

1 **CO<sub>2</sub> fluxes and ecosystem dynamics at five European**  
2 **treeless peatlands – Merging data and process oriented**  
3 **modelling**

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18

19 ***Abstract***

20 The carbon dioxide (CO<sub>2</sub>) exchange of five different peatland systems across Europe with a  
21 wide gradient in landuse intensity, water table depth, soil fertility and climate was simulated  
22 with the process oriented CoupModel. The aim of the study was to find out whether CO<sub>2</sub>  
23 fluxes, measured at different sites, can be explained by common processes and parameters or  
24 to what extend a site specific configuration is needed. The model was calibrated to fit  
25 measured CO<sub>2</sub> fluxes, soil temperature, snow depth and leaf area index (LAI) and resulting  
26 differences in model parameters were analysed. Finding site independent model parameters

1 would mean that differences in the measured fluxes could be explained solely by model input  
2 data: water table, meteorological data, management and soil inventory data.

3 Seasonal variability in the major fluxes was well captured, when a site independent  
4 configuration was utilized for most of the parameters. Parameters that differed between sites  
5 included the rate of soil organic decomposition, photosynthetic efficiency, and regulation of  
6 the mobile carbon (C) pool from senescence to shooting in the next year.

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

14 Specific parameter values for the timing of plant shooting and senescence, the photosynthesis  
15 response to temperature, litter fall and plant respiration rates, leaf morphology and allocation  
16 fractions of new assimilates, were not needed, even though the gradient in site latitude ranged  
17 from 48°N (South-Germany) to 68°N (northern Finland) differed largely in their vegetation.  
18 This was also true for common parameters defining the moisture and temperature response for  
19 decomposition, leading to the conclusion, that a site specific interpretation of these processes  
20 is not necessary. In contrast, the rate of soil organic decomposition, photosynthetic efficiency,  
21 and the regulation of the mobile carbon (C) pool need to be estimated from available  
22 information on specific soil conditions, vegetation and management of the ecosystems, to be  
23 able to describe CO<sub>2</sub> fluxes under different conditions.

24

## 25 **1 Introduction**

26 In recent years, many datasets have been collected from a number of sites and across multiple  
27 years, containing detailed and high resolution measurements of carbon (C) fluxes, plant and  
28 soil characteristics, meteorological and water table data (Baldocchi et al., 2001; Baldocchi,  
29 2007). Several of the measured sites are peatlands, which have accumulated vast amount of C  
30 since the last deglaciation. Under drained conditions, peatlands have a high carbon dioxide  
31 (CO<sub>2</sub>) emission potential (e.g. van den Bos, 2003; Lohila, 2004; Drösler et al., 2008;

1 Maljanen et al., 2010). Understanding the processes driving CO<sub>2</sub> emissions is essential in the  
2 development of management practices to reduce greenhouse gas emissions.

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

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

1 A systematic evaluation of one model against data from multiple sites with a common set of  
2 parameters will allow a better understanding of processes not only at the individual sites but  
3 also on the site-specific differences which control the resulting fluxes (e.g. Calanca et al.,  
4 2007; van Huissteden et al., 2006; van Huissteden et al., 2009). This is a necessary  
5 precondition for accurate predictions of CO<sub>2</sub> fluxes under different climate scenarios or at  
6 different locations. On peatlands, some attempts have been made to consider site differences  
7 using simplified process models on national (e.g. ECOSSE, Bell et al., 2012) and global  
8 scales (e.g. InTec, Ju and Chen, 2005; McGill, St-Hilaire et al., 2010) and up to millennial  
9 timescale (Schuldt et al., 2013). However we are not aware of any studies comparing  
10 differences in parameter distributions of CO<sub>2</sub> related processes between treeless peatland  
11 sites, using an uncertainty based approach and a detailed process oriented model running on  
12 site scale.

13 Many carbon ecosystem models are available for site scale application such as Biome-BC  
14 (Feng et al., 2011), DNDC (Li et al., 1992a; Li et al., 1992b; Dietiker et al., 2010), PaSim  
15 (Calanca et al., 2007), PIXGRO (Adiku et al., 2006), CANDY (Franko et al., 1997), or  
16 DAYCENT (CENTURY) (Del Grosso et al., 2005). Some models were explicitly created or  
17 adapted to peatlands such as PDM (Frolking et al., 2001), PCARS (Frolking et al., 2002),  
18 CASA (Potter et al., 2001), NASA-CASA (Del Grosso et al., 2005), *ecosys* (Grant et al.,  
19 2012), wetland-DNDC (Zhang et al., 2002), peatland DOS-TEM (Fan et al., 2013),  
20 PEATLAND-VU (van Huissteden et al., 2006) or GUESS-ROMUL (Yurova et al., 2007).

21 In this work the CoupModel was used, which is a detailed process oriented model coupling  
22 heat and mass transfer for soil-plant-atmosphere systems (Jansson and Karlberg, 2010). The  
23 CoupModel was chosen for the following reasons: The model was designed for a wide range  
24 of soil types and different ecosystems and applications (see Jansson, 2012 for review) which  
25 might be useful as some of the sites in this study are already quite degraded and might not  
26 respond like a typical, intact peatland anymore. The model has been shown to be capable of  
27 simulating all three main greenhouse gases from peatlands: CO<sub>2</sub> (Klemedtsson et al., 2008),  
28 nitrous oxide (N<sub>2</sub>O) (Norman et al., 2008) and methane (CH<sub>4</sub>) (Ravina, 2007). Further, the  
29 CoupModel includes detailed sub modules for the most relevant processes in the carbon  
30 cycle: It predicts plant growth, plant transpiration and autotrophic respiration, soil nitrogen  
31 (N) and C processes, energy and heat fluxes, soil temperature, soil frost and snow depth. It  
32 supports an hourly time step for input and output data and can run in even finer time

1 resolution, which is necessary for analysing e.g. chamber flux data. The user can select  
2 between different sub models, different equations and different complexities and easily access  
3 all parameters via a user interface. Calibration procedures with randomized parameter values  
4 and methods for visualisation and detailed analysis of the model output are supported. An  
5 extensive model description can be found in Jansson and Karlberg (2010). The model and its  
6 documentation as well as several tutorials for its application can be downloaded from the  
7 CoupModel homepage (CoupModel, 2014).

8 The main aim of this study was to find out to what extend the large differences in measured  
9 CO<sub>2</sub> fluxes between five data rich European flux measurement sites can be solely explained  
10 by the differences in meteorology, water table and management. Therefore the process  
11 oriented CoupModel was applied using an uncertainty based Monte Carlo approach. Specific  
12 objectives were:

13 (I) to identify differences and similarities between various sites in CO<sub>2</sub> related processes,  
14 corresponding parameters and responses to forcing data.

15 (II) to identify and discuss the impact of available data for estimating key parameters in CO<sub>2</sub>  
16 flux models in general.

17 (III) to identify problems related to the model representation of the different ecosystem  
18 processes for open peatlands.

19

## 20 **2 Methods**

### 21 **2.1 Description of sites and investigations**

22 The CoupModel was applied to five treeless peatland sites with a wide gradient in land use  
23 intensity, water level, soil nutrient status and mean annual temperature (Tab. 1). Together with  
24 the climatic gradient from North-Finland to South-Germany and a different growing season,  
25 this leads to great differences in amplitude and dynamics of gross primary productivity (GPP),  
26 ecosystem respiration (R<sub>eco</sub>) and different amounts of biomass. This is reflected in the annual  
27 accumulated net ecosystem exchange (NEE) based on measurements, ranging from -395 g C  
28 m<sup>-2</sup> to 636 g C m<sup>-2</sup> (Fig. 1).

1 Dynamic forcing data for model input (water table and meteorology) was available from  
2 measurements at all sites (Tab. S1 in the supplement). Data used for model parameter  
3 constraint included measurements of LAI, soil temperature and NEE (Tab. S2 in the  
4 supplement). Measured NEE was partitioned into  $R_{\text{eco}}$  and GPP by the use of empirical  
5 models based on  $R_{\text{eco}}$  from night time NEE respectively opaque chambers at FsA and FsB.  
6 The empirical  $R_{\text{eco}}$  models are based on temperature (Lloyd and Taylor, 1994), while light  
7 level based functions were used for GPP according Falge et al. (2001). Corrections and gap  
8 filling at flux tower sites was done according the methods described in Reichstein et al.  
9 (2005). A detailed description is given in the references listed in Table S2 in the supplement.  
10 Though  $R_{\text{eco}}$  and GPP are not explicitly measured, this will be called measured data in the  
11 following for simple distinction from the simulated fluxes by the CoupModel.

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

19 The Scottish site, Auchencorth Moss (Amo) is an ombrotrophic bog, with vegetation  
20 consisting of grasses, sedges and soft rushes, covering a primarily Sphagnum base layer. The  
21 site is managed for low intensity sheep grazing with less than one livestock unit per hectare,  
22 but this was not accounted for in the model. Amo encompasses a small area of peat extraction  
23 in the south west of the catchment, which is unlikely to fall within the flux footprint of the EC  
24 system. The site was drained over a century ago, however, the drains are no longer considered  
25 to be in operation. The mean water table was  $-12.5$  cm between 2006 and 2010. Mean  
26 temperature during this period was  $10$  °C,  $\text{CO}_2$  data from EC during the same period was used  
27 for model calibration. A detailed description of the site and measurements can be found in  
28 Helfter et al. (2014), Drewer et al. (2010) and Dinsmore et al. (2010).

29 Horstermeer fen (Hor) is located in the Netherlands in a drained natural lake. It used to be  
30 agricultural land, but was abandoned more than 15 years ago. The water table was raised  
31 during restoration leading to a mean value of  $-10$  cm during the simulation period from 2004  
32 to 2010. It became a semi-natural grassland, a nature reserve without any mowing

1 management. The vegetation is very heterogeneous with reed, grass and small shrubs  
2 (Hendriks, 2009). The mean temperature during the simulation period was 10 °C. CO<sub>2</sub> fluxes  
3 were measured half hourly by EC and biweekly with opaque chambers between 2004 and  
4 2010. A detailed description of the site and measurements methods can be found in Hendriks  
5 et al. (2007).

