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Simulation of CO_2 and attribution analysis at six European peatland sites using the ECOSSE model

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Abstract

In this study, we simulated heterotrophic CO_2 (Rh) fluxes at six European peatland sites using the ECOSSE model and compared them to estimates of Rh made from eddy covariance (EC) measurements. The sites are spread over four countries with different climates, vegetation and management. Annual Rh from the different sites ranged from 110 to 540 g C m^{-2}. The maximum annual Rh occurred when the water table (WT) level was between -10 and -25 cm and the air temperature was above 6.2^oC. The model successfully simulated seasonal trends for the majority of the sites. Regression relationships (r^2) between the EC-derived and simulated Rh ranged from 0.28 to 0.76 and the root mean square error and relative error were small, revealing an acceptable fit. The overall relative deviation value between annual EC-derived and simulated Rh was small (-1%) and model efficiency ranges across sites from -0.25 to +0.41. Sensitivity analysis highlighted that increasing temperature, decreasing precipitation and lowering WT depth could significantly increase Rh from soils. Thus, management which lowers the WT could significantly increase anthropogenic CO_2, so from a carbon emissions perspective, should be avoided. The results presented here demonstrate a robust basis for further application of the ECOSSE model to assess the impacts of future land management interventions on peatland carbon emissions, to help guide best practice land-management decisions.

1 Introduction

Peatlands are spread over 175 countries and represent approximately 4 million km^2 or 3% of the world's land area (Global Peat lands Initiative, 2002). Most of the wetlands (60%) contain peat soils of which about 7% are under crop production and forestry. European peatlands cover about 515,000 km^2, mostly in the north of the continent (Figure 1). The biggest areas of peatlands in Europe are found in Finland (1/3) and Sweden (1/4). The rest are in European Russia, Poland, the UK, Norway, Germany, Ireland, Estonia, Latvia, the Netherlands and France. However, other countries like Denmark, the Czech Republic, Hungary and Lithuania contain small areas of peaty-top soils (Montanarella et al., 2006). In a review, Yu (2012) found that sequestration of more than 50% of carbon (C) (>270 Gt C) in peatlands took place during the Holocene, about 7000 years ago.

Peatlands are one of the biggest terrestrial C stores that contain one third of the global soil C stock (Joosten et al., 2013) and thus an essential component of the global greenhouse gas (GHG) budget at the Holocene time scale (Frolking et al., 2006). Under natural, unmanaged conditions, peatlands could represent a sink ecosystem for atmospheric carbon dioxide (CO_2), due to the absence of aerobic decomposition and associated CO_2 emissions under waterlogged soil conditions, resulting in the accumulation of soil organic matter (SOM) (Dise, 2009). Nevertheless, managed peatlands show a higher variability in GHG emissions at both spatial and temporal levels due to active systems in soil moisture dynamics, redox potential, availability of substrate materials and man-made alterations to hydrology and vegetation (Ward et al., 2007; Chen et al., 2008; Schrier-Uijl et al., 2010). Practices like drainage and cultivation of peatlands allow more oxygen to enter the soil, which increases the aerobic decomposition of the stored organic material, and in turn, increases CO_2 emissions (Kasimir-Klemedtsson et al., 1997; Couwenberg, 2011). The attribution of CO_2 emissions to anthropogenic and natural drivers is a great challenge, and is a prerequisite to successfully assess the potential to reduce CO_2 emissions from peatlands in Europe.

Eddy covariance (EC) (McMillen, 1988; Aubinet et al., 2012) is a technique developed to estimate land-atmosphere exchange of gas and energy at ecosystem scale. This technique is based on three-dimensional wind speed measurements along with gas concentration and temperature measurements at high frequency (5-20 Hz). By calculating the covariance between vertical wind speed and the scalar of interest (e.g. CO_2), the land-atmosphere flux can be computed. The measured CO_2 flux, known as net ecosystem exchange (NEE), includes ecosystem respiration (R_{eco}) which consists of heterotrophic (from living micro-organisms + decomposition of old C sources i.e. sapotrophic) and autotrophic (from plants + plant roots) respiration, and gross primary production (GPP) at ecosystem scale which is C assimilated by the plants during photosynthesis. As photosynthesis only occurs during daylight hours, the night time flux is typically used to partition the NEE signal between GPP and R_{eco} (Reichstein et al., 2005). A flux partitioning algorithm that defines a short-term temperature sensitivity of ecosystem respiration, to avoid the bias introduced by confounding factors in seasonal data was applied to extrapolate from night to day (Reichstein et al., 2005). This algorithm performs gap filling of the covariance between fluxes and meteorological parameters and the temporal autocorrelation of the fluxes. However, the daytime data can also be used to calculate the parameters of the vegetation light response curve accounting for the temperature sensitivity of R_{eco} and water vapour pressure deficit limitation of GPP (Lasslop et al., 2010). Respiration can then be extrapolated into the night time using the temperature relationship curve. The use of isotopes as a partitioning technique is popular (Schuur and Trumbore, 2006) and can provide valuable information on terrestrial carbon cycling (Ehleringer et al., 2000; Harrison et al., 2000). In an isotopic experiment (Hardie et al., 2009), annual heterotrophic respiration (Rh) due to soil microorganisms for temperate bogs, was found to be approximately 36% of R_{eco}. Annual CO_2 derived from the older sources of C in the catotelm (sapotrophic) ranged from 10 to 23% of R_{eco} (Hardie et al., 2009). Therefore, the total Rh from the whole soil profile could contribute between 46 and 59% of the total R_{eco} as shown in equation (1) below (Hardie et al., 2009).

The ECOSSE model was developed to simulate C and nitrogen (N) cycling and GHG fluxes in organic soils, using principles initially used for mineral soils in the two mother models, RothC (Jenkinson and Rayner, 1977; Jenkinson et al., 1987; Coleman and Jenkinson, 1996) and SUNDIAL (Bradbury et al., 1993; Smith et al., 1996). Following these established models, ECOSSE uses a pool type approach, describing SOM as pools of inert organic matter, humus, biomass, resistant plant material and decomposable plant material (Smith et al., 2010a, b). In summary, during the decomposition process, material is exchanged between the SOM pools according to first order rate equations, characterised by a specific rate constant for each pool, which are dependent on the temperature, moisture, crop cover and pH of the soil.

The objectives of this study were to 1) simulate Rh from selected European peatland sites with their respective climate, vegetation and management using the ECOSSE model, and 2) obtain a more comprehensive understanding of the terrestrial C cycle and attribution of Rh to variability in natural and anthropogenic drivers (climate and management) in European peatland ecosystems.

2 Materials and Methods

2.1 The study sites

Six European peatland sites were investigated in this study (Figure 1). These sites were part of the GHG-Europe project. The sites are spread over four northern European countries: Auchencorth Moss (Scotland, UK), Horstermeer (the Netherlands), Fäjemyr (Sweden), Degerö Stormyr (Sweden), Kaamanen (Finland) and Lompolojänkkä (Finland). Full site descriptions can be found in Drewer et al. (2010), Hendricks et al. (2007), Lund et al. (2007), Sagerfors et al. (2008), Maanavilja et al. (2010) and Aurela et al. (2009), respectively. The sites have different climatic conditions, vegetation and management. Average annual temperatures and precipitation ranged from -1.4 to 10^{o}C and from 441 to

1155 mm, respectively. Coordinates, annual mean climatic conditions as well as peat types and management are given in Table 1. The soil type for all sites is histosol (FAO, 1998) which generally has a surface or shallow subsurface histic or folic horizon, consisting of moderately decomposed plant debris with / without mixed sand, silt and / or clay. A histic horizon is wet for about one month in almost all years, and is consequently badly aerated. These soils, have >12% organic carbon (OC), which is >20% SOM by weight, but contain approximately 18% OC (30% SOM) if there is a mineral portion with >60% clay (FAO, 1998). SOM were estimated using soil % C, bulk density and peat depth. Details of peat depth and soil characteristics can be found in Table 2.

