



## Abstract

The carbon dioxide (CO<sub>2</sub>) exchange of five different peatland systems across Europe with a wide gradient in landuse intensity, water table depth, soil fertility and climate was simulated with the process oriented CoupModel. The aim of the study was to find out to what extent CO<sub>2</sub> fluxes measured at different sites, can be explained by common processes and parameters implemented in the model. The CoupModel was calibrated to fit measured CO<sub>2</sub> fluxes, soil temperature, snow depth and leaf area index (LAI) and resulting differences in model parameters were analysed. Finding site independent model parameters would mean that differences in the measured fluxes could be explained solely by model input data: water table, meteorological data, management and soil inventory data.

The model, utilizing a site independent configuration for most of the parameters, captured seasonal variability in the major fluxes well. Parameters that differed between sites included the rate of soil organic decomposition, photosynthetic efficiency, and regulation of the mobile carbon (C) pool from senescence to shooting in the next year.

The largest difference between sites was the rate coefficient for heterotrophic respiration. Setting it to a common value would lead to underestimation of mean total respiration by a factor of 2.8 up to an overestimation by a factor of 4. Despite testing a wide range of different responses to soil water and temperature, heterotrophic respiration rates were consistently lowest on formerly drained sites and highest on the managed sites. Substrate decomposability, pH and vegetation characteristics are possible explanations for the differences in decomposition rates.

Applying common parameter values for the timing of plant shooting and senescence, and a minimum temperature for photosynthesis, had only a minor effect on model performance, even though the gradient in site latitude ranged from 48° N (South-Germany) to 68° N (northern Finland). This was also true for common parameters defining the moisture and temperature response for decomposition.

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CoupModel is able to describe measured fluxes at different sites or under different conditions, providing that the rate of soil organic decomposition, photosynthetic efficiency, and the regulation of the mobile carbon (C) pool are estimated from available information on specific soil conditions, vegetation and management of the ecosystems.

## 1 Introduction

In recent years, many datasets have been collected from a number of sites and across multiple years, containing detailed and high resolution measurements of carbon (C) fluxes, plant and soil characteristics, meteorological and water table data (Baldocchi et al., 2001; Baldocchi, 2007). Several of the measured sites are peatlands, which have accumulated vast amount of C since the last deglaciation. Under drained conditions, peatlands have a high carbon dioxide (CO<sub>2</sub>) emission potential (e.g. van den Bos, 2003; Lohila, 2004; Drösler et al., 2008; Maljanen et al., 2010). Understanding the processes driving CO<sub>2</sub> emissions is essential in the development of management practices to reduce greenhouse gas emissions.

Direct comparison of measured data can be used to explore the effect of single variables if the site conditions are similar or differ only in few variables, e.g. in manipulation experiments (Chivers et al., 2009; Ward et al., 2013) or different vegetation types at the same site (e.g. Chojnicki et al., 2010). However, the sites in this study have different characteristics with respect to climate, hydrology, management, vegetation and soils. Direct site comparisons of measured flux data (e.g. Alm et al., 1999; Humphreys et al., 2006; Lund et al., 2009; Drewer et al., 2010) are often uninformative when trying to distinguish between responses of several individual factors. Typically multiple factors are linked and interact with each other complicating the analysis. Therefore, important drivers at one site might not play a significant role on another site (e.g. Lafleur et al., 2005). Process oriented modelling provides a method to identify to what extent observations at different sites can be described by the same processes, while accounting for such interactions.

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Process oriented modelling requires (1) that the model can describe the observations and (2) that the parameters used in the model to describe the observations can be estimated from available data. Typically studies focus on demonstrating how well the model can describe a certain set of data (e.g. van Huissteden et al., 2009; Calanca et al., 2007; Frolking et al., 2001; St-Hilaire et al., 2010). In contrast, the focus of this study was exploring differences between the sites while model performance was subordinate. Process oriented models often require a large number of input parameters which are typically difficult to estimate based on available data from less intensively investigated sites (Juston et al., 2010). Parameters may interact with each other and the available information does not allow a single or unambiguous mathematical solution (Beven and Freer, 2001; Beven, 2006; van Oijen et al., 2013). However, for all sites in this study, accurate gas flux measurements in combination with detailed measurements of soil and plant conditions were available. Such extensive measurements have been demonstrated to be useful in identifying the governing properties for specific sites. For example the modelling of CO<sub>2</sub> from forest sites has shown that dynamics of CO<sub>2</sub> fluxes are restricted to a certain range of parameter values (Wu and Jansson, 2013; Wu et al., 2013).