6 Freisinger Moos (FsA and FsB) is a drained nutrient rich fen in the south of Germany. The  
7 two sites FsA and FsB lie next to each other in a drained sedge meadow which was cut once  
8 per year. The mean annual hay yield was 4.19 or 4.07 t dry weight ha<sup>-1</sup> a<sup>-1</sup> for FsA and 5.67  
9 or 6.17 t dry weight ha<sup>-1</sup> a<sup>-1</sup> for FsB for the years 2010 and 2011, respectively. FsB is located  
10 in a small depression with a mean water level of -20 cm compared to -25 cm for FsA during  
11 the years 2007 to 2011. Mean temperature during this period was 7.5 °C. FsB contains mainly  
12 tall sedges with little reed while FsA is vegetated by a mixture of sedges, grasses and herbs.  
13 Manual transparent and opaque chamber data of CO<sub>2</sub> fluxes (n=3 for each plot), measured  
14 several times a day every 3 to 4 weeks and half hourly meteorological data were available for  
15 the time period of 2007 to 2011. A detailed description of chamber configuration,  
16 measurement technique and empirical model approach were given in Drösler (2005), Beetz et  
17 al. (2013) and Leiber-Sauheitl et al. (2014). Measured R<sub>eco</sub> and empirical modelled GPP  
18 during measurement period of each measurement day were used for parameter constraint,  
19 empirically modelled values between measurement days were only used for visualisation and  
20 comparison.

## 21 **2.2 Model description**

22 CoupModel v4 from 12<sup>th</sup> April 2013 was used for simulations. The current version can be  
23 downloaded from KTH, 2014. A detailed description can be found in Jansson and Karlberg  
24 (2010). The model represents the ecosystem by a description of C and N fluxes in the soil and  
25 in the plant. It includes all main abiotic fluxes, such as soil heat and water fluxes that  
26 represent the major drivers for regulation of the biological components of the ecosystem. The  
27 most important equations with the corresponding parameters and switches differing from the  
28 default setup in the used version can be found in Tables S3, S4, S5 and S6 in the supplement.  
29 The major model assumptions relating to the model application to peatlands are described

1 below. Figure 2 shows a scheme of the main carbon fluxes and pools in the current  
2 CoupModel setup.

### 3 **2.2.1 Meteorological driving variables and integration time step of the model**

4 Hourly values of global radiation, relative humidity, precipitation, wind speed, and air  
5 temperature, measured at each site were used as input. Data was gap filled by simple linear  
6 interpolation for gaps < 6 hours. Larger gaps were filled by values from other adjacent climate  
7 stations. At Hor the station used for gap filling provided only daily values. Hourly values  
8 were retrieved assuming uniform distribution over 24 hours for precipitation, wind speed and  
9 relative humidity and sinusoidal distribution for temperature and global radiation.

10 Model performance was only evaluated for the years when meteorological data was available.  
11 The simulations were started two years prior to the evaluation period, so the system (in  
12 particular the plant) could adapt to the site conditions and become more independent of initial  
13 values. Data from the available years was copied to previous years if not available from an  
14 adjacent climate station.

15 The model internal time step was half-hourly for abiotic processes and hourly for nitrogen and  
16 carbon related processes.

### 17 **2.2.2 Dynamic coupled heat and water model for above soil surface conditions**

18 An interception model for both, radiation and precipitation, a snow model and a surface pool  
19 model was used to provide boundary conditions at the soil surface. Interception and plant  
20 evaporation was dependent on the simulated leaf area index of the plant as well as the degree  
21 of coverage, while transpiration depended additionally on the simulated water uptake of the  
22 plant. Cloud fraction was calculated from global radiation input and latitude. Incoming  
23 radiation was partitioned between one part, which was absorbed by the plant canopy and  
24 another part, which reached the soil. Surface temperature was simulated based on an energy  
25 balance approach, where the radiation reaching the soil equals the sum of sensible and latent  
26 heat flux to the air and heat flux to the soil. Soil evaporation was derived from an iterative  
27 solution of the soil surface energy balance of the soil surface, using an empirical parameter  
28 for estimating the vapour pressure and temperature at the soil surface. Vapour pressure deficit  
29 was calculated from the relative humidity input. Snow fall was simulated from precipitation  
30 and air temperature, snow melt from global radiation, air temperature and simulated soil heat  
31 flux. Surface runoff was controlled by a surface pool of water that covers various fractions of



1 the soil surface. Under over saturated periods the flow of water in the upper soil compartment  
2 could be directed up-wards, towards the surface pool. Surface runoff was calculated as a  
3 function of the amount of water in the surface pool.

4

### 5 **2.2.3 Dynamic heat and water model for the soil**

6 The soil profiles were divided into 12 layers with an increasing layer depth from 5 cm for the  
7 upper layer to 100 cm in the lowest layer. Heat flow between adjacent soil layers were  
8 calculated based on thermal conductivity functions accounting for the content of ice and  
9 water. The heat flow equation is based on a coupled equation accounting for the freezing and  
10 thawing in the soil (Jansson and Halldin, 1979). Convection was not accounted for. The lower  
11 boundary was calculated as temperature based on a sine variation at the soil surface and a  
12 damping depth for the whole soil profile as well as a parameter for the annual mean  
13 temperature  $T_{mean}$  and annual amplitude of temperature  $T_{aamp}$  at the site (a list of symbols and  
14 abbreviations can be found in Table 2).

15 Soil water depended on infiltration to the soil, soil evaporation, water uptake by plant roots  
16 and ground water flow. Soil moisture represented as liquid water content, was calculated  
17 based on the water storage and temperature. Water flows between adjacent soil layers were  
18 calculated according Richards equation (1931), considering hydraulic conductivity, water  
19 potential gradient and vapour diffusion. Soil water characteristics were described by the  
20 Brooks & Corey (1964) equation between two threshold water tensions, while a log linear  
21 expression was applied at higher water tensions and a linear expression at water contents  
22 close to saturation. Unsaturated conductivity was simulated according Mualem (1976) with  
23 additionally accounting for the conductivity in macro pores. The ground water level was  
24 defined by assuming a continuous zone of saturation from water table level down to the lower  
25 boundary of the considered soil profile. To force saturation at the measured ground water  
26 level, water was added to or removed from the corresponding layer.

27

## 1 2.2.4 Vegetation

2 Vegetation was simulated according to the explicit big leaves concept (e.g. Dai et al., 2004)  
3 but only one plant canopy layer, representing the complete plant community was defined.  
4 Albedo, LAI, vegetation height and vegetation cover were simulated. Permanent, perennial  
5 vegetation was configured with maximal plant height of 0.6 m, a lowest root depth of -0.6 m  
6 and a maximal plant cover of 100%. Grain development was assumed to play a minor role  
7 and was therefore disabled. Plant respiration was assumed to be depended on growth and  
8 maintenance (e.g. Hansen and Jensen, 1977).

9 For leaf assimilation, the light use efficiency approach (Monteith, 1972; Monteith and Moss,  
10 1977, see e.g. Hilker et al., 2008 for review) was used, at which total plant growth is  
11 proportional to the global radiation absorbed by canopy but limited by unfavourable  
12 temperature and limited soil water. For simplicity plant assimilation was simulated  
13 independent of dynamics in N availability. This might be justified as none of the sites was  
14 fertilized in the recent years and the vegetation community was assumed to be adapted to the  
15 nutrient conditions at each site. Differences in N availability between sites are included in the  
16 radiation efficiency ( $\epsilon_L$ ). Plants were assumed to be well adapted to wet conditions (Keddy  
17 1992, Steed et al. 2002), including aerenchyma to tolerate water saturated soil conditions  
18 (Jackson & Armstrong 1999). Plant stress due to high water saturation was therefore disabled.

19 Plant development started every spring when the accumulated sum of air temperatures above  
20 a threshold value ( $T_{EmergeTh}$ ) reached the value of  $T_{EmergeSum}$ . Both parameters were calibrated  
21 (Tab. S4, in the supplement). The accumulation of temperatures started when the day length  
22 exceeds 10 hours. Snow cover hindered shooting by reducing the radiation passing through to  
23 the plant, while low soil temperatures reduced plant water uptake.

24 Beside a small amount of litter fall occurring during the whole plant growth period (Robson,  
25 1973; Duru and Ducrocq, 2000; Fulkerson and Donaghy, 2001), senescence was assumed to  
26 start after the plant reached maturity and therefore depended on growth stage (e.g. Thomas  
27 and Stoddart, 1980) and temperature sums (e.g. Davidson and Campbell, 1983). As this was  
28 not yet directly supported by the model, the stem pool was used for brown, senescent,  
29 standing biomass. Therefore new assimilates were constantly allocated to roots and leaf only,  
30 while existing leaf biomass was reallocated after maturity to the stem pool. A third stage of  
31 litter fall was configured depending on a minimum threshold temperature sum: Five

1 consecutive days in the autumn with day lengths shorter than 10 hours and with temperatures  
2 below  $T_{DormTh}$  terminated the growing season and plants went to dormancy.

3 During litter fall part of the C is stored in a mobile pool, which can be then reused for  
4 shooting in the next year (e.g. White, 1973; Wingler, 2005).

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

### 10 **2.2.5 Soil carbon and nitrogen**

11 The organic substrate was represented by two C and N pools for each of the 12 soil layers:  
12 one with a slow and one with a high turnover rate coefficient. Decomposition products from  
13 the fast pools are partitioned into CO<sub>2</sub> which is released to the atmosphere and C which is  
14 partly moved to the slow pools and partly returned to the fast pools. Decomposition products  
15 from the slow pools are partly released as CO<sub>2</sub> and partly returned to the slow pools. The  
16 initial values for the amount of C and N per layer was given by measurements and partitioned  
17 into the two pools for each layer according the measured C:N ratio as described in section  
18 2.2.5 and Table 3. Beside the turnover rate coefficients and amount of substrate in each pool  
19 per layer, decomposition rates depended on the response to soil moisture and temperature in  
20 the corresponding layer.

21 As the rate coefficients for decomposition were expected to strongly affect each other, only  
22 the coefficient for the fast decomposition pools were calibrated. The coefficient for the slow  
23 pools ( $k_h$ ) was kept constant at a low value of  $2 \cdot 10^{-8} \text{ d}^{-1}$  during the calibration runs which  
24 might be justified as decomposition of resistant carbon is less responsible for the variation in  
25 soil respiration (e.g. Whalen et al., 2000).

26 Nitrogen and methane related processes were considered by a model including the most  
27 important pathways and fluxes. However no emphasize on the calibration of these processes  
28 were made in this study since the current objective was on CO<sub>2</sub> fluxes from the peatlands.