2.2 Flux measurements

The R_{eco} data were obtained from EC measurements (McMillen, 1988; Aubinet et al., 2012) using either open or closed path infra-red gas analysers (Table 1). Meteorological data were collected during the period 2002 to 2010; however, measurement durations differed between sites and ranged from 2 to 8 years. All details regarding the EC data corrections, quality control, footprint and gap filling procedures can be found in Aurela et al. (2002), Hendricks et al. (2007), Lund et al. (2007), Aurela et al. (2009), Drewer et al. (2010) and Sagerfors et al. (2008). The night time fluxes (photosynthetic active radiation (PAR) threshold of 5μmol m^{-2} s^{-1}) were used to partition NEE flux measurements into GPP and R_{eco} (Reichstein et al., 2005), and the approach of Hardie et al. (2009) was applied to estimate Rh from R_{eco} as shown in equation (1) below.

$$Rh = Rh_{\text{(from surface peat)}} + Rh_{\text{(from catotelm)}} = 46\text{-}59\%\ R_{eco} \quad (1)$$

To represent the variations in Rh throughout the year, Rh was assumed to be at the lowest value of the range (46% R_{eco}) during the summer (June-August), highest value (59% R_{eco}) during the winter (December-February) and mean value (52.5% R_{eco}) during the rest of the year (March-May and September-November). Because we are using a relatively crude method for estimating Rh from R_{eco}, for comparison with modelled Rh values, we are providing a challenging test for the model.

2.3 ECOSSE model and input data

In this study we applied the latest version (v. 5.0.1) of the ECOSSE model to simulates Rh (from surface peat + decomposition of old C sources i.e. sapotrophic). Model outputs were compared to EC-derived Rh values (as estimated from R_{eco} measured by the EC, as described in Section 2.2). The ECOSSE model uses a pool type approach, and all of the major processes of C and N turnover in the soil are included and described using simple equations driven by readily available input variables. It can be used to carry out site-specific simulations with detailed input data, or national-scale simulations using the limited data typically available at larger scales. Data describing SOC, soil water, plant inputs, nutrient applications and timing of management operations are used to run the model for each site (Tables 1 and 2).

The water module in ECOSSE is based on SUNDIAL (Wu and McGechan, 1998), where water streams through the soil pores as 'piston flow'. The soils profile is divided into 5 cm layers. Each layer is filled with water until saturation: the water then either drains to the layer below or evaporates from the topmost layer. Addition or loss of C and N from different vegetation types are estimated using the C and N amounts in different parts of the plant (and harvest index for crops). Potential evapotranspiration is calculated on a daily basis using the Thornthwaite equation (Thornthwaite, 1948). Total soil organic carbon (SOC) and inert organic C amounts are added as inputs. The ECOSSE model then estimates the amount of organic matter (OM) input from plant materials if information on plant yield is not provided. This is carried out using the amount of SOC as an input. The total SOC estimated by a steady-state (10,000 year) run using default plant inputs is compared to the total measured SOC, and a revised estimate is made of the OM inputs so that simulated steady state SOC matches the measured values. Plant material is divided into resistant and decomposable material, based on a decomposable plant material (DPM): resistant plant material (RPM) ratio of 1.44 (as used in the RothC model). More details about the ECOSSE approach is found in Smith et al. (2010c).

2.4 ECOSSE sensitivity and attribution

The sensitivity of ECOSSE and the attribution of Rh to anthropogenic and natural drivers were quantified to assess the impacts of these factors on the gas flux. This was done separately for each site. We altered only one input value at a time, whilst all others parameters were kept constant (Smith and Smith, 2007). Simulations were run to assess how Rh was affected by changes in climate variables: mean temperature (increasing/ decreasing the daily mean temperature by 1 to 6^{o}C with an increment of 1^{o}C) and precipitation (altering the daily precipitation over a range from -50 to +50% with an increment of 10%). Simulations were also run to assess how Rh was affected by changes in soil physical properties and management i.e. SOC, pH and WT depth. SOC and pH were altered over a range from -50 to +50% with an increment of 10% whilst WT was lowered up to 50 cm with an increment of 10 cm.

2.5 Statistics and Model validations

Statistical analyses were carried out using the PRISM (GraphPad, San Diego CA, USA) software package. 1-way analysis of variance (ANOVA) was applied to compare the mean annual EC-derived Rh of different sites. Annual cumulative Rh for model outputs were calculated as the sum of simulated daily fluxes (Cai et al., 2003). Multi-criteria evaluation of the EOSSE model was applied to identify how well it predicted EC-derived Rh. Comparisons of simulated with EC-derived Rh were undertaken for each site separately. Analysis was carried out to detect the coincidence and association between measured and simulated values, following methods described in Smith et al. (1997) and Smith and Smith (2007). Model accuracy and performance were evaluated by calculating the relative deviation (RD), regression coefficient (r^2) to measure correlation, root mean square error (RMSE) to measure total error, and relative error (RE) to measure bias. The Model Efficiency (ME; Nash and Sutcliffe, 1970) compares the squared sum of the absolute error with the squared sum of the difference between the observations and their mean value. It compares the ability of the model to reproduce the daily data variability with a much simpler model that is based on the arithmetic mean of the measurements. Negative ME value shows a poor performance, a value of 0 indicates that the model does not perform better than using the mean of the observations, and values close to 1 indicate a ‘near-perfect’ fit (Nash and Sutcliffe, 1970; Huang et al., 2003).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad (2)$$

$$\mathrm{RE} = \frac{100}{n}\sum_{i=1}^{n}\frac{(P_i - O_i)}{O_i} \qquad (3)$$

$$ME = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (4)$$

O_i is the observed value, P_i is the simulated value, *n* are the total number of observations and *i* the current observation.

3 Results

3.1 EC-derived Rh

Seasonal and annual changes in temperature and precipitation at the experimental sites, in the period 2002-2010, are shown in Appendix 1. The temperatures and precipitation totals showed significant variation between years at each site and between sites. However, R_{eco} for all sites were strongly correlated with annual precipitation ($y = 0.66x + 49.8$; $r^2 = 0.42$) and temperature ($y = 212e^{0.12x}$; $r^2 = 0.72$) as shown in Figure 2. The dynamics of EC-derived daily Rh followed these seasonal and annual patterns of temperature and precipitation, in addition to management and vegetation type (Figure 3). However, in all cases, the highest peak of Rh was recorded during the late summer and autumn, whilst the lowest emissions were measured during cold periods in the winter (Appendix 1 and 3). Overall, across sites, the flux ranged from 0 to 4 g C m^{-2} d^{-1}. The annual average daily fluxes for each site were 0.85 g C m^{-2} (Auchencorth Moss), 1.60 g C m^{-2} (Horstermeer), 0.69 g C m^{-2} (Fäjemyr), 0.34 g C m^{-2} (Degerö Stormyr), 0.31 g C m^{-2} (Kaamanen) and 0.48 g C m^{-2} (Lompolojänkkä) (Table 3), which equates to average annual calculated Rh between 110 to 559 g C m^{-2} (Table 4). Generally, the maximum annual Rh occurred when the WT level was between -10 and -25 cm and the average annual air temperature was above 6.2°C. Annual Rh values at the sites were significantly different from each other ($p<0.05$) (Table 4).