A systematic evaluation of one model against data from multiple sites with a common set of parameters will allow a better understanding of processes not only at the individual sites but also on the site-specific differences which control the resulting fluxes (e.g. Calanca et al., 2007; van Huissteden et al., 2006; van Huissteden et al., 2009). This is a necessary precondition for accurate predictions of CO<sub>2</sub> fluxes under different climate scenarios or at different locations. On peatlands, some attempts have been made to consider site differences using simplified process models on national (e.g. ECOSSE, Bell et al., 2012) and global scales (e.g. InTec, Ju and Chen, 2005; McGill, St-Hilaire et al., 2010) and up to millennial timescale (Schuldt et al., 2013).

Many carbon ecosystem models have been run on site scale such as Biome-BC (Feng et al., 2011), DNDC (Li et al., 1992a, b; Dietiker et al., 2010), PaSim (Calanca et al., 2007), PIXGRO (Adiku et al., 2006), CANDY (Franko et al., 1997), DAYCENT

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(CENTURY) (Del Grosso et al., 2005). Some models were explicitly created or adapted to peatlands such as PDM (Frolking et al., 2001), PCARS (Frolking et al., 2002), CASA (Potter et al., 2001), NASA-CASA (Del Grosso et al., 2005), *ecosys* (Grant et al., 2012), wetland-DNDC (Zhang et al., 2002), peatland DOS-TEM (Fan et al., 2013), PEATLAND-VU (van Huissteden et al., 2006) or GUESS-ROMUL (Yurova et al., 2007).

In this work the CoupModel was used, which is a detailed process oriented model coupling heat and mass transfer for soil–plant–atmosphere systems (Jansson and Karlberg, 2010). The model was designed for a wide range of soil types and different ecosystems and applications (see Jansson, 2012 for review). It is capable of simulating CO<sub>2</sub> (Klemmedtsson et al., 2008), nitrous oxide (N<sub>2</sub>O) (Norman et al., 2008) and methane (CH<sub>4</sub>) fluxes (Ravina, 2007). The CoupModel combines the advantages of an hourly time step, necessary for analysing e.g. chamber flux data and detailed sub modules for predicting plant growth and respiration, soil nitrogen (N) and C processes, energy and heat fluxes, soil temperature, soil frost and snow depth. The CoupModel also allows the user to select between different sub models and access all parameters via a user interface. An extensive model description can be found in Jansson and Karlberg (2010).

The main aim of this study was to extend the knowledge on ecosystem modelling of peatlands by applying and calibrating the process oriented CoupModel to five data rich European flux measurement sites. Specific objectives were:

- I. to identify differences and similarities in CO<sub>2</sub> related processes between various sites which largely differ in their forcing data.
- II. to identify problems related to the model representation of the different ecosystem processes for peatlands.
- III. to identify and discuss the impact of available data for estimating CO<sub>2</sub> fluxes from peatlands in general.

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## 2 Methods

### 2.1 Description of sites and investigations

The CoupModel was applied to five treeless peatland sites with a wide gradient in land use intensity, water level, soil nutrient status and mean annual temperature (Table 1). Together with the climatic gradient from North-Finland to South-Germany and a different growing season this leads to great differences in amplitude and dynamics of gross primary productivity (GPP), ecosystem respiration ( $R_{\text{eco}}$ ) and different amounts of biomass. This is reflected in the annual accumulated NEE based on measurements, ranging from  $-364 \text{ g C m}^{-2} \text{ a}^{-1}$  to  $592 \text{ g C m}^{-2} \text{ a}^{-1}$  (Fig. 1).

Dynamic forcing data for model input (water table and meteorology) was available from measurements at all sites (Table S1 in the Supplement). Data used for model parameter constraint included measurements of LAI, soil temperature and NEE (Table S2 in the Supplement). Measured NEE was partitioned into  $R_{\text{eco}}$  and GPP by the use of empirical models based  $R_{\text{eco}}$  from night time NEE or opaque chambers. Though this will be called measured data in the following.

The northernmost site, Lompolojännkä fen (Lom), located in Finland is a nutrient rich natural mire with sedges, shrubs and mosses. Mean air temperature from 2006 to 2010 was  $-1.4^\circ\text{C}$  and the mean groundwater table during the snow-free season was close to the peat surface. Data for model calibration were available from 2006 to 2010 and consisted of eddy covariance (EC) and automatic chamber data of  $\text{CO}_2$  fluxes, snow depth and leaf area index (LAI) measurements. A detailed description of the site and measurement methods can be found in Aurela et al. (2009), Drewer et al. (2010) and Lohila et al. (2010).