## 1 **2.2.6 Independent approach to find values of site specific parameters**

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

4 Water retention parameters were assigned to each soil layer according to soil data from each  
5 site. However, at Amo and Lom, water retention and at all sites unsaturated conductivity was  
6 assigned from the CoupModel soil database as suggested by Lundmark, (2008) for peat soils.  
7 Measured total soil organic carbon (SOC) per layer was partitioned to the two SOC pools per  
8 layer on the basis of the measured total C:N ratio per layer whereas the initial C:N ratios of  
9 the slow decomposing pools were assumed to be 10, while for the fast pools 27.5 was chosen  
10 according to measured C:N of leaf tissues at FsA and FsB (Tab. 3).

## 11 **2.3 Parameter calibration approach**

12 The aim of the calibration was to find out to what extent the same parameter values could be  
13 used for all sites compared to a site specific representation. A stepwise approach was carried  
14 out starting with finding the best site specific parameter representations and then trying to  
15 merge them to common values valid for all sites. Finally the common representation was  
16 revised to some few parameters showing great site specific effect on model performance. An  
17 overview of the different steps can be found in Figure 3, details on the calibration procedures  
18 are presented as supplementary material.

19 For the basic calibration (step I, Fig. 3) 350'000 to 700'000 runs were performed for each  
20 site. 45 parameters which were suspicious of eventually being site specific were selected and  
21 calibrated with an assumed uniform random range (Tab. S4 in the supplement). Parameter  
22 ranges were then constrained based on selected runs (step I and II, Fig. 3), showing acceptable  
23 performance to multiple variables (Tab. S7 in the supplement), measured at the sites.

24 Several additional multiple calibration runs were performed, with few selected parameters  
25 each, to unravel parameter interactions (step III, Fig. 3). A number of simulations were also  
26 made by single value representations of parameters (step IV, Fig. 3) to visualize the impact of  
27 certain parameter values on interacting parameters and on performance. These runs are called  
28 single runs in the following, numbered with C1 to C7 and described in Tab. S8 in the  
29 supplement.

1 Selection of runs and evaluation of performance was based on three indices: coefficient of  
2 determination ( $R^2$ ) assesses how well the dynamics in the measurement derived values are  
3 represented by the model. Mean error (ME), also called y-intercept (Willmott, 1982) indicates  
4 a lag or lead between model predictions and measured data (Moriassi et al., 2007). Nash-  
5 Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) accounts for both, deviation of dynamics  
6 and magnitude. It ranges from  $-\infty$  to 1, whereas 1 means the best fit of modelled to measured  
7 data and values  $< 0$  indicate that the mean measured value is a better predictor than the  
8 simulated value, which indicates an unacceptable performance (Moriassi et al., 2007).

### 9 **3 Results**

#### 10 **3.1 Model performance – results of basic calibration and selected common** 11 **configuration**

12 Model performance showed distinct differences between the sites, depending on the  
13 investigated variable and on the number of considered runs (Tab. 4). Figure 4 shows the  
14 differences between measurements and model C1.

##### 15 **3.1.1 Fluxes**

16 At all sites dynamics in  $R_{eco}$  fluxes were simulated considerably better than GPP (Tab. 4).  
17 Performances for NEE were worse as simulation errors in GPP and  $R_{eco}$  are summed up.

18 In respect to  $R_{eco}$  and GPP the selected single runs represent a parameter configuration close  
19 to the best ones possible in the tested range: their  $R^2$  value did not differ more than 0.05 from  
20 the best result achieved in the multiple calibration, while ME values were smaller  $|0.1| \text{ g C}$   
21  $\text{m}^{-2} \text{day}^{-1}$ . Clearly lower  $R^2$  and higher ME values in single runs for biomass and LAI  
22 simulation, indicates that none of the runs could give best results for all variables at the same  
23 time. E.g., best values for GPP can only be achieved if poorer performance would have been  
24 accepted for other parameters like winter  $R_{eco}$  or LAI (see criteria for accepted runs in Table  
25 S7 in the supplement).

26 The ME values in Table 4 show a clear overestimation of winter fluxes by 3.21 and 2.11  $\text{g C}$   
27  $\text{m}^{-2} \text{day}^{-1}$  for the single runs at FsA and FsB, respectively, and a weaker overestimation for  
28 the accepted runs. The overestimation was less pronounced at Amo ( $0.13 \text{ g C m}^{-2} \text{day}^{-1}$ ) and  
29 Lom ( $0.01 \text{ g C m}^{-2} \text{day}^{-1}$ ). At Hor winter fluxes were underestimated with a ME of  $-0.26 \text{ g C}$

1  $\text{m}^{-2} \text{day}^{-1}$ . This was reflected in the accumulated NEE (Fig. 4) leading to a much higher  $\text{CO}_2$   
2 loss compared to the  $\text{CO}_2$  balance estimated by the empirical model approach at FsA and FsB.  
3 At Lom higher accumulated NEE due to the overestimation of winter  $R_{\text{eco}}$  was visible in the  
4 first months of each year. It was nearly compensated due to the underestimated spring  $R_{\text{eco}}$ , or  
5 overcompensated due to GPP overestimation, as e.g. in summer 2006, which was very dry.

### 6 **3.1.2 Explanatory variables**

7 Of all variables, the highest  $R^2$  values were achieved for soil temperature at all sites.  
8 Temperatures in deeper soil layers ( $-50$  or  $-60$  cm) had better fits than in upper layers with  $R^2$   
9 values close to 0.9 or higher and maximum mean deviation of  $0.15$  °C. The fit of modelled vs.  
10 measured snow depth, which was only available at Lom, had a  $R^2$  value of 0.75 with a mean  
11 error of less than 10 cm.

12 Simulation of LAI represented the measurements quite well with  $R^2$  values between 0.53 and  
13 0.76 and mean error of maximum  $0.12 \text{ m}^2 \text{ m}^{-2}$ . An exception was Hor, where LAI was  
14 underestimated by ME of  $-0.61$  and  $1.49 \text{ m}^2 \text{ m}^{-2}$  in the accepted 75 runs and in the selected  
15 single run C1, respectively. At Hor, root biomass was underestimated in the single run by ME  
16 of  $-281 \text{ g C m}^{-2}$  and living leaf biomass by  $-122 \text{ g C m}^{-2}$ .

17 In most of the runs of the basic calibration at Hor, either GPP was overestimated or leaf  
18 biomass and LAI was underestimated. Therefore, beside the common configuration C1, a  
19 different configuration was tested where plant respiration and litter fall parameters for Hor  
20 were set to much lower values than in the tested range to fit to GPP and LAI at the same time.  
21 However, this reduced performance for  $R_{\text{eco}}$   $R^2$  to 0.66 compared to 0.75 in C1 and led to an  
22 overestimation of winter  $R_{\text{eco}}$  with a ME of  $0.75 \text{ g C m}^{-2} \text{ day}^{-1}$ .

### 23 **3.2 Parameter constraint**

24 Site specific calibration was needed for the speed at which the maximum surface cover is  
25 reached ( $p_{ck}$ ), the mean value in the analytical air temperature function ( $T_{\text{amean}}$ ), temperature  
26 sum for reaching plant maturity ( $T_{\text{MatureSum}}$ ), coefficient for determining allocation to mobile  
27 internal storage pool ( $m_{\text{retain}}$ ), decomposition rate of the fast SOC pools ( $k_l$ ) and radiation use  
28 efficiency ( $\epsilon_L$ ).

29 Activity under saturated conditions ( $p_{\theta\text{Satact}}$ ), threshold temperature for plant dormancy  
30 ( $T_{\text{DormTh}}$ ), response to a  $10$  °C soil temperature change on the microbial activity ( $t_{Q10}$ ) and base

1 temperature for the microbial activity ( $t_{Q10bas}$ ) covary with performance indices but showed  
2 different patterns for different validation variables and for different sites.  
3 Most of the parameters did not show any influence on performance indices within the tested  
4 range (Fig. S1 in the supplement), demonstrating that either the relatively low effect of the  
5 parameter was overcompensated by the effect of more sensitive parameters, or the range used  
6 for calibration is sufficiently constraining. Each of these parameters did not reduce model  
7 performance indicated by  $R^2$  by more than 0.05 for GPP or  $R_{eco}$  after setting them to a  
8 common value.

### 9 **3.3 Correlations between parameters**

10 In the basic calibration, the following parameters were identified to interact with other  
11 parameters:  $p_{ck}$  covaried with the extinction coefficient in the Beer law ( $k_{rn}$ ) which is used to  
12 calculate the partitioning of net radiation between canopy and soil surface. Strong linear  
13 negative correlation between coefficients for growth ( $k_{gresp}$ ) and maintenance respiration  
14 ( $k_{mrespleaf}$ ) was detected.

15 The effect of the different parameter in the water response function  $p_{\theta Satact}$ ,  $p_{\theta Upp}$  and  $p_{\theta p}$   
16 compensated each other. They could not be constrained without a very high measurement  
17 resolution of fluxes and water table combined with high water table fluctuation at the same  
18 time. Therefore  $p_{\theta Upp}$  and  $p_{\theta p}$  were set to default values and  $p_{\theta Satact}$  constrained by additional  
19 multiple runs together with  $k_l$ . Differences between sites in  $k_l$  are reduced with higher  $p_{\theta Satact}$   
20 (Fig. 5), however, higher  $p_{\theta Satact}$  increase overestimation of winter  $R_{eco}$  at FsA and FsB (Fig. 6  
21 and Fig. 7 d). A wider range of  $p_{\theta Satact}$  was acceptable for summer  $R_{eco}$  (Fig. 6).

22 Beside moisture response, decomposition rate ( $k_l$ ) and temperature response ( $t_{Q10}$ ,  $t_{Q10bas}$ )  
23 control soil respiration. The effect on  $R_{eco}$  was cofounded by plant respiration. Different  
24 patterns for different sites and variables for each of the parameters were even more  
25 pronounced when only  $k_l$ ,  $t_{Q10}$  and  $k_{mrespleaf}$  were in calibration (Fig. 6).

26 Single runs with different configurations (Fig. 7) revealed that higher plant respiration as well  
27 as steeper temperature response can lead to less overestimation of respiration in winter (Fig.  
28 7 d) but lead to reduced performance (Fig. 7 c). In all single runs, despite the different  
29 configurations, FsA always showed the highest  $k_l$  while Amo had the lowest (Fig. 7 a). A

1 higher saturation activity reduces the difference in  $k_l$  values, but leads to higher  
2 overestimation of winter fluxes.