3.2 ECOSSE model simulation and evaluation

The ECOSSE model was evaluated by comparing the outputs to the EC-derived Rh fluxes from the six sites described in Section 2.1. Relationships between Rh estimated from measured NEE and modelled Rh are shown in Figure 3. In all cases, ECOSSE was able to predict the timing of the Rh peaks correctly (Figure 3). The regressed relationships between the daily measured and predicted values of Rh are shown in Figure 4. Generally, the model was able to predict seasonal trends in Rh at most of the sites with r^2 ranging from 0.28 to

0.76. However, the model often over / under-estimated the flux values during the warm weather in spring and summer. The differences in Rh between the daily EC-derived and simulated values were compared by calculating RMSE and RE as shown in Table 3. The RMSE values ranged from 0.23 to 1.10 g C m^{-2} d^{-1} (Table 3). The RE ranged from -31 to +26 and the model efficiency from -0.25 to +0.41. The cumulative annual simulated Rh at most of the sites agreed reasonably with the EC-derived values (Table 4), where the RD ranged from -38 to +38% showing variable performance for individual sites, but an overall RD of -1% indicates overall good fit. The modelled Rh at these peatland sites and the estimated Rh using the Hardie et al (2009) are close, despite the latter being a relatively crude method to estimate Rh from R_{eco}, thus providing a challenging test for the model.

3.3 Attribution and model sensitivity

The ECOSSE sensitivity / attribution analysis reveals similar responses to input factors at almost all sites (Figure 5). The Rh flux increased with increasing (decreased with decreasing) mean daily air temperature, depth to WT, SOC and soil pH but decreased with increasing (increased with decreasing) annual precipitation. Significant increases in Rh fluxes, of 30% to 224% and 60% to 142% were calculated when SOC and temperature were increased by 50%, respectively. Decreasing SOC by 50% decreased the flux by 29% to 68% and decreasing temperature by 50%, compared to present temperature, decreased the flux by 41% to 61%. Increasing the precipitation by 50% compared to present precipitation, decreased Rh by 7% to 51% whilst decreasing the precipitation by 50% increased the flux by 4% to 90%. Lowering WT by 50 cm increased Rh by >130% whilst a 50% higher pH, increased the flux by 22% to 120%, and a 50% lower pH decreased the flux by 74% to 79%.

4 Discussion

4.1 EC-derived Rh

In this study, Rh from the six investigated peatland sites varied due to differences in climates, vegetation types and management (Table 1; Appendix 1). Previous studies using the same data sets reported that the fluxes were controlled by a set of parameters including temperature, ground water level and plant biomass and growth (Aurela et al., 2002; Hendricks et al., 2007; Lund et al., 2007; Aurela et al., 2009; Dinsmore et al., 2009; Sagerfors et al., 2008). Nevertheless, these ecosystem processes are different from one site to another and difficult to describe using simple linear models (Lloyd, 2006; Lund et al., 2010). The higher Rh, from the investigated sites, during the late summer and autumn was mainly due to the high soil temperature and moist soil conditions during this period (Appendix 1 and 3). Higher air temperature also affects evapotranspiration rate and has a direct effect on Rh (Christensen et al., 1999). In this study, higher annual Rh was mostly reported at sites of higher average annual temperature and lower WT depth (Tables 1 and 4). In a meta-analysis, Yi et al. (2010) found that the sensitivity of NEE to mean annual temperature stops at ∼16◦C, above which CO_2 uptake was not sensitive to temperature and the influence of soil moisture, overrides the influence of soil temperature. In a study by Lindroth et al. (2007), in northern Europe, the southernmost, warmest, site (Fäjemyr in the present study) was found to have the highest ecosystem respiration and highest GPP as compared to the northernmost, coldest site (Kaamanen in the present study).

Water table plays an important role in plant community structure, peat accumulation, and decomposition dynamics of OM (Reiley and Page, 2005; Wu et al., 2013). When WT level is near to the surface, the decomposition of OM within the peat profile is constrained by low O_2 availability resulting in low Rh. A high WT causes anaerobic conditions which are unfavourable for oxidation of soil OM and plant debris (Hendricks et al., 2007). Management practices, such as drainage, restoration, re-wetting, peat extraction and grazing also influence the flux. Drainage increases CO_2 from peat decomposition, whilst restoration and re-wetting decrease the flux (Van Huissteden et al., 2006). Peat extraction leads to on-site flux from peat deposits during the extraction phase and off-site flux due to the use of peat, either for producing energy or for agricultural uses (IPCC, 2006). In the UK, grazing and trampling of peat soils have been shown to alter C exchange gas and GHG emissions (Ward et al., 2007; Clay and Worrall, 2013).

4.2 ECOSSE simulations and evaluation

Evaluation of the ECOSSE model showed that it was able to predict broad seasonal and annual changes in Rh from the peatland sites (Figure 3), despite use of a simple generic method to estimate “measured Rh” from R_{eco}. Although some studies reported differences in ecological responses to climatic drivers between fens and bogs (Sulman et al 2010, Humphreys et al 2006, Lund et al 2010), we considered the differences between them negligible due to the lack of comparative studies. We applied Hardie et al. (2009) approach, which was the only available method at the time of this study, to partition autotrophic and heterotrophic respiration from both fens and bogs sites. The ECOSSE was able to predict seasonal trends in Rh at most of the sites with r^2 ranging from 0.28 to 0.76. The model satisfactorily simulated seasonal trends for Auchencorth Moss, Fäjemyr, Lompolojänkkä and Kaamanen with RE ranging from -13 to +13. However, for Horstermeer and Degerö Stormyr the model performance was poorer (RE was -31 and +26, respectively). Total model error values, as indicated by RMSE were small compared to daily mean fluxes and ME was positive for all sites except Horstermeer, revealing a reasonable fit between the measured and predicted fluxes for most of the measurement periods. The larger discrepancies between the predicted and EC-derived Rh values for Horstermeer and Degerö Stormyr resulted in higher RD values at the two sites however, the overall RD value for all sites was small (-1%) (Figure 3; Table 4). Generally, predicted results agree well with the annual EC-derived Rh estimated from fluxes measured using the EC method (particularly considering the relatively crude estimate of Rh from R_{eco} using the Hardie et al (2009) method), with similar uncertainty estimations for both methods (Oren et al., 2006; Rannik et al., 2006). The ECOSSE model responded appropriately to changes in air temperature, timing of precipitation events, land use and system management, which have strong impacts on Rh. Both EC measurements and model simulations showed that Rh was clearly controlled by a combination of factors, as discussed in Section 4.1. The sensitivity test suggests that ECOSSE is capable of simulating responses of these ecosystems to field WT manipulations. Nevertheless, although the model results were reasonable, some limitations of the ECOSSE model are revealed, such as the lack of explicit peatland vegetation types in the model. Improving the plant parameters in ECOSSE will improve the utility of the model for spatially simulating GHG emissions from peatlands. Additionally, some processes like soil-root interactions and transport of labile carbon through the soil profile, which could affect decomposition, are not fully considered in ECOSSE, and more work on these is required.

4.3 Model sensitivity and attribution

Sensitivity analysis of the ECOSSE model showed that Rh from peat soils increased with increasing temperature. The model simulated a significant increase in Rh when temperature rose by up to 6°C. Therefore, the future C sink potentials of peatlands will be affected by changes in temperature and the hydrological cycles, in addition to higher nitrogen (N) deposition and levels of atmospheric CO_2 which would all be expected all increase C losses (Zhuang et al., 2003; Carrasco et al., 2006; Fan et al., 2008). Rh is sensitive to changes in SOC and pH. Increasing SOC increased Rh. In a simulation study using the Dynamic Organic Soil Terrestrial Ecosystem Model (peatland DOS-TEM), Fan et al. (2013) predicted that sequestration of SOC in a rich fen will become higher for the next 50 years. This is due to increased C uptake by the vegetation under a warmer climate. The increased Rh with increasing pH is in agreement with the findings of Bergman et al. (1999) and Ye et al. (2012) who suggested that low pH of a peatland ecosystem limited microbial metabolism. The sites we investigated had pH's range from 3.9 to 5.5.