The Scottish site, Auchencorth Moss (Amo) is an ombrotrophic bog, with vegetation consisting of grasses, sedges and soft rushes, covering a primarily Sphagnum base layer. The site is managed for low intensity sheep grazing with less than one livestock unit per hectare, but this was not accounted for in the model. Amo encompasses a small area of peat extraction in the south west of the catchment, which is unlikely to fall within

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the flux footprint of the EC system. The site was drained over a century ago, however, the drains are no longer considered to be in operation. The mean water table was  $-12.5 \text{ cm}$  between 2006 and 2010. Mean temperature during this period was  $10^\circ\text{C}$ ,  $\text{CO}_2$  data from EC during the same period was used for model calibration. A detailed description of the site and measurements can be found in Helfter et al. (2014), Drewer et al. (2010) and Dinsmore et al. (2010).

Horstermeer fen (Hor) is located in the Netherlands in a drained natural lake. It used to be agricultural land, but was abandoned more than 15 years ago. The water table was raised during restoration leading to a mean value of  $-10 \text{ cm}$  during the simulation period from 2004 to 2010. It became a semi-natural grassland, a nature reserve without any mowing management. The vegetation is very heterogeneous with reed, grass and small shrubs (Hendriks, 2009). The mean temperature during the simulation period was  $10^\circ\text{C}$ .  $\text{CO}_2$  fluxes were measured half hourly by EC and biweekly with opaque chambers between 2004 and 2010. A detailed description of the sites and measurements methods can be found in Hendriks et al. (2007).

Freisinger Moos (FsA and FsB) is a drained nutrient rich fen in the south of Germany: the two sites FsA and FsB lie next to each other in a drained sedge meadow which was cut once per year. The mean annual hay yield was  $4.19$  or  $4.07 \text{ t dry weight ha}^{-1} \text{ a}^{-1}$  for FsA and  $5.67$  or  $6.17 \text{ t dry weight ha}^{-1} \text{ a}^{-1}$  for FsB for the years 2010 and 2011, respectively. FsB is located in a small depression with a mean water level of  $-20 \text{ cm}$  compared to  $-25 \text{ cm}$  for FsA during the years 2007 to 2011. Mean temperature during this period was  $7.5^\circ\text{C}$ . FsB contains mainly tall sedges with little reed while FsA is vegetated by a mixture of sedges, grasses and herbs. Manual transparent and opaque chamber data of  $\text{CO}_2$  fluxes ( $n = 3$  for each plot), measured several times a day every 3 to 4 weeks and half hourly meteorological data were available for the time period of 2007 to 2011. A detailed description of chamber configuration, measurement technique and empirical model approach were given in Drösler (2005), Beetz et al. (2013) and Leiber-Sauheittl et al. (2014). Measured  $R_{\text{eco}}$  and empirical modelled GPP during measurement period of each measurement day were used for parameter constraint,

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## 2.2.4 Vegetation

Vegetation was simulated according to the explicit big leaves concept (e.g. Dai et al., 2004) but only one plant canopy layer, representing the complete plant community was defined. Albedo, LAI and vegetation height were simulated. Permanent, perennial  
5 vegetation was configured with maximal plant height of 0.6 m and lowest root depth of  $-0.6$  m. Grain development was assumed to play a minor role and was therefore disabled. Plant respiration was assumed to be depended on growth and maintenance (e.g. Hansen and Jensen, 1977).

For leaf assimilation, the light use efficiency approach (Monteith, 1972; Monteith and Moss, 1977; see e.g. Hilker et al., 2008 for review) was used, at which total plant growth  
10 is proportional to the global radiation absorbed by canopy but limited by unfavourable temperature and limited soil water. For simplicity plant assimilation was simulated independent of dynamics in N availability. This might be justified as none of the sites was fertilized in the recent years and the vegetation community was assumed to be adapted  
15 to the nutrient conditions at each site. Differences in N availability between sites are included in the radiation efficiency ( $\epsilon_L$ ). Plants were assumed to be well adapted to wet conditions, including aerenchyma to tolerate water saturated soil conditions. Plant stress due to high water saturation was therefore disabled.

Plant development started every spring when the accumulated sum of air temperatures above a threshold value ( $T_{\text{EmergeTh}}$ ) reached the value of  $T_{\text{EmergeSum}}$ . Both parameters were calibrated (Table S4, in the Supplement). The accumulation of temperatures started when the day length exceeds 10 h. Snow cover hindered shooting by reducing the radiation passing through to the plant, while low soil temperatures reduced plant water uptake. Five consecutive days in the autumn with day lengths shorter than 10 h  
20 and with temperatures below  $T_{\text{DormTh}}$  terminated the growing season and plants went to dormancy.