### 3 **4 Discussion**

4 Despite not being specifically developed for peatland CoupModel was able to simulate  
5 measured fluxes quite well. The model was run in a simple configuration with only two SOC  
6 pools per layer, no explicit representation of microbes, and only one plant layer. Even though,  
7 CoupModel was capable to adequately reproduce the measurements. Several points were  
8 identified, where further, peatland specific processes or more detailed representations might  
9 improve the model. Those are discussed in the following subsections.

10 From the 45 calibrated parameters, 8 parameters could be identified to actually need a site  
11 specific representation to achieve acceptable performance. Those parameters are discussed in  
12 section 4.3 to 4.10. The remaining 37 parameters were not sensitive in the tested ranges, even  
13 though site specific values could have been expected: For example, it is known that grassland  
14 species differ in their assimilation and growth response to temperatures (Billings et al., 1978;  
15 Wohlfahrt et al., 1999). Plant respiration rates in graminoids differ between species (Poorter et  
16 al., 1991; Scheurwater et al., 1998; van der Werf et al., 1988) and depend among others on  
17 light (Rovira, 1969; Bahn et al., 2013) nutrient (Paterson and Sim, 2000) and moisture  
18 conditions (Crow and Wieder, 2005) as well as on cutting regime (Bokhari, 1977). Allocation  
19 fractions to different plant parts differ between species and depend on nutrients conditions  
20 (Aerts et al., 1991; Gong et al., 2014) as well as shading (Bahn et al., 2013). Values for  
21 specific leaf area are species specific (e.g. Poorter et al., 1990; Reich et al., 1998) and differ in  
22 response to nutrient availability (Meziane and Shipley, 1999). Leaf life time (e.g. Ryser and  
23 Urbas, 2000) as well as leaf and root turnover rates (Schläpfer and Ryser, 1996) vary between  
24 graminoid species.

25 The five peatland sites largely differed in their vegetation composition, plant life-forms and  
26 species. Nevertheless common values for all sites could be applied for parameters related to  
27 these processes, without reducing model performance on  $R_{eco}$  and GPP in  $R^2$  values by more  
28 than 0.05. That shows that either the studied sites on a vegetation community level did not  
29 differ much in these processes, or that the impact of those parameters is subordinate compared  
30 to the impact of other parameters, meteorological input and other site conditions.

31 Models with a focus on multiple year carbon fluxes do therefore not need a site specific  
32 interpretation of these processes.



## 1 **4.1 Model initialisation**

2 Many models use spin-up routines of many years until SOC pools reach a steady state (e.g.  
3 Dimitrov et al., 2010; Smith et al., 2010; Thornton and Rosenbloom, 2005). Here, measured  
4 C:N values were used to partition the SOC between pools, while ranges for parameter values  
5 were chosen in a way, that the amount of carbon in the soil pools did not change very  
6 drastically. However no further effort was made to force the pools to be in equilibrium. It was  
7 assumed that this might not be the case in the real world either: Drainage ditches at FsA and  
8 FsB are still maintained, leading to high carbon losses and changes in substrate quality. Land  
9 use at Hor was quite recently changed from a fertilized and deeply drained crop land to a  
10 nature reserve with restored water table. Also Amo used to be more intensively managed and  
11 drained, but the drainage system was not maintained. Land use history was not known and  
12 SOC measurements were available from only one date per site. The measured carbon fluxes  
13 were therefore the only indication about carbon loss or addition to the complete system, while  
14 changes in relative pool sizes were not known. The partitioning of the SOC has implications  
15 on the parameter distribution for the rate coefficient for decomposition, which is discussed in  
16 section 4.10.

## 17 **4.2 Model performance**

18 The best achieved performance highly differed between the different validation variables and  
19 between the different sites. This was not only caused by the models ability to simulate the  
20 different output parameters but also due to measurement quality, measurement uncertainty,  
21 measurement methods (temporal and spatial resolution) and heterogeneity of the sites.

22 GPP was simulated markedly poorer as compared to  $R_{eco}$  at all sites and not only in the single  
23 runs, but also in the complete set of performed multiple runs. An explanation might be that in  
24 the model the whole plant community consisting of different individuals, species and even  
25 functional types, with different life cycles and adaptations to light availability and temperature  
26 was simplified to only one plant. Especially mosses differ largely from vascular plants in  
27 respect to their ecology and response to water, temperature and light conditions (Gaberšček  
28 and Martinčič, 1987; Harley et al., 1989; Murray et al., 1993; Turetsky, 2003), which might be  
29 important at the moss rich Lom and Amo. The vegetation at Hor consists of species with very  
30 different strategies and requirements for nutrient and water. At FsB, reed, which is known for

1 a late emerge, was well present in some of the years while it did hardly appear in other years.  
2 FsA is relatively species rich and several of these species are abundant only during parts of  
3 the vegetation period. Also, using a more complex photosynthesis model like e.g. Farquhar et  
4 al. (1980, 2001) and testing a wider range of parameters might lead to a better fit. Including  
5 plant stress due to high water levels and nutrient limitation might improve the performance on  
6 some sites. E.g. Sagerfors et al. found 2008 photosynthesis to be limited also by too high  
7 water levels, so that the McGill wetland model assumes reduced photosynthesis outside a  
8 water level range of  $-10$  to  $-20$  cm (Wu et al., 2013). Furthermore, GPP cannot be measured  
9 directly neither by the chamber nor the EC method. Instead it was derived from NEE and  $R_{eco}$   
10 or night time NEE, including the uncertainty of two different measurements and empirical  
11 modelling.

12 Heterogeneity of vegetation was very distinct at Hor, which might explain the difficulties to  
13 simulate the right amounts of GPP and biomass at the same time. The biomass and LAI taken  
14 into account for this study might not be fully representative of the whole EC fetch for all wind  
15 directions. Hor is also a site which deviates strongly with respect to other sites, with recent  
16 large changes in management. It is in successional transition from intensively used dairy  
17 farming meadow (approximately 20 years ago) towards reed fen with willow thickets. Soil  
18 and vegetation still show the imprint of high nutrient level derived from manuring practices  
19 (e.g. patches with abundant *Urtica dioica*). This likely still affects GPP. These features could  
20 be a better explanation of the deviating GPP than the additionally tested configuration with  
21 strongly reduced litter fall and plant respiration rates.

22 Even though the winter fluxes are small compared to the summer fluxes they have a marked  
23 role in the annual NEE balances (Fig. 4). Overestimation of winter  $R_{eco}$  in combination with  
24 slightly underestimated winter GPP lead to high overestimation of annual accumulated NEE,  
25 emphasising the importance of winter flux dynamics in the annual balances. At all sites except  
26 Hor, winter  $R_{eco}$  was overestimated in the selected single run. For FsB and especially FsA,  
27 this was also true for all multiple runs. As  $R_{eco}$  at Lom and Amo are typically relative low, the  
28 effect was less pronounced.

29 Several different reasons for the winter  $R_{eco}$  overestimation are possible: explanations due to  
30 model setup and parameterisation are discussed in the sections 4.7, 4.8 and 4.9. Additionally,  
31 gases might be trapped within the snow and under the ice (Bubier et al., 2002; Maljanen et al.,  
32 2010) and therefore be seen by the measurement instruments only in spring time, when they

1 are released. A gastight ice cover was not realised in the current model setup. Frozen or ice  
2 covered soils are quite common at the boreal Lom, but also at FsA and FsB which have a  
3 more continental climate than the other sites.

4 The ability of the model in simulating soil moisture could not be evaluated, as this variable  
5 was measured only at Lom, where the soil was close to saturation throughout the year.  
6 Therefore, and as ground water level was used as input, hydraulic properties could not be  
7 constraint. Further, swelling, shrinking and hysteresis effect which are important factors in  
8 hydraulic characteristics of peat soils (e.g. Kellner & Halldin 2002) were not accounted for.  
9 This could have an effect on model performance and parameter values, especially those  
10 related to the soil moisture response.

11

### 12 **4.3 Soil temperature dynamics**

13 Due to the isolating impact of the snow cover (e.g. Zhang, 2005), the value of mean annual  
14 soil temperature ( $T_{amean}$ ) was expected to be slightly higher than the mean annual air  
15 temperature. Constrained values of soil temperature were 1.5 to 5 °C higher than the mean  
16 annual air temperature at all sites. If the model was run under different conditions without  
17 further fitting, factors causing differences between mean annual soil temperatures and  
18 corresponding air temperature need to be considered.

### 19 **4.4 The role of soil temperature and GPP to constrain the plant cover**

20 Accepted fits for soil temperature in the uppermost measured soil layer led to  $p_{ck}$  values, close  
21 to the measured coverage of vascular plants for each sites. Therefore the measured coverage  
22 could directly be used in the configuration C1 (Fig. 6 a). Setting  $p_{ck}$  to a common value of  
23 100% reduced the differences in  $\varepsilon_L$  between the sites C7 (Fig. 6 e), but led to underestimation  
24 of soil temperature in the uppermost soil layer by at most  $-0.45$  °C in ME at Amo. An  
25 explanation could be that mosses are contributing to the plant coverage in respect to GPP but  
26 not to temperature, especially at sites where they are the main peat forming material.

## 1 **4.5 Start of senescence**

2 Site specific calibration was needed for the temperature sum initiating the start of senescence  
3 ( $T_{MatureSum}$ ). However, if the resulting day of the year was plotted instead, the differences  
4 between sites became small (Fig. 6) and setting it to the mean value of all sites did not reduce  
5 model performance in GPP  $R^2$  by more than 0.05. Induction of senescence with graminoids is  
6 known to depend on both, temperature and day length (Nuttonson, 1958; Proebsting et al.,  
7 1976; Thomas and Stoddart, 1980; Davidson and Campbell, 1983). However the differences  
8 between the sites in this study could be explained solely by the relative day length.

## 9 **4.6 Seasonal and management control of mobile plant pool for regrowth**

10 The proportion of C in the plant which does not become litter, but instead is stored for  
11 shooting in the next year ( $m_{retain}$ ), differed largely between sites. At Lom, a value of at least  
12 40% led to accepted performance while a maximum of 3% was found for FsA and FsB; a  
13 mean value of 20% would reduce  $R^2$  of GPP by at least 0.04 for these sites. At Amo and Hor  
14 neither a value of 3% nor 40% reduced  $R^2$  of GPP by more than 0.01. An explanation for low  
15  $m_{retain}$  at FsA and FsB could be that the same pool is used for regrowth after cut and therefore  
16 not available for shooting anymore, as the regrowth rate in both early spring and after cut  
17 depend on carbohydrate reserve (White, 1973; Davies, 1988; Klimeš and Klimešová, 2002).  
18 Steele et al. (1984) conclude that defoliation late in the year will affect spring regrowth.