The sensitivity analysis to water-table depth shows that lowering of the WT increases the Rh from these peat soils. Conversely, raising the WT reduced the Rh. The model results suggest that lowering WT, e.g. through drainage, could have a significant effect on Rh. Similar conclusions were drawn by Lund et al. (2012), who found that a temperate peatland (Fäjemyr in the present study) acted as an annual source for atmospheric CO_2 during years with prolonged periods of drought. Drainage increases oxidation and therefore increases CO_2 production from decomposing peat (Van den Bos, 2003; Van Huissteden et al., 2006), whilst re-wetting or restoration may reduce the flux (IPCC, 2006). However, following re-wetting, higher CH_4 flux is expected, which may (partially) counterbalance the reduction in CO_2 emissions.

Many studies have suggested that raising the WT to near the surface of the peat soils (i.e. reversal of drainage) is a suitable future solution for improving C sequestration in peatlands (Alm et al., 1999; Moore, 2002; Belyea and Malmer, 2004; Tarnocai, 2006, Aurela et al., 2007, Lund et al., 2012). However, converting arable land back to natural peatland vegetation (sometimes *via* grassland), reducing the intensity of land-use, or maintaining the ground WT to its original level may increase C sequestration in peatlands (Freibauer et al., 2004, Drösler et al., 2008).

5 Conclusions

In this study, Rh from six peatland sites was found to be controlled by a set of parameters, including temperature, vegetation and ground water level. Higher Rh was mostly reported at sites of higher average annual temperature and lower WT. Despite using rather simple methods to estimate Rh from R_{eco} measured by EC, the Rh from peatlands was reasonably well estimated using the ECOSSE model. The regression relationships (r^2) between the EC-derived and simulated Rh fluxes ranged from 0.28 to 0.76, RE and RMSE were small, and the model efficiency ranged from -0.25 to +0.41, revealing a reasonable fit, particularly considering the relatively crude method of estimating Rh from R_{eco}. The overall relative deviation (RD) value between the annual EC-derived and annual simulated Rh was small (-1%). The sensitivity analysis highlighted that increasing temperature, pH, SOC and lowering WT depth could significantly increase Rh, whilst higher annual precipitation decreased the flux. Thus, management which lowers the WT, such as drainage could significantly increase anthropogenic CO_2 emissions and therefore, alternative strategies at a regional level are required. The ECOSSE model can be applied to investigate the impacts of potential future land management strategies on peatland C emissions, and contribute to shape land-management decisions.

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Figure’s captions

Figure 1: Relative cover (%) of peat and peat-topped soils (0–30cm) in Europe (Adapted from Montanarella et al., 2006). Investigated sites are Auchencorth Moss (a), Horstermeer (b), Fäjemyr (c), Degerö (d), Kaamanen (e) and Lompolojänkkä (f).

Figure 2: Correlations between R_{eco} and annual temperature (a) and rainfall (b). For the annual temperature $y = 212e^{0.12x}$ and $r^2 = 0.72$; for annual rainfall $y = 0.66x + 49.8$ and $r^2 = 0.42$.

Figure 3: Eddy Covariance derived (Filled circle) and modeled (solid line) daily heterotrophic CO_2 (Rh) during the measurements period 2002-2010.

Figure 4: Regression relationships (1:1) between the Eddy Covariance-derived and modeled heterotrophic CO_2 (Rh) form Auchencorth Moss (a), Horstermeer (b), Fäjemyr (c), Degerö (d), Kaamanen (e) and Lompolojänkkä (f).

Figure 5: The attribution/ sensitivity response of the heterotrophic CO_2 (Rh) to variations in soil properties and climate input factors at Auchencorth Moss (a), Horstermeer (b), Fäjemyr (c), Degerö (d), Kaamanen (e) and Lompolojänkkä (f). Currently = model Rh at the present climate and soil parameters.

Figures

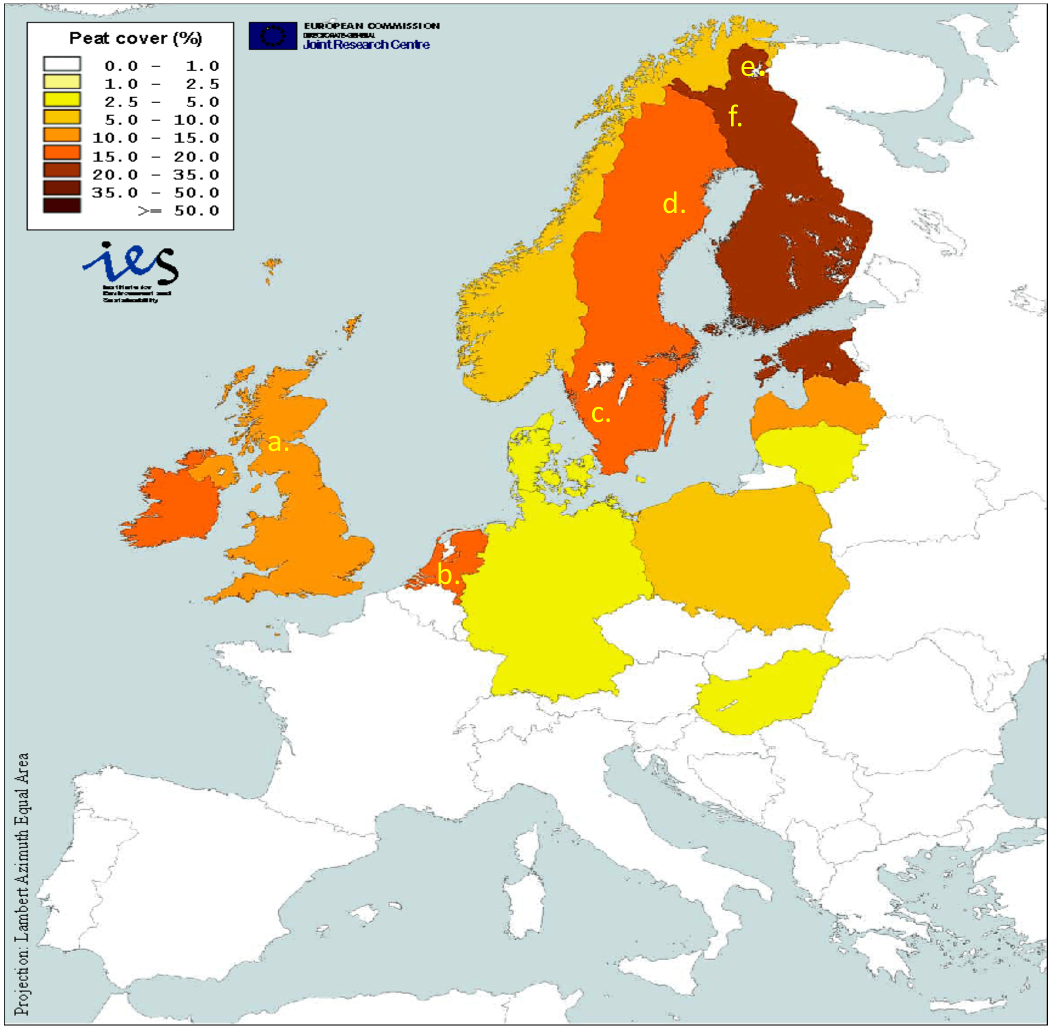


Figure 1: Relative cover (%) of peat and peat-topped soils (0–30cm) in Europe (Adapted from Montanarella et al., 2006).