Beside a small amount of litter fall occurring during the whole plant growth period (Robson, 1973; Duru and Ducrocq, 2000; Fulkerson and Donaghy, 2001), senescence

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was assumed to start after the plant reached maturity and therefore depended on growth stage (e.g. Thomas and Stoddart, 1980) and temperature sums (e.g. Davidson and Campbell, 1983). As this was not yet directly supported by the model, the stem pool was used for brown, senescent, standing biomass. Therefore new assimilates were constantly allocated to roots and leaf only, while existing leaf biomass was  
5 reallocated after maturity to the stem pool. A third stage of litter fall was configured depending on a minimum threshold temperature sum for dormancy. During litter fall part of the C is stored in a mobile pool, which can be then reused for shooting in the next year (e.g. White, 1973; Wingler, 2005).

Harvest took place at FsA and FsB. Based on observations in the field, 85 % of the above ground plant material was removed at harvest. Harvest dates were known and implemented in the model. After harvest the growth stage was allowed to be reset to a lower value (e.g. Thomas and Stoddart, 1980). Reallocation of C from root to leaves could take place like reported for e.g. *Festuca pratensis* (Johansson, 1992, 1993).  
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### 2.2.5 Independent approach to find values of site specific parameters

Dry and wet N deposition, latitude and thickness of the organic layer were used as constant site specific input.

The soil profile was divided into several layers with different depths. To each layer water retention, hydraulic conductivity, initial organic N, C : N and pH parameters were  
20 assigned according to soil data from each site. Total soil organic carbon (SOC) per layer was attributed to SOC pools on the basis of their C : N ratio whereas C : N ratio of the slow decomposing pool was assumed to be 10, while for the fast pool 27.5 was chosen according to measured C : N of leaf tissues at FsA and FsB (Table 3).

## 2.3 Parameter calibration approach

The aim of the calibration was to find out to what extent the same parameter values could be used for all sites compared to a site specific representation. A stepwise  
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**Table 1.** Site characteristics.

Code	Lom	Amo	Hor	FsA and FsB
Country	Finland	UK	Netherlands	Germany
Site name	Lompolojänkämä	Auchencorth moss	Horstermeer	Freisinger Moos
Area [m <sup>2</sup> ]	120 000	250 000	120 000	400
Latitude;	67°59'83" N;	55°47'34" N;	52°14'25" N	48°22'50" N
longitude	24°12'55" E	3°14'35" W	5°4'17" E	11°41'12" E
Peatland type	fen	bog	fen	fen
Dominant vegeta- tion	mosses, sedges, shrubs	grasses, sedges, soft rush, mosses	grass, reeds, small shrubs	sedges, herbs, grasses (A), tall sedges (B)
Landuse and management	natural mire	restored; grazed	restored; nature reserve	drained, 1 cut a <sup>-1</sup>
Mean temperature/range <sup>a</sup> [°C]	-1.4/-15-13	10/4-15	9.8/3-17	7.5/-2-17
Mean water table [cm]	+1.2	-12.5	~ -10	-25 (A) -20 (B)
Annual precipita- tion [mm]	484	1155	797	788
N deposition [kg ha <sup>-1</sup> a <sup>-1</sup> ]	8.13	1.59		7.1
Peat depth [m]	2-3	0.5-5	2	3
pH	5.5-6.0	4.4	4.8-6.0	5.5-6.7

<sup>a</sup> Annual range of mean monthly temperatures.

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**Table 2.** Abbreviations and symbols.