19 At Lom high  $m_{retain}$  might be an adaption to the short vegetation period (Kistriz et al., 1983).  
20 Evergreen parts of the vegetation like dwarf shrubs, lower leaf parts of graminoides and  
21 mosses were not accounted for which also affects regrowth in spring. Saarinen (1998) found  
22 that 60-70% of shoots and 20% of green biomass in a *Carex rostrata* fen survived the winter  
23 and hypothesised based on comparison with other studies that the proportion increase with  
24 increasing latitude.

25 The storage pool is an important parameter needing site specific calibration but can be fitted if  
26 several measurements during spring and early summer of either GPP, biomass or LAI are  
27 available.

## 28 **4.7 Radiation use efficiency**

29 As plants were not nutrient limited in the model setup, lowest values for  $\epsilon_L$  were expected  
30 under the most nutrient poor conditions (Longstreth and Nobel, 1980; Reich et al., 1994;

1 Haxeltine and Prentice, 1996; Gamon et al., 1997; Wohlfahrt et al., 1999). The opposite was  
2 true if site specific values were used for  $p_{ck}$ . However, a common value for  $p_{ck}$  reduced the  
3 differences in  $\varepsilon_L$  and led to low  $\varepsilon_L$  at the ombrotrophic Amo site, but to an even lower value at  
4 the minerotrophic Lom. Nutrient status of the soil can therefore not explain the differences in  
5  $\varepsilon_L$ . The assumption of plants being well adapted to nutrient and water stress might not be true  
6 for the restored Hor site, where parts of the vegetation still consists of species which are not  
7 typical for wetlands. This might explain the low productivity at that site, but could only be  
8 covered by a model, if site specific plant responses to high water levels would be applied.  
9 Additionally,  $\varepsilon_L$  is known to be species specific (Sinclair and Horie, 1989; Reich et al., 1998;  
10 Wohlfahrt et al., 1999).

11 Radiation use efficiency is an important parameter needing site specific calibration. If  
12 common values were used for  $\varepsilon_L$ ,  $p_{ck}$  and  $m_{retain}$ , mean GPP would be underestimated by a  
13 factor of 2.4 (FsB) or overestimated by a factor of 3 (Lom). If site specific values were used  
14 for  $p_{ck}$  and  $m_{retain}$  the discrepancy would be even higher. However  $\varepsilon_L$  can easily be fitted if  
15 either GPP, biomass or LAI is known.

#### 16 **4.8 The control of decomposition and plant respiration by soil temperature**

17 The whole year  $R_{eco}$ , which was dominated by summer  $R_{eco}$  could be described by a single  
18 temperature response function at all sites. However, it was not possible to find an equal good  
19 fit to both summer and winter  $R_{eco}$ , using the same  $t_{Q10}$  value. Higher  $t_{Q10}$  would decrease  
20 overestimation of winter  $R_{eco}$  especially at the southern sites FsA and FsB, but also reduce  
21 model performance for whole year  $R_{eco}$ . Different temperature responses for different sites  
22 (e.g. Jacobs et al., 2007), seasons (e.g. Lipson et al., 2002) and temperature ranges (e.g. Lloyd  
23 and Taylor, 1994; Paul, 2001; Atkin et al., 2003) are reported in the literature. This is partly  
24 explained by multiplicative effects of several temperature sensitive processes (Davidson et al.,  
25 2006; Kirschbaum, 2006) but still, a constant  $t_{Q10}$  might be a wrong assumption (Atkin et al.,  
26 2005).

27 More sophisticated temperature responses like the Ratkowsky-function (Ratkowsky et al.,  
28 1982) might improve the performance for individual sites. This might also be true for separate  
29 temperature response functions for plant and soil, as summer  $R_{eco}$  includes autotrophic and  
30 heterotrophic respiration, while winter  $R_{eco}$  is strongly dominated by heterotrophic respiration.

## 1 **4.9 The control of decomposition by soil moisture**

2 The activity under saturated conditions in respect to unsaturated conditions is described by  
3  $p_{\theta Satact}$  and was strongly negative correlated with decomposition rate  $k_l$ . Patterns for  $p_{\theta Satact}$   
4 differed between sites and variables. At all sites a minimum value of around 5% led to  
5 acceptable performance in whole year  $R_{eco}$ , while also quite high values did not reduce the  
6 performance except at FsB. At Lom only winter  $R_{eco}$  was considered, as conditions were  
7 always saturated during summer. For acceptable winter  $R_{eco}$ ,  $p_{\theta Satact}$  needed to be very low.  
8 This was not true for Lom, where water in the upper soil layer partly froze in the model and  
9 led to high winter respiration.

10 As the soil at FsA and FsB was saturated during winter, a common lower value for  $p_{\theta Satact}$   
11 would decrease overestimation of winter fluxes. However it would also reduce model  
12 performance at all sites and increase the site specific differences in  $k_l$  (Fig. 7).

13 Permanently saturated soils contain less  $O_2$  than temporally saturated ones (e.g. Kettunen et  
14 al., 1999), which effects decomposition (e.g. Reddy and Patrick, 1975; DeLaune et al., 1981;  
15 Holden et al., 2004). Therefore lower  $p_{\theta Satact}$  would be justified for wetter sites. If  $k_l$  was  
16 constant between sites and instead  $p_{\theta Satact}$  fitted, this would lead to the value of  $p_{\theta Satact}$  to  
17 decrease in the order  $FsB > FsA > Lom > Hor > Amo$  (Fig. 5) which cannot be justified by  
18 the differences in water levels which increase in  $FsA < FsB \ll Amo < Hor \ll Lom$ .  
19 Therefore a different  $p_{\theta Satact}$  cannot explain differences in soil respiration between sites.  
20 However, amount of aerenchymous plants, leading to soil aeration (e.g. Armstrong, 1980;  
21 Bendix et al., 1994; Grosse et al., 1996) were not taken into account. They reach the highest  
22 coverage at FsB (90%), followed by FsA (62%), Hor (50%), Lom (around 10%) and Amo  
23 (around 6%). Modelling water response depending on soil  $O_2$  and redox potential, including  
24  $O_2$  conductance from plants, might help to analyse the differences in decomposition rate and  
25 reduce winter overestimation. E.g. in the Wetland-DNDC model, the water response function  
26 depends on redox potential: decomposition under saturated condition is reduced by a factor of  
27 0.6 if redox potential is high, but by a factor of 0.2 if redox potential is low (Zhang et al.,  
28 2002).

## 1 **4.10 The control of decomposition by substrate**

2 The largest differences of parameters between sites appeared for the maximum decay rate of  
3 the fast C pools  $k_l$ . Setting it to a common value would lead to an underestimation of mean  
4  $R_{eco}$  by a factor of 2.8 at FsB or an overestimation by a factor of 4 at Amo.

5 Despite different temperature and water response curves being tested,  $k_l$  values at FsA and  
6 FsB are substantially higher than at Amo (Fig. 5 and Fig. 7). Higher  $t_{Q10}$  values lead to two  
7 groups of  $k_l$  values: similar high ones for Lom, FsA and FsB and substantially lower ones for  
8 Hor and Amo (Fig. 7).

9 The partitioning into SOC pools strongly effects the differences, as can be shown by  
10 calculating decomposition rates for the total SOC ( $k_{tot}$ ) based on  $k_l$ ,  $k_h$  and SOC in the pools of  
11 the upper 30 cm as used in the C1 scenario (Fig. 8). However, FsB and FsA still have much  
12 higher rates than Amo. Resulted values and ranges of  $k_{tot}$  ( $0.02$ - $0.16$   $a^{-1}$ ) are comparable with  
13 reported values from laboratory incubation studies of peat cores ( $0.03$ - $1.66$   $a^{-1}$ , Moore and  
14 Dalva, 1997;  $0.01$ - $0.35$   $a^{-1}$ , Glatzel et al., 2004;  $0.008$   $a^{-1}$ , Kechavarzi et al., 2010; a SOC  
15 content of 30% was assumed for conversion from dry mass).

16 Lower decomposability is often associated with higher C:N ratios (e.g. Zeitz and Veltz, 2002;  
17 Limpens and Berendse, 2003; Bragazza et al., 2006; Zhang et al., 2008), which might be  
18 important especially for the moss rich Amo and Lom. Assuming a C:N ratio of 60 for the fast  
19 pools (Fig. 7, C6) leads to a decomposition rate at Lom which is close to those at FsA and  
20 FsB, while those of Hor and Amo remain substantially lower.

21 Low pH might be one reason for the low  $k_l$  at Amo (e.g. DeLaune et al., 1981; Bergman et al.,  
22 1999). Despite being nutrient rich and having a high pH and high biomass production, leading  
23 to large amounts of labile carbon added to the soil,  $k_l$  values at Hor were very low. This might  
24 be connected to land use history and the origin of the peat from partly clayey-lake sediment.  
25 Most of the labile C in the parent peat in the upper, formerly drained soil layers might have  
26 been decomposed before and therefore stabilised.

27 In the current setup the slow pools were almost inert. A higher decay rate for the slow pools  
28 would result in a lower  $k_l$  for sites with high C stock in the slow pools (cf Tab. 3). This would  
29 decrease the differences between FsA and FsB compared to Lom and Amo, but increase the  
30 differences between FsA compared to FsB and compared to Hor.

1 Substrate quality is known to effect decomposition rates (e.g. Raich and Schleisinger, 1992;  
2 Belyea, 1996; Fang and Moncrieff, 2005; Yeloff and Mauquoy, 2006). Therefore, many other  
3 SOC models use several different SOC pools (e.g. Franko et al., 1997; Smith et al., 1997; Cui  
4 et al., 2005; Del Grosso et al., 2005; van Huissteden et al., 2006) to account for differences in  
5 substrate quality. This leads to the problem of partitioning total SOC into the pools (e.g.  
6 Helfrich et al., 2007; Zimmermann et al., 2007). In some models, the various SOC pools  
7 differ also in their response functions (e.g. Smith et. al, 2010).