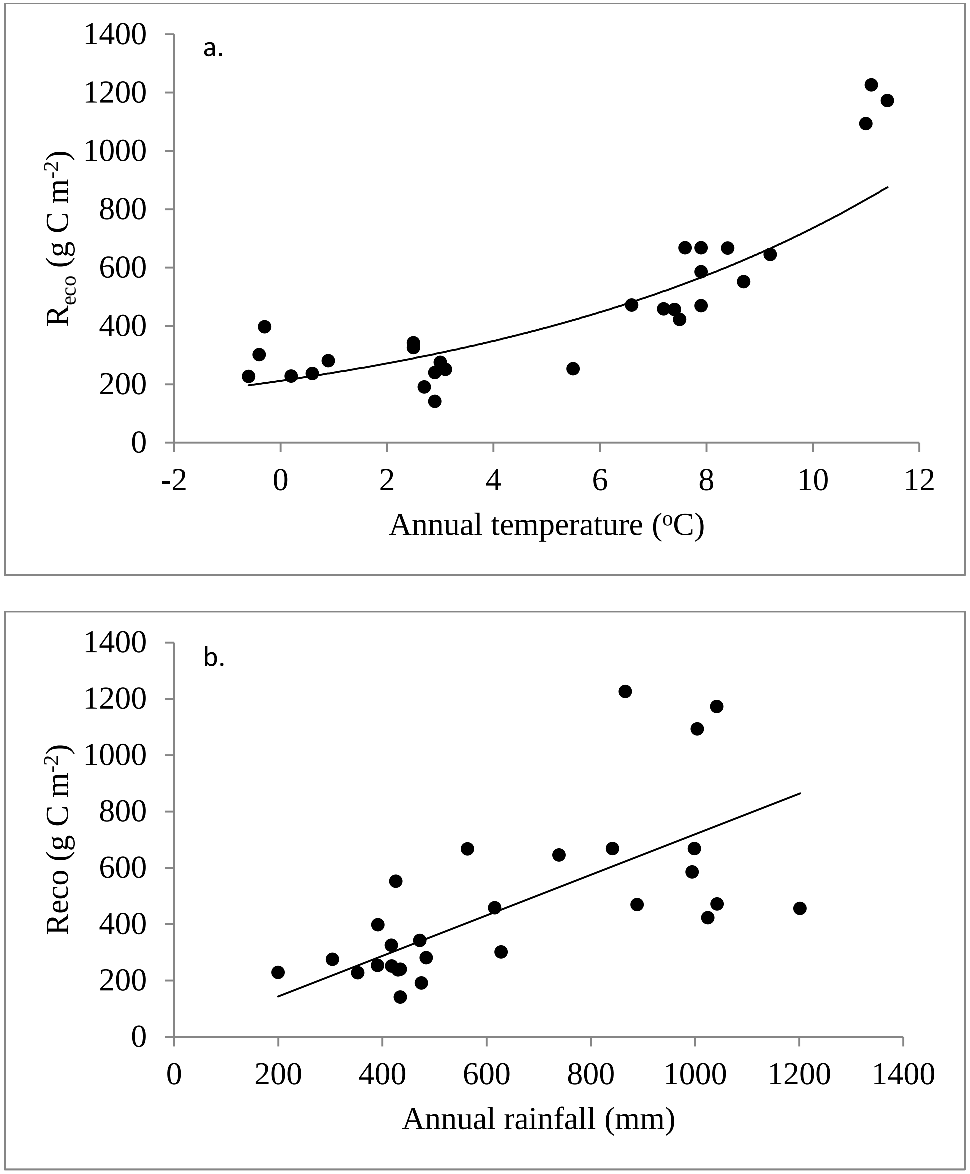
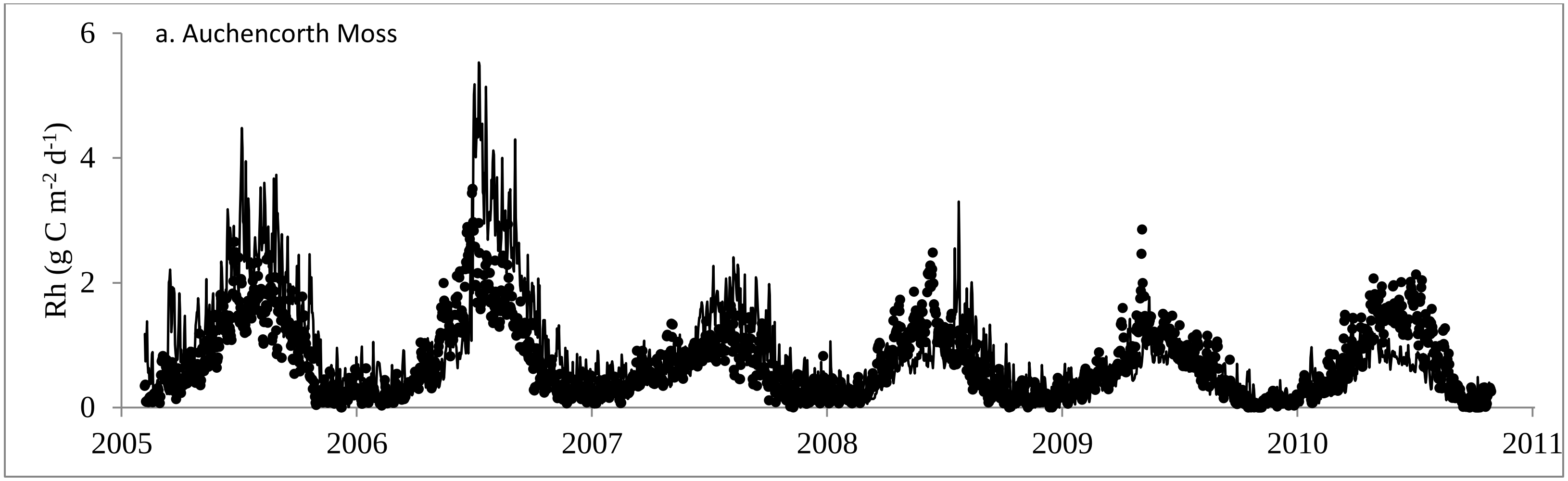
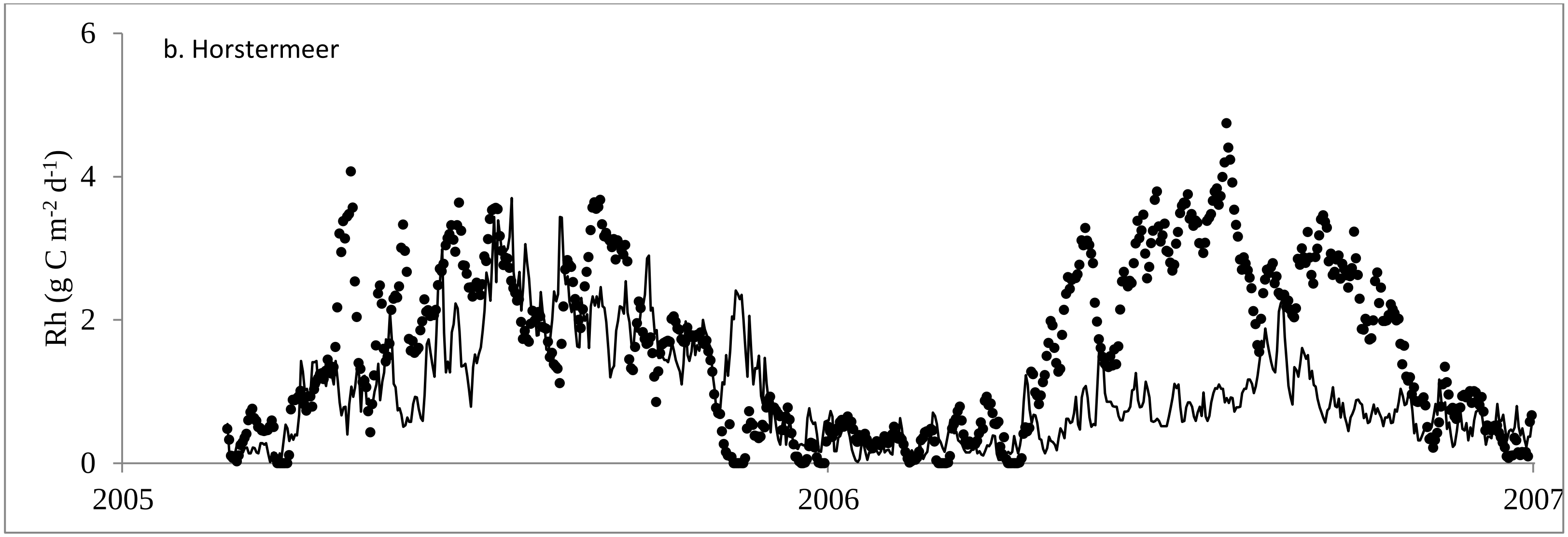
