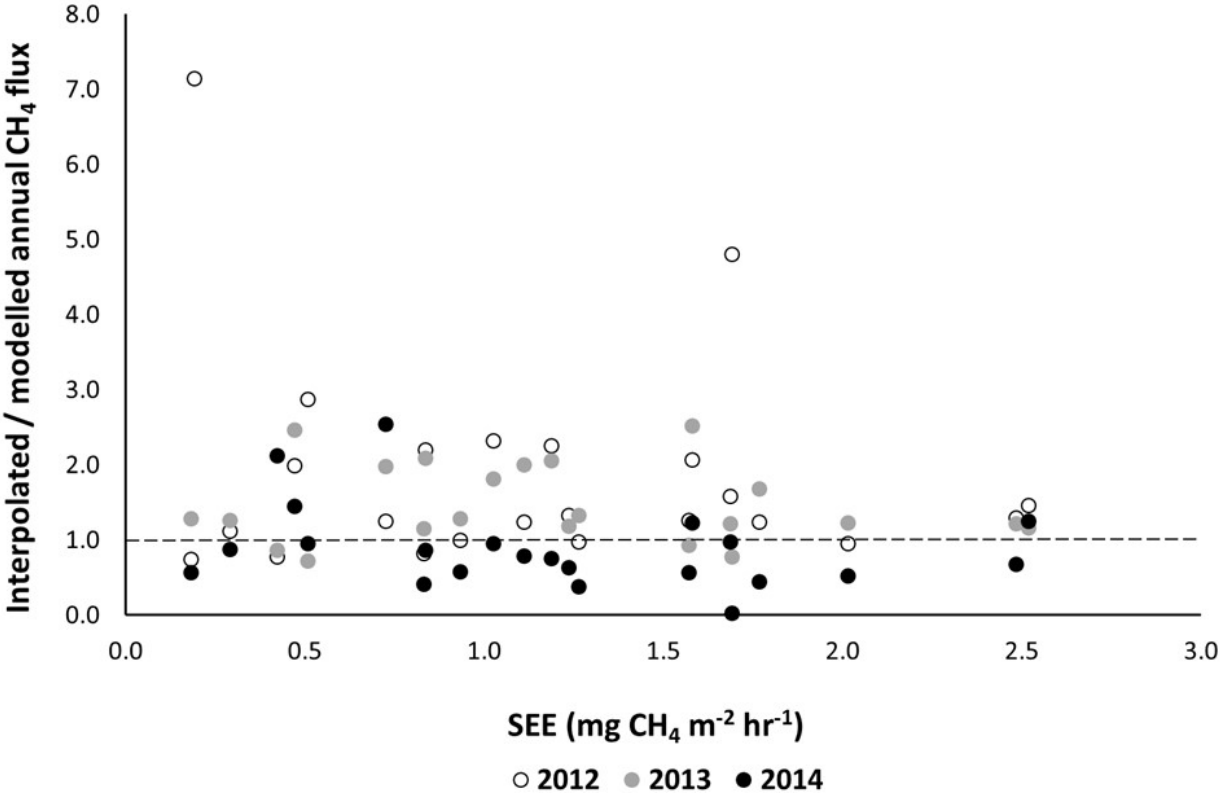

Figure 4. Model standard error of the estimate (SEE) *versus* the quotient of interpolated to modelled annual methane (CH_4) flux. Note: for 2013 there is a quotient of 77, and for 2014 a quotient of -11.2 for a model with a SEE of 0.19 mg CH_4 m^{-2} hr^{-1} (not shown).

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and seasonal timing of 'snapshot' chamber measurements. In comparison, the modelling approach is dependent on the resolution and quality of the supporting datasets and the number of data points included in the model calibration dataset.

An alternative way of considering the differences in estimates between the approaches is to convert the CH_4 into CO_2-e and combine it with net ecosystem CO_2 exchange (NEE). To illustrate this alternative, we considered 22 of the 24 collars for which we also had measured and modelled values of NEE (methods not explained here, see Green *et al*. 2016b). By combining the NEE for a collar with its CH_4 flux expressed in CO_2-e we were able to estimate the overall radiative forcing effect of the patch of peatland within the collar. The 22 collars had CH_4 models with SEE in the range 0.18–2.5 mg CH_4 m^{-2} hr^{-1}. When all 22 collars are averaged, the CH_4 flux is estimated as 19.0 g CH_4 m^{-2} y^{-1} (interpolated) and 15.1 g CH_4 m^{-2} y^{-1} (modelled), which are comparable to CH_4 annual emissions in other ombrotrophic peatlands (Blain *et al*. 2014, Wilson *et al*. 2016). NEE for the 22 collars was estimated at -108 g CO_2 m^2 y^{-1} (i.e. a CO_2 sink). When combining the CO_2 and CH_4 fluxes into a single CO_2-e value, over a 100-year time frame, we obtained a value of 424 g CO_2-e m^2 y^{-1} (CH_4 interpolation) and 314 g CO_2-e m^2 y^{-1} (CH_4 modelled). Notably, the difference in the CO_2-e estimates is similar to the absolute value of the NEE. Interpolation produces a 26 % increase in terms of estimated CH_4 and a 35 % increase in the estimated CO_2-e flux. This is because NEE for each of the 22 collars is relatively small in magnitude, so that a substantial part of the CO_2-e estimate for each collar comprises the contribution from CH_4.