8 The highest decomposition rates occurred at sites with highest biomass production. A  
9 correlation of productivity with soil respiration was found in several comparison studies (e.g.  
10 Janssens et al., 2001; Reichstein et al., 2003). Fresh material provided by the plants might  
11 lead to higher microbial activity and priming effect (e.g. Kuzyakov, 2002; Fontaine et al.,  
12 2007). Higher plant to soil respiration ratio reduced the differences in  $k_l$  between the sites and  
13 lowered winter  $R_{eco}$ , especially at the highly productive FsA and FsB, but also reduced the  
14 model performance at all sites except Amo.

15 Vegetation at Amo and Lom consist largely of mosses which are more resistant to  
16 decomposition then vascular plants (Rudolph and Samland, 1985; Verhoeven and Toth, 1995;  
17 Limpens and Berendse, 2003; Moore et al., 2007) and might further explain the low  $k_l$  value  
18 at Amo. Despite the lower biomass production, higher moss cover and higher C:N ratio  
19 compared to Hor, FsA or FsB, Lom has a relative high decomposition rate. This can be  
20 explained by the very low dry bulk density, resulting in low amount of C in the upper soil  
21 layers (Tab. 3) which are most exposed to decomposition (e.g. Fang and Moncrieff, 2005).  
22 Also, a low dry bulk density accompanies with low degree of degradation and therefore high  
23 amounts of labile carbon (e.g. Grosse-Brauckmann, 1990).

24 Despite the large differences in accumulated NEE (Fig. 1) between FsA and FsB, they almost  
25 do not differ in their decomposition rates. This confirms the expectations that the differences  
26 in NEE between FsA and FsB can be fully explained by the differences in water table,  
27 biomass and carbon stocks.

## 28 **5 Conclusions**

29 Differences between sites in respect to  $CO_2$  fluxes could be explained if beside air  
30 temperature, water table and soil C- & N- stocks, also site specific plant productivity and  
31 decomposition rates were taken into account. Differences in nutrients availability and soil  
32 wetness could not explain the differences in plant productivity between the sites. Substrate



1 quality, litter input, as well as pH values were likely explanations for the differences in  
2 decomposition rates. A site specific interpretation was not needed for processes related to  
3 plant phenology, their response to temperature, allocation of new assimilates and plant  
4 respiration and litter fall rates.

5 The model parameters which strongly affected model performance were successfully  
6 constrained by the available long term measurement data on NEE, partitioned into GPP and  
7  $R_{eco}$ , LAI and biomass, including rooting depth and root biomass at one site, water table, soil  
8 temperature and soil C and N stocks as well as meteorological data and snow data at one site.  
9 It would have been useful if additional information was available about root biomass at all  
10 sites, root litter fall and soil water content to validate the model performance in the  
11 corresponding processes. A second measurement of C and N stocks, several years after the  
12 first, as well as information about the degree of decomposition on all sites would have been  
13 very helpful to constrain decomposition rates and partitioning between SOM pools.

14 Some improvements in the model and its configuration were identified to obtain a better  
15 performance for simulations of GHG fluxes from treeless peatlands. Examples include  
16 separate temperature responses for plant and soil heterotrophic respiration. The static response  
17 to water saturated conditions needs to be replaced by a function that considers the change of  
18  $O_2$  in the soil.

19

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15 The simulation files with the setup according the common configuration together with the  
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## 1 **Appendix A:**

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- 14

# 1 *Tables*

## 2 Table 1. Site characteristics

Code	Lom	Amo	Hor	FsA and FsB
Country	Finland	UK	Netherlands	Germany
Site name	Lompolojänkä	Auchencorth moss	Horstermeer	Freisinger Moos
Area [m <sup>2</sup> ]	120000	250000	120000	400
Latitude; longitude	67°59'83"N; 24°12'55"E	55°47'34"N; 3°14'35"W	52°14'25"N 5°4'17"E	48°22'50"N 11°41'12"E
Peatland type	fen	bog	fen	fen
Dominant vegetation	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 precipitation [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

3 <sup>a</sup> annual range of mean monthly temperatures

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## 1 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
$k_{gresp}$	growth respiration coefficient
$k_h$	rate coefficient for the decay of the slow C pools
$k_f$	rate coefficient for the decay of the fast C pools
$k_{tot}$	Total rate of decomposition calculated from $k_h$ , $k_f$ and SOC of the corresponding pools in the upper 30 cm
$k_{mrespleaf}$	maintenance respiration coefficient for leaves
$k_{rn}$	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
$m_{retain}$	coefficient for determining allocation to mobile internal storage pool
N	nitrogen
NSE	Nash-Sutcliffe efficiency
$p_{ck}$	speed at which the maximum surface cover of plants is reached
$p_{\theta p}$	power coefficient in the response function of microbial activity in dependency of soil moisture
$p_{\theta Satact}$	activity under saturated conditions in the soil moisture response function for microbial activity, mineralisation-immobilisation, nitrification and denitrification
$p_{\theta Upp}$	water content interval in the soil moisture response function for microbial activity, mineralisation-immobilisation, nitrification and denitrification
R <sup>2</sup>	coefficient of determination
R <sub>eeco</sub>	ecosystem respiration
SOC	soil organic carbon
$T_{amean}$	assumed value of mean air temperature for the lower boundary condition for heat conduction
$T_{aamp}$	assumed value of the amplitude of the sine curve, representing the lower boundary condition for heat conduction
$T_{MatureSum}$	temperature sum beginning from grain filling stage for plant reaching maturity stage
$T_{DormTh}$	critical air temperature that must be undershoot for temperature sum calculation
$T_{EmergeSum}$	air temperature sum that is the threshold for start of plant development
$T_{EmergeTh}$	critical air temperature that must be exceeded for temperature sum calculation
$t_{Q10}$	response to a 10 °C soil temperature change on the microbial activity, mineralisation-immobilisation, nitrification, denitrification and plant respiration
$t_{Q10bas}$	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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1 Table 3. Partitioning of measured SOC to the pools. The data in the table is aggregated into 3  
 2 soil layers, however 12 layers were used in the model

	depth [m]	Lom	Amo	Hor	FsA	FsB
Measured total C [kg m <sup>-3</sup> ]	0-0.1	24	190	72	107	88
	0.1-0.3	30	187	79	104	90
	> 0.3	51	175	156	70	61
Measured C:N [kg m <sup>-3</sup> ]	0-0.1	27	23	13	11	12
	0.1-0.3	20	22	13	14	13
	> 0.3	20	21	22	17	17
Estimated fraction of fast pool / total C	0-0.1	95%	72%	18%	3%	9%
	0.1-0.3	56%	73%	20%	20%	16%
	> 0.3	55%	68%	62%	35%	41%
Dry bulk density [g cm <sup>-3</sup> ]	0-0.1	0.06 <sup>a</sup>	0.39	0.35	0.59	0.33
	0.1-0.3	0.06	0.37	0.48	0.29	0.52
	> 0.3	0.10	0.37 <sup>b</sup>	0.50	0.18	0.17

3 <sup>a</sup> no data available, value from lower layer used

4 <sup>b</sup> no data available, value from upper layer used

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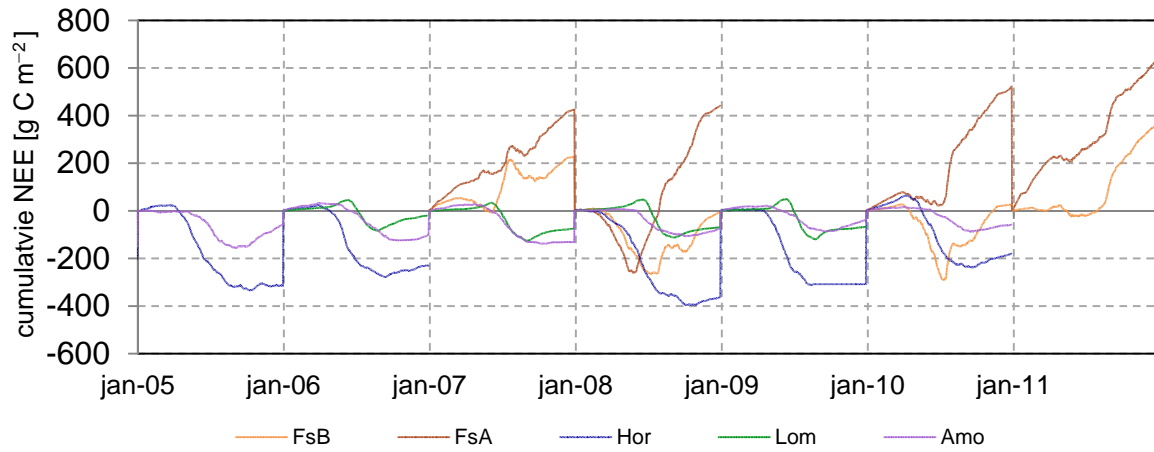
1 Table 4. Highest achieved values for selected performance indices