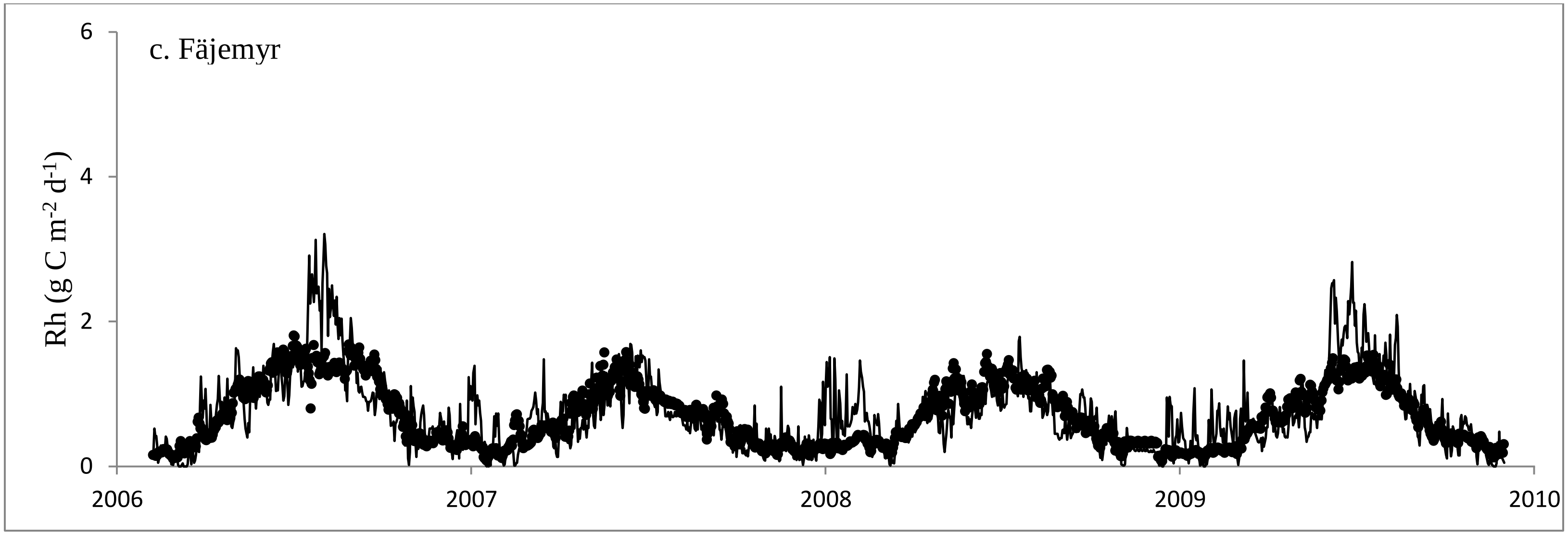
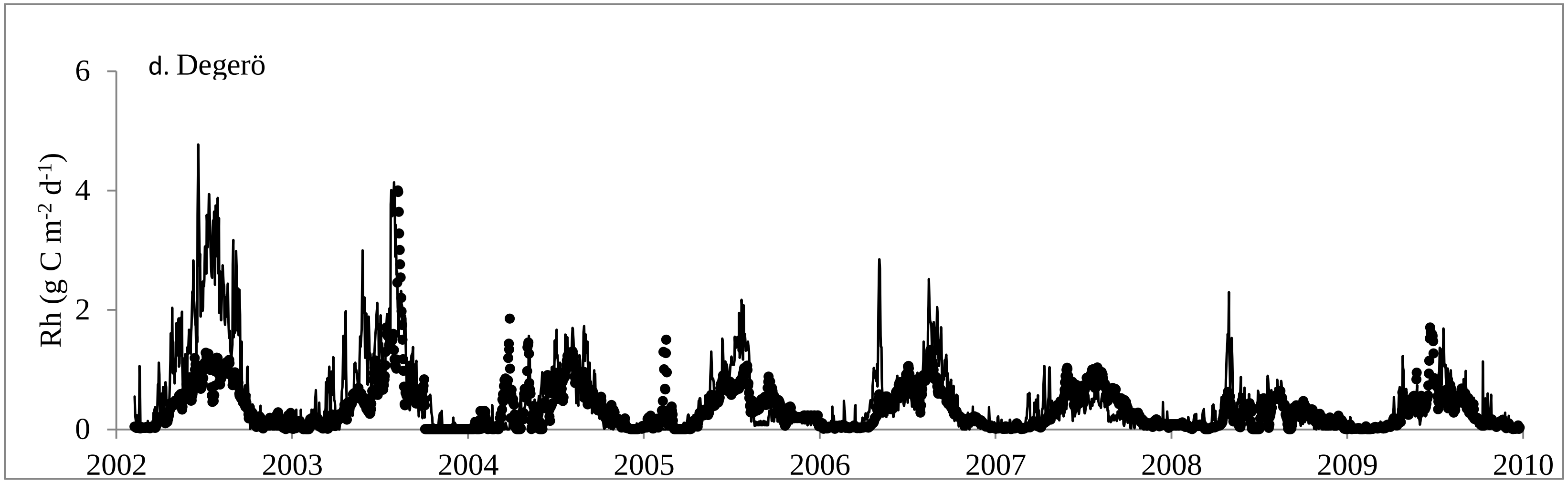