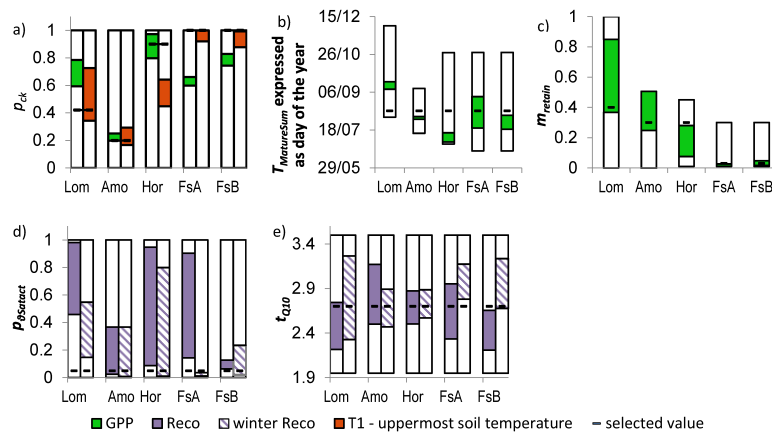
Abbreviation	Description
C	carbon
CO <sub>2</sub>	carbon dioxide
EC	eddy covariance
GHG	greenhouse gas
GPP	gross primary production
$k_{\text{gresp}}$	growth respiration coefficient
$k_h$	rate coefficient for the decay of the slow C pool
$k_f$	rate coefficient for the decay of the fast C pool
$k_{\text{mrespleaf}}$	maintenance respiration coefficient for leaves
$k_m$	extinction coefficient in the Beer law used to calculate the partitioning of net radiation between plant canopy and soil surface
LAI	leaf area index
ME	mean error
$m_{\text{retain}}$	coefficient for determining allocation to mobile internal storage pool
N	nitrogen
NSE	Nash-Sutcliffe efficiency
$p_{\text{ck}}$	speed at which the maximum surface cover of plants is reached
$p_{\theta\text{Low}}$	water content interval in the soil moisture response function for microbial activity, mineralisation-immobilisation, nitrification and denitrification
$p_{\theta\text{Upp}}$	water content interval in the soil moisture response function for microbial activity, mineralisation-immobilisation, nitrification and denitrification
$R^2$	coefficient of determination
$R_{\text{eco}}$	ecosystem respiration
SOC	soil organic carbon
$T_{\text{amean}}$	assumed value of mean air temperature for the lower boundary condition for heat conduction
$T_{\text{MatureSum}}$	temperature sum beginning from grain filling stage for plant reaching maturity stage
$T_{\text{DormTh}}$	critical air temperature that must be undershoot for temperature sum calculation
$T_{\text{EmergeSum}}$	air temperature sum that is the threshold for start of plant development
$T_{\text{EmergeTh}}$	critical air temperature that must be exceeded for temperature sum calculation
$t_{\text{Q10}}$	response to a 10 °C soil temperature change on the microbial activity, mineralisation-immobilisation, nitrification, denitrification and plant respiration
$t_{\text{Q10bas}}$	base temperature for the microbial activity, mineralisation-immobilisation, nitrification and denitrification at which the response is 1
$\varepsilon_L$	radiation use efficiency

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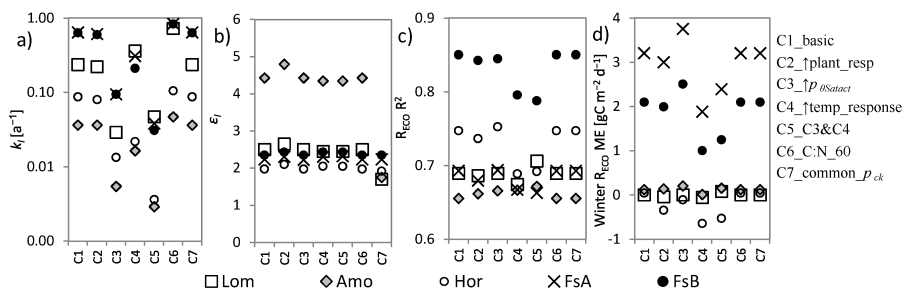






**Figure 5.** Obtained distributions of parameter values as constrained by additional multiple runs (calibration step III). Ranges for  $k_{11}$  and  $\varepsilon_L$  are not shown due to their interactions with several parameters. Coloured bars show the range of the 10 runs with the best performance for each validation variable. Prior ranges are indicated by the frame around the bar. Black dash is the value chosen for the common configuration C1.

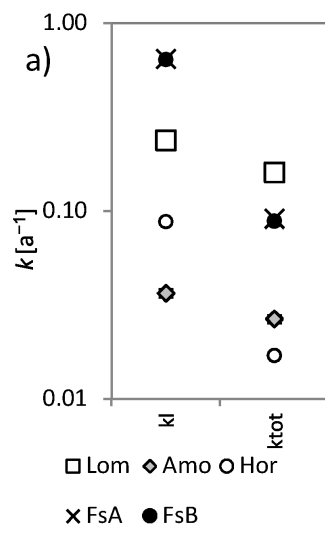
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**Figure 6.** Values for the parameters decomposition rate (a) and light use efficiency (b) and resulting model performance (c, d) when applying various single value representations of parameters (C1–C7, see Table S8 in the Supplement).

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**Figure 7.** Decomposition rates of fast pool ( $k_f$ ) and calculated rate of total organic matter if only one pool was used ( $k_{tot}$ ).