Variable	Index	Lom		Amo		Hor		FsA		FsB	
		all/selec ted runs	single run	all/selec ted runs	single run	all/selec ted runs	single run	all/selec ted runs	single run	all/selec ted runs	single run
NEE	R <sup>2</sup>	0.61/0.6 0	0.59	0.59/0.5 8	0.55	0.53/0.5 1	0.48	0.20/0.1 6	0.15	0.25/0.2 1	0.19
	ME	0.00	0.05	0.00	0.04	0.00	0.02	0.00	1.43	0.00	-0.05
GPP	R <sup>2</sup>	0.66/0.6 6	0.65	0.68/0.6 8	0.66	0.58/0.5 7	0.55	0.38/0.3 5	0.34	0.40/0.3 9	0.35
	ME	0.00	0.05	0.00	-0.09	0.00	0.04	0.00	0.06	0.00	-0.03
R <sub>eco</sub> EC	R <sup>2</sup>	0.79/0.7 4	0.69	0.71/0.7 1	0.66	0.78/0.7 7	0.75	n.a.	n.a.	n.a.	n.a.
	ME	0.00	0.00	0.00	-0.05	0.00	-0.06	n.a.	n.a.	n.a.	n.a.
R <sub>eco</sub> chamber	R <sup>2</sup>	0.73/0.7 1	0.64	0.67/0.5 7	0.38	0.52/0.4 8	0.45	0.73/0.6 6	0.69	0.87/0.8 1	0.85
	ME	0.00	-0.06	0.00	0.04	0.00/-4. 74	-5.38	0.00	-0.01	0.00	-0.08
R <sub>eco</sub> winter	R <sup>2</sup>	0.67/0. 63	0.63	0.14/0. 08	0.06	0.28	0.28	0.51/0. 43	0.32	0.92/0. 89	0.89
	ME	0.00	0.01	0/0.04	0.13	0.00	-0.26	0/1.60	3.21	0.00/0. 73	2.11
upper soil temperat ure	R <sup>2</sup>	0.88/0. 87	0.87	0.86	0.84	0.92	0.91	0.88/0. 86	0.84	0.88/0. 86	0.84
	ME	0.00	-0.01	-0.03	-0.08	-1.37/ -1.51	-1.77	0.00/0. 58	0.35	0/1.20	0.35
lower soil temperat ure	R <sup>2</sup>	0.95	0.95	0.90	0.89	0.89	0.89	0.97/0. 96	0.94	0.92/0. 91	0.94
	ME	0.00	-0.03	0.00	0.02	0.00	-0.08	0.00	-0.15	0.00	-0.15
Snow depth	R <sup>2</sup>	0.75	0.75	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	ME	-0.1	-0.06	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LAI	R <sup>2</sup>	0.65/0. 51	0.53	n.a.	n.a.	0.36/0. 31	0.33	0.75/0. 69	0.61	0.82/0. 76	0.61
	ME	0.00	0.11	n.a.	n.a.	0.00/ -0.61	-1.49	0.00	0.12	0.00	0.05
Above ground living biomass	R <sup>2</sup>	n.a.	n.a.	n.a.	n.a.	0.02/0. 00	0.00	0.31/0. 26	0.24	0.47/0. 43	0.32
	ME	n.a.	n.a.	n.a.	n.a.	0	-112	0/-20	-21	0/-36	-48
Root biomass	R <sup>2</sup>	n.a.	n.a.	n.a.	n.a.	0.28/ 0.07	0.01	n.a.	n.a.	n.a.	n.a.
	ME	n.a.	n.a.	n.a.	n.a.	0.00	-282	n.a.	n.a.	n.a.	n.a.

2 n.a. not available

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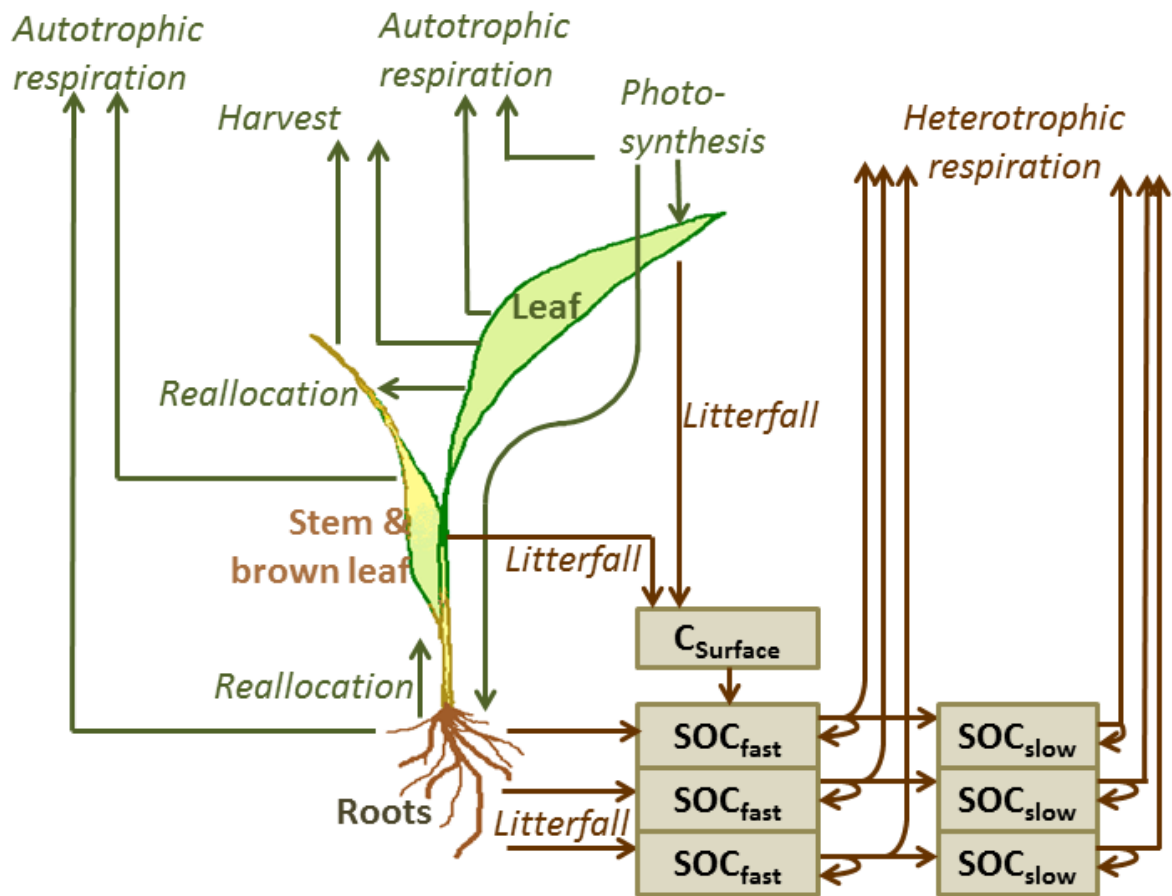
1 Figures



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3 Figure 1. Measured NEE from gapfilled time series. Positive values indicate CO<sub>2</sub> emission,  
4 negative CO<sub>2</sub> uptake by the ecosystem.

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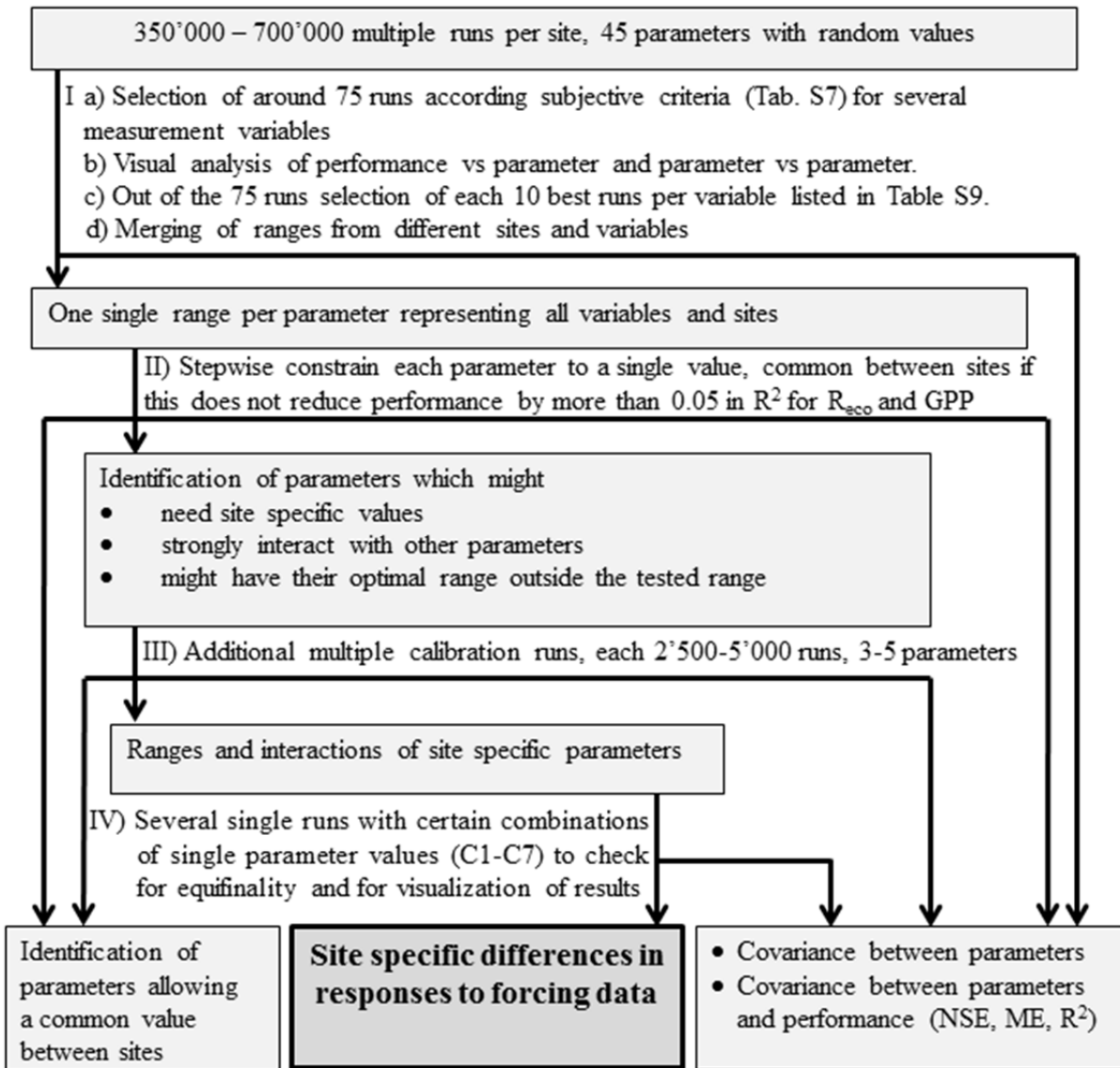
2 Figure 2. Scheme of carbon fluxes and pools in the current CoupModel setup