Figure 2: Correlations between R_{eco} and annual temperature (a) and rainfall (b).


a. Auchencorth Moss
Rh (g C m^{-2} d^{-1})
0
2
4
6
2005
2006
2007
2008
2009
2010
2011


b. Horstermeer
Rh (g C m^{-2} d^{-1})
0
2
4
6
2005
2006
2007


c. Fäjemyr
Rh (g C m-2 d-1)
6
4
2
0
2006
2007
2008
2009
2010


d. Degerö
Rh (g C m-2 d-1)
6
4
2
0
2002
2003
2004
2005
2006
2007
2008
2009
2010

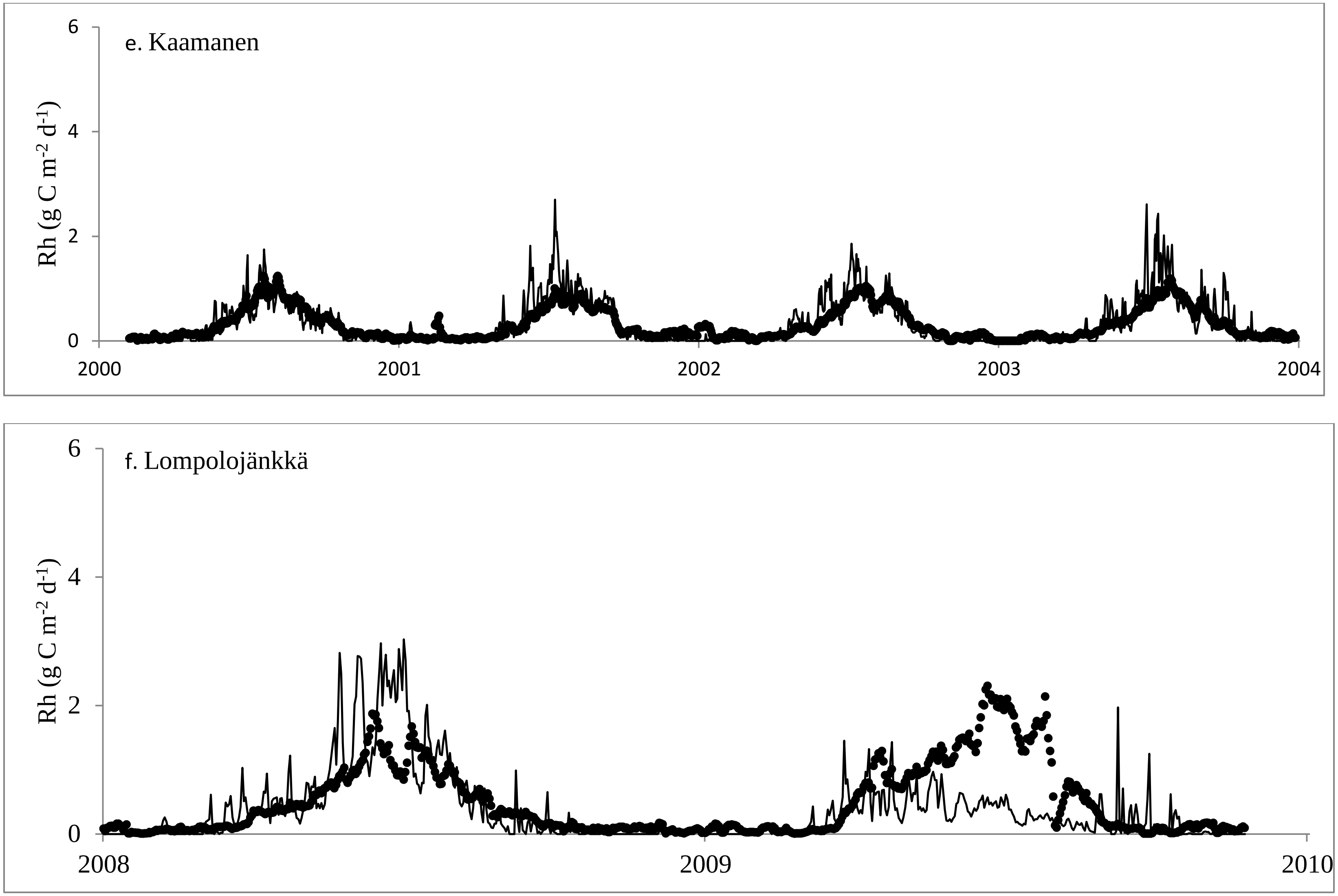
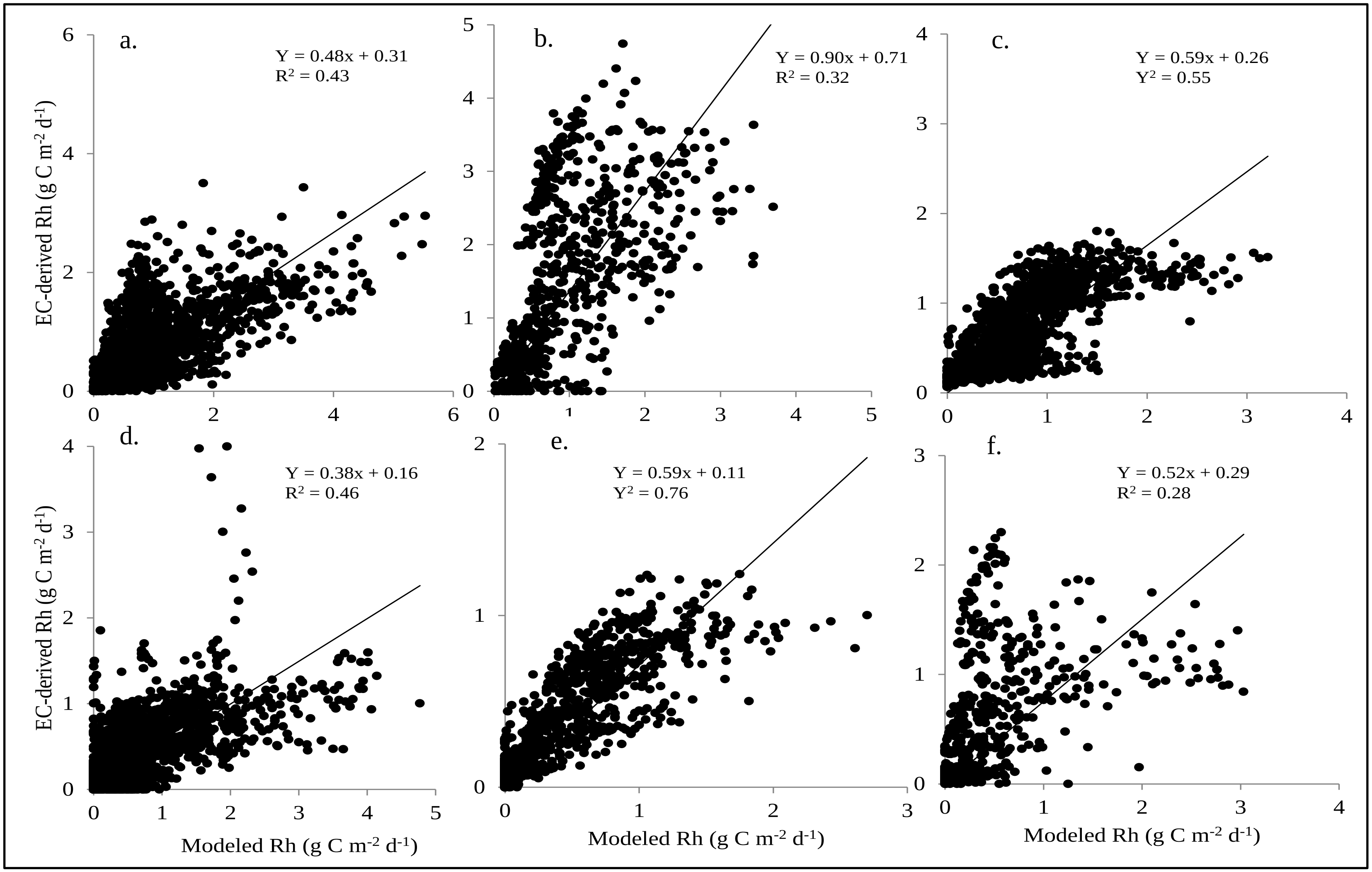


Figure 3: Eddy Covariance derived (Filled circle) and modeled (solid line) daily heterotrophic CO_2 (Rh).