CONCLUSION

Our results show that the two approaches, interpolation and modelling, can lead to substantial relative and absolute differences in estimates of peatland–atmosphere CH_4 fluxes and estimates of the radiative forcing effect of a peatland. Given the potential for such large differences, we recommend future studies on bogs take account of the effects of different integration approaches when estimating annual fluxes of CH_4, and report the alternative sets of estimates. This information is clearly policy-relevant given interest in, for example, how best to restore peatlands while also minimising CH_4 fluxes (e.g. Baird *et al*. 2009) and in the accurate MRV (measurement, reporting and verification) of peatland emissions and the calculation of emission factors for land-use change in peatlands (e.g. Couwenberg 2009). In our analysis, we did not discriminate between models based on their SEE. If good (accurate) models can be developed, they are likely to provide better estimates than interpolation, unless fluxes are measured at very high frequencies (much more often than weekly, e.g. Lai *et al*. 2014). However, it is notable that the differential between modelled and interpolated fluxes in this study was not related to model quality or accuracy as represented by SEE. Therefore, care should be taken when deciding which approach to use.

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REFERENCES

Alm, J., Talanov, A., Saarnio, S., Silvola, J., Ikkonen, E., Aaltonen, H., Nykänen, H. & Martikainen, P.J. (1997) Reconstruction of the carbon balance for microsites in a boreal oligotrophic pine fen, Finland. *Oecologia*, 110, 423–431.

Baird, A.J., Holden, J. & Chapman, P. (2009) *A Literature Review of Evidence on Emissions of Methane in Peatlands*. Report, UK Government Department of Environment Fisheries and Rural Affairs (Defra) Project SP0574, University of Leeds, Leeds, UK, 54 pp. Online at: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=15992, accessed 07 Mar 2017.

Baird, A.J., Stamp, I., Heppell, C.M. & Green, S.M. (2010) CH_4 flux from peatlands: a new measurement method. *Ecohydrology*, 3, 360–367.

Blain, D., Murdiyarso, D., Couwenberg, J., Nagata, O., Renou-Wilson, F., Sirin, A., Strack, M., Tuittila, E.S. & Wilson, D. (2014) Chapter 3. Rewetted organic soils. In: Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. & Troxler, T.G. (eds.) (2013) *Supplement to the 2006 IPCC Guidelines for*

 DOI: 10.19189/MaP.2016.OMB.254

National Greenhouse Gas Inventories: Wetlands. Intergovernmental Panel on Climate Change (IPCC), Switzerland. Online at: http://www.ipcc-nggip.iges.or.jp/public/wetlands/pdf/Wetlands_separate_files/WS_Chp3_Rewetted_Organic_Soils.pdf, accessed 07 Mar 2017.

Bubier, J.L., Crill, P.M., Moore, T.R., Savage, K. & Varner, R.K. (1998) Seasonal patterns and controls on net ecosystem CO_2 exchange in a boreal peatland complex. *Global Biogeochemical Cycles*, 12, 703–714.

Couwenberg, J. (2009) *Methane Emissions from Peat Soils (Organic Soils, Histosols): Facts, MRV-ability, Emission Factors*. Wetlands International, Ede, The Netherlands, 14 pp.

Denmead, O.T. (2008) Approaches to measuring fluxes of methane and nitrous oxide between landscapes and the atmosphere. *Plant and Soil*, 309, 5–24, doi: 10.1007/s11104-008-9599-z.

Dinsmore, K.J., Skiba, U.M., Billett, M.F., Rees, R.M. & Drewer, J. (2009) Spatial and temporal variability in CH_4 and N_2O fluxes from a Scottish ombrotrophic peatland: Implications for modelling and up-scaling. *Soil Biology and Biochemistry*, 41(6), 1315–1323.

Dise, N.B., Gorham, E. & Verry, E.S. (1993) Environmental factors controlling methane emissions from peatlands in northern Minnesota. *Journal of Geophysical Research*, 98(D6), 10583–10594, doi:10.1029/93JD00160.

Grant, R.F. & Roulet, N.T. (2002) Methane efflux from boreal wetlands: Theory and testing of the ecosystem model Ecosys with chamber and tower flux measurements. *Global Biogeochemical Cycles*, 16(4), 1054, doi:10.1029/2001GB001702.