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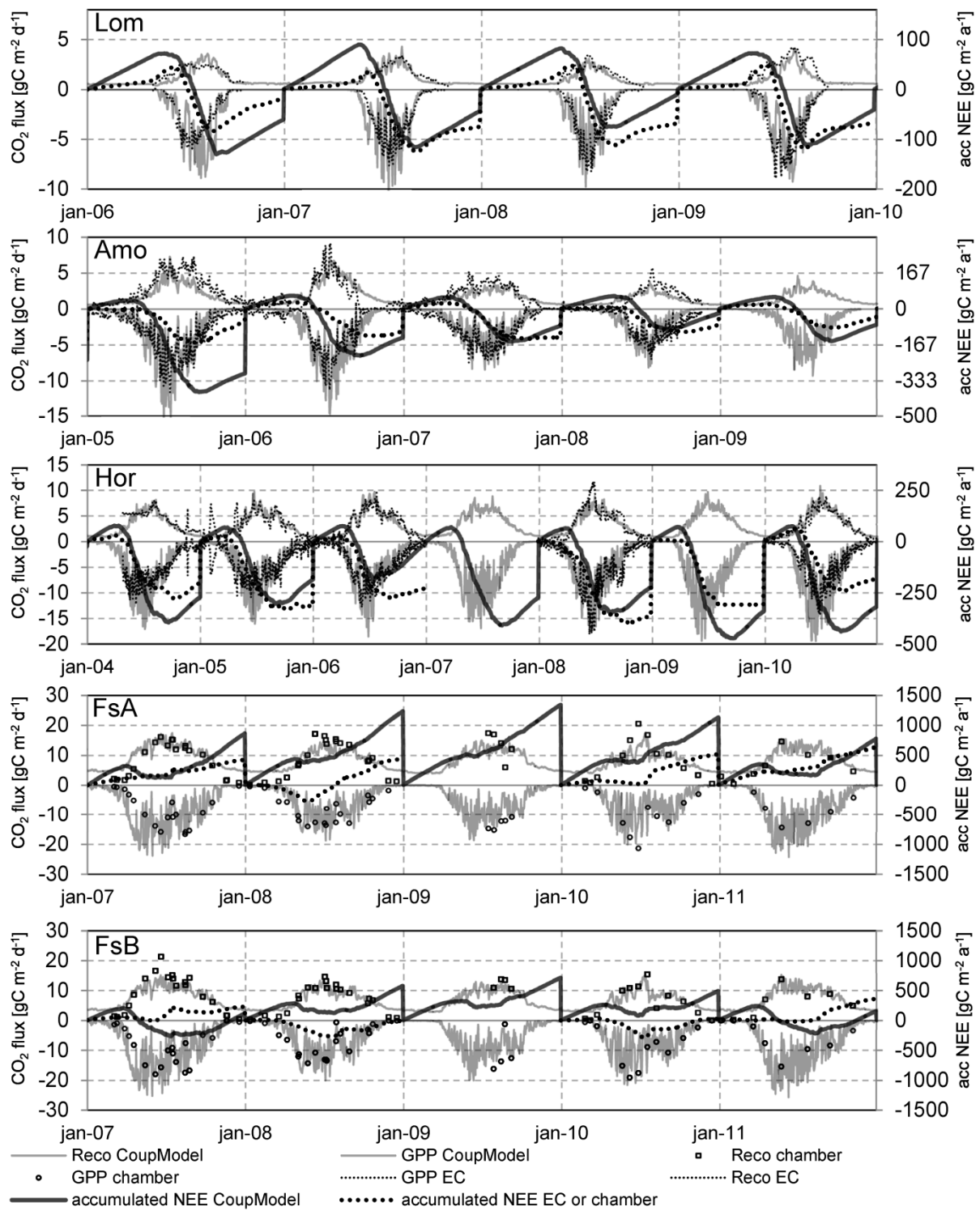
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2 Figure 3. Stepwise parameter calibration. Boxes show the outcome of each step. Description  
3 for scenarios C1-C7 can be found in Table S8 in the supplement.

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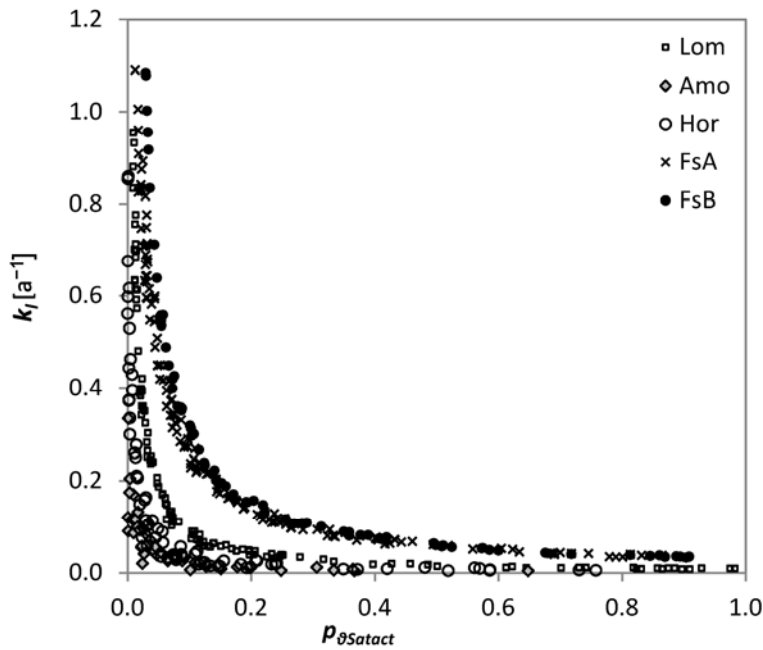
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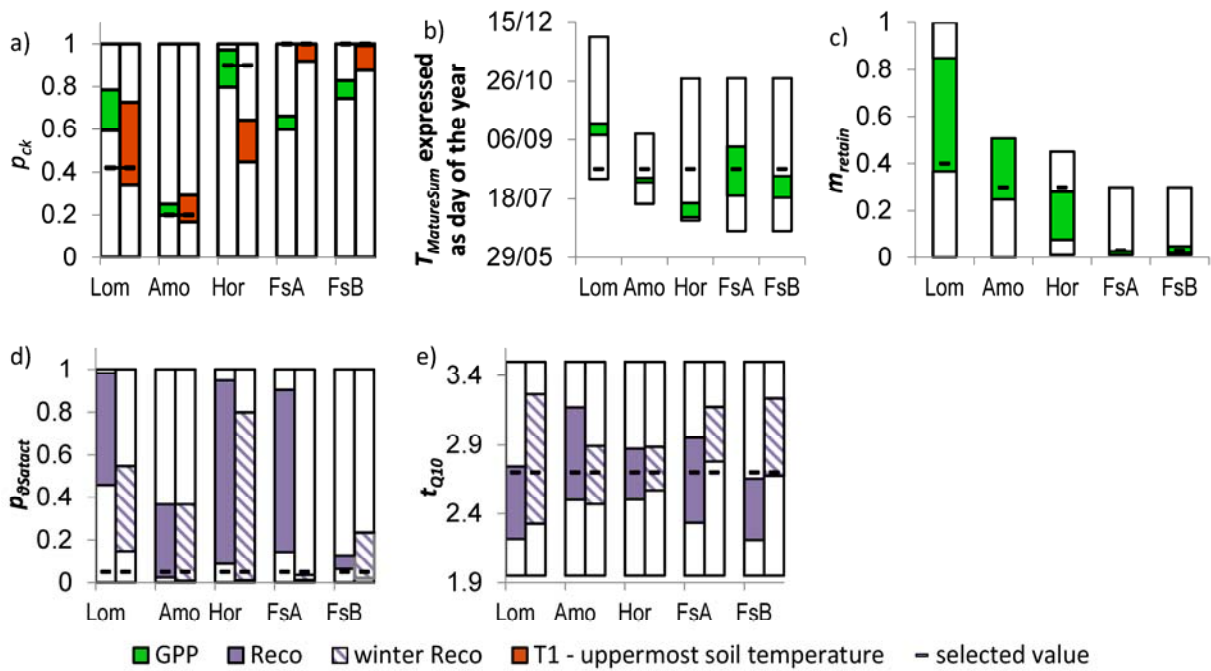
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2 Figure 4. Simulated and measured  $R_{\text{eco}}$  (positive) and GPP (negative) fluxes and accumulated  
 3 NEE for one selected set of parameter values (C1) common between all sites. Note the  
 4 different scales.



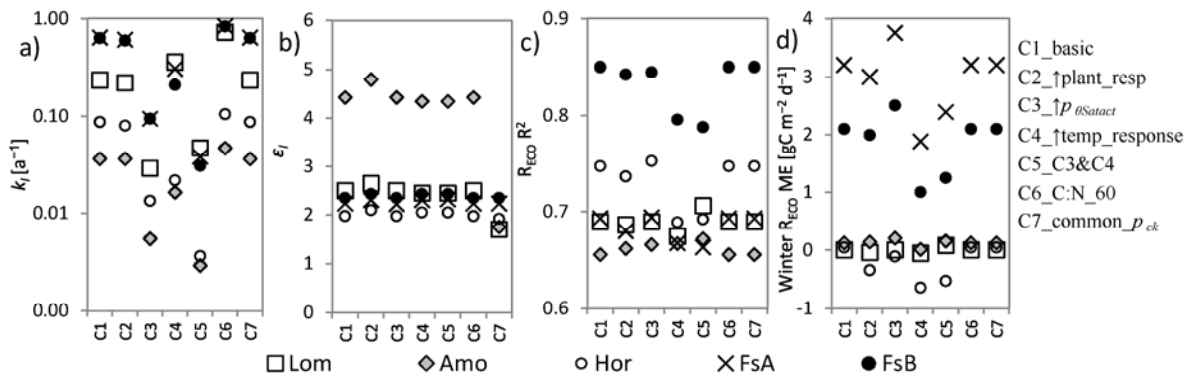
1  
2 Figure 5. Dependencies between the parameters for decomposition rate and saturation activity  
3 for the different sites, based on additional multiple runs.

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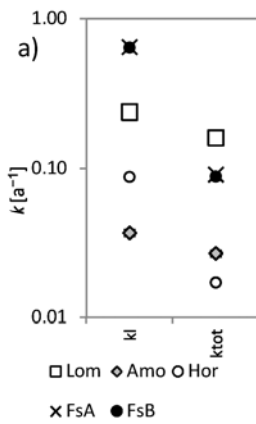
5  
6 Figure 6. Obtained distributions of parameter values as constrained by additional multiple  
7 runs (calibration step III). Ranges for  $k_{ll}$  and  $\varepsilon_L$  are not shown due to their interactions with  
8 several parameters. Coloured bars show the range of the 10 runs with the best performance for

1 each validation variable. Prior ranges are indicated by the frame around the bar. Black dash is  
 2 the value chosen for the common configuration C1.



3  
 4 Figure 7. Values for the parameters decomposition rate (a) and light use efficiency (b) and  
 5 resulting model performance (c, d) when applying various single value representations of  
 6 parameters (C1-C7, see Tab. S8 in the supplement).

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10  
 11 Figure 8. Decomposition rates of fast pools ( $k_l$ ) and calculated rates of total organic matter  
 12 decomposition if only one pool was used ( $k_{tot}$ ) for each site and each layer

13