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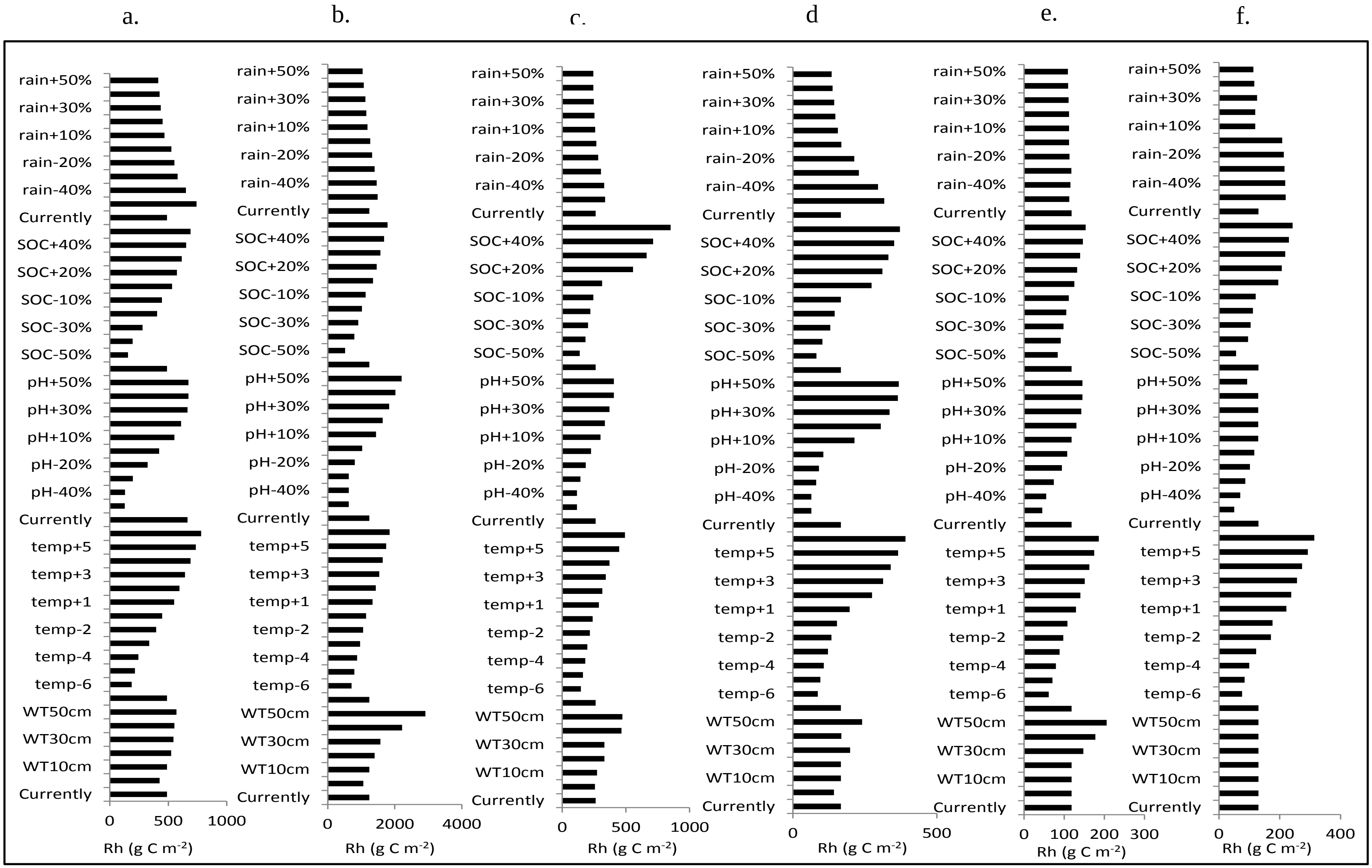

Figure 5: The attribution/ sensitivity response of the heterotrophic CO_2 (Rh) to variations in soil properties and climate input.

Tables

Table 1: Site coordinates, water table (WT) depth, type of peatland and management and annual mean climatic conditions.

Ecosystem/ location	Coordinates	WT depth (cm)	Peatland type	Management	Average Precipitation (mm)	Average temperature	Method of CO_2 flux measurements
Auchencorth, UK*	55^{o}79’N, 3^{o}24’W	0-25	Bog	drainage ditches, restored; sheep grazing	1155	10^{o}C	EC (closed path) (Li-COR 7000 IRGA)
Horstermeer, NL	52^{o}15’N, 05^{o}05’	0-10	Fen	restored; nature reserve	800	9.8^{o}C	EC (open path) (Li-COR7500)
Fäjemyr, SWE	56^{o}25’N, 13^{o}33’E	0-16	Bog	natural mire	700	6.2^{o}C	EC (closed path) (Li-COR 6262 IRGA)
Degerö, SWE	64^{o}18’N, 19^{o}55’	5-15	Fen	natural mires.	523	1.2^{o}C	EC (closed path) (Li-COR 6262 IRGA)
Kaamanen, FIN	69^{o}14’N, 27^{o}17’E	0-10	Fen	natural mire	441	0.4^{o}C	EC (closed path) (Li-COR 7000 IRGA)
Lompolojänkkä, FIN	67^{o}59’N, 24^{o}12’E	0-10	Fen	natural mire	484	-1.4^{o}C	EC (closed path) (Li-COR 7000 IRGA)

*UK is United Kingdom; NL is the Netherlands; FIN is Finland and SWE is Sweden.

Table 2: Characteristics of the peatland soils (histosol).

Ecosystem and location	Peat depth (m)	Bulk density (g cm^{-3})	pH	Estimated soil organic matter to 50 cm depth (t C ha^{-1})
Auchencorth, UK*	0.5-5	0.2	4.2	512
Horstermeer, NL	2	0.5	5.3	621
Fäjemyr, SWE	4-5	0.4	3.9	810
Degerö, SWE	3-4	0.1	3.9	450
Kaamanen, FIN	1-2	0.1	4.5	240
Lompolojänkkä, FIN	2-3	0.1	5.5	190

*UK is United Kingdom; NL is the Netherlands; FIN is Finland and SWE is Sweden.

Table 3: Measurement period, average daily measured and modeled heterotrophic CO_2 (g C $m^{-2}d^{-1}$), root mean square error (RMSE) (g C m^{-2} d^{-1}), regression coefficient (R^2), relative error (RE) and model efficiency (ME) for the peatland sites.

Site	Measurement period	EC-derived Rh*	Modelled Rh	RMSE	R^2	RE	ME
Auchencorth	2005-2010	0.85	0.71	0.60	0.43	+13	+0.38
Horstermeer	2005-2006	1.60	0.97	1.10	0.32	-31	-0.25
Fäjemyr	2006-2009	0.69	0.74	0.36	0.55	+5	+0.23
Degerö	2002-2009	0.34	0.46	0.44	0.46	+26	+0.41
Kaamenen	2000-2003	0.31	0.33	0.23	0.76	+7	+0.11
Lompolojänkkä	2008-2009	0.48	0.37	0.54	0.28	-13	+0.04

* derived from NEE measured by Eddy Covariance and then partitioned into GPP and Reco. Reco was then further partitioned into autotrophic and heterotrophic (Rh) respiration respectively according to Hardie et al. (2009).

Table 4: Statistical analysis of annual heterotrophic CO_2 respiration (Rh; g C $m^{-2}y^{-1}$) for the peatland sites during the experimental period (2002-2010). RD is the average relative deviation between the measured and annual modeled flux. Different letters in the column mean that Rh values are significantly different ($p<0.05$). n is the number of years.

Site	Measured Rh	Modeled Rh	n	RD (%)
Auchencorth	256a	305	6	+19
Horstermeer	540b	334	2	-38
Fäjemyr	312d	262	4	-6
Degerö	121f	167	8	+38
Kaamenen	110e	118	4	+8
Lompolojänkkä	166c	129	2	-22