Green, S.M., Baird, A.J., Evans, C., Ostle, N., Holden, J., Chapman, P.J. & McNamara, N. (2016a) *Investigation of Peatland Restoration (Grip Blocking) Techniques to Achieve Best Outcomes for Methane and Greenhouse Gas Emissions/Balance: Field Trials and Process Experiments. Final Report*. Defra Project SP1202, University of Leeds, Leeds, UK, 17 pp. Online at: file:///C:/Users/Setup/Downloads/13868_SP1202_FinalReport.pdf, accessed 01 Mar 2017.

Green, S.M., Baird, A.J., Evans, C., Peacock, M., Holden, J., Chapman, P., Gauci, V. & Smart, R. (2016b) Appendix D: The effect of drainage ditch blocking on the CO_2 and CH_4 budgets of blanket peatland. In: Green, S.M., Baird, A.J., Evans, C., Ostle, N., Holden, J., Chapman, P.J. & McNamara, N. *Investigation of Peatland Restoration (Grip Blocking) Techniques to Achieve Best Outcomes for Methane and Greenhouse Gas Emissions/Balance: Field Trials and Process Experiments*. Final Report, Defra Project SP1202, University of Leeds, Leeds, UK, 30 pp. Online at: file:///C:/Users/Setup/Downloads/13871_SP1202_FinalReport_AppendixD.pdf, accessed 01 Mar 2017.

Lai, D.Y.F., Moore, T.R. & Roulet, N.T. (2014) Spatial and temporal variations of methane flux measured by auto chambers in a temperate ombrotrophic peatland. *Journal of Geophysical Research - Biogeosciences*, 119, 864–880, doi:10.1002/2013JG002410.

Laine, A., Wilson, D., Kiely, G. & Byrne, K.A. (2007) Methane flux dynamics in an Irish lowland blanket bog. *Plant & Soil*, 299, 181–193, doi: 10.1007/s11104-007-9374-6.

Meng, L., Roulet,. N., Zhuang, Q., Christensen, T.R. & Frolking, S. (2016) Focus on the impact of climate change on wetland ecosystems and carbon dynamics. *Environmental Research Letters*, 11(10), 100201.

Moore, T., De Young, A., Bubier, J., Humphreys, E., Lafleur, P. & Roulet, N. (2011) A multi-year record of methane flux at the Mer Bleue bog, southern Canada. *Ecosystems*, 14(4), 646–657.

Moore, T.R. & Knowles, R. (1990) Methane emissions from fen, bog and swamp peatlands in Quebec. *Biogeochemistry*, 11, 45–61, doi: 10.1007/BF00000851.

Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestvedt, F., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. & Zhang, H. (2013) Chapter 8. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Available online at: http://www.ipcc.ch/report/ar5/wg1/, accessed 07 Mar 2017.

Olson, D.M., Griffis, T.J., Noormets, A., Kolka, R. & Chen, J. (2013) Interannual, seasonal, and retrospective analysis of the methane and carbon dioxide budgets of a temperate peatland. *Journal of Geophysical Research - Biogeosciences*, 118, 226–238, doi:10.1002/jgrg.20031.

Roulet, N.T., Lafleur, P.M., Richard, P.J.H., Moore, T.R., Humphreys, E.R. & Bubier, J. (2007) Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Global Change Biology*, 13, 397–411, doi:

10.1111/j.1365-2486.2006.01292.x.

Strack, M., & Zuback, Y.C.A. (2013) Annual carbon balance of a peatland 10 yr following restoration. *Biogeosciences*, 10(5), 2885–2896.

Tuittila, E-S., Komulainen, V-M., Vasander, H. & Laine, J. (1999) Restored cutaway peatland as a sink for atmospheric CO_2. *Oecologia*, 120, 563–574.

Vanselow-Algan, M., Schmidt, S.R., Greven, M., Fiencke, C., Kutzbach, L. & Pfeiffer, E.M. (2015) High methane emissions dominated annual greenhouse gas balances 30 years after bog rewetting. *Biogeosciences*, 12(14), 4361–4371.

Waddington, J.M. & Roulet, N.T. (1996) Atmosphere-wetland carbon exchanges: Scale dependency of CO_2 and CH_4 exchange on the developmental topography of a peatland. *Global Biogeochemical Cycles*, 10(2), 233–245.

Wilson, D., Blain, D., Couwenberg, J., Evans, C.D., Murdiyarso, D., Page, S., Renou-Wilson, F., Rieley, J., Sirin, A., Strack, M. & Tuittila, E.-S. (2016) Greenhouse gas emission factors associated with rewetting of organic soils. *Mires and Peat*, 17, Article 04, 1–28, doi: 10.19189/MaP.2016.OMB.222.

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