

# 1 Forests on drained agricultural peatland are potentially 2 large sources of greenhouse gases – insights from a full 3 rotation period simulation

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5 H. He<sup>1</sup>, P.- E. Jansson<sup>2</sup>, M. Svensson<sup>2</sup>, J. Björklund<sup>1, 3</sup>, L. Tarvainen<sup>4, 5</sup>, L.  
6 Klemedtsson<sup>1</sup> and Å. Kasimir<sup>1</sup>

7 [1]{Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden}

8 [2]{Department of Land and Water Resources Engineering, Royal Institute of Technology  
9 (KTH), Stockholm, Sweden}

10 [3]{Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf,  
11 Switzerland}

12 [4]{Department of Forest Ecology and Management, Swedish University of Agricultural  
13 Sciences, Umeå, Sweden}

14 [5]{Department of Biological and Environmental Sciences, University of Gothenburg,  
15 Gothenburg, Sweden}

16  
17 Correspondence to: H. He (hongxing.he@gvc.gu.se)

## 18 19 **Abstract**

20 The CoupModel was used to simulate a Norway spruce forest on fertile drained peat over 60-  
21 years, from planting in 1951 until 2011, describing abiotic, biotic and greenhouse gas (GHG)  
22 emissions (CO<sub>2</sub> and N<sub>2</sub>O). By calibrating the model against tree ring data we obtained a  
23 ‘vegetation fitted’ model by which we were able to describe the fluxes and controlling factors  
24 over the 60 years. We discuss some conceptual issues relevant to improving the model in  
25 order to better understand peat soil simulations. However, the present model was able to  
26 describe the most important ecosystem dynamics such as the plant biomass development and  
27 GHG emissions. The GHG fluxes are composed of two important quantities, the spruce forest  
28 carbon (C) uptake, 413 g C m<sup>-2</sup> yr<sup>-1</sup> and the decomposition of peat soil, 399 g C m<sup>-2</sup> yr<sup>-1</sup>. N<sub>2</sub>O  
29 emissions contribute to the GHG emissions by up to 0.7 g N m<sup>-2</sup> yr<sup>-1</sup>, corresponding to 76 g C

1  $\text{m}^{-2} \text{yr}^{-1}$ . The 60-year-old spruce forest has an accumulated biomass of  $16.0 \text{ kg C m}^{-2}$ .  
2 However, over this period,  $26.4 \text{ kg C m}^{-2}$  have been added to the atmosphere, which means a  
3 net emission of GHGs. The main losses are from the peat soil and, indirectly, from forest  
4 thinning products, which we assume have a short lifetime. We conclude that after harvest at  
5 an age of 80 years, most of the stored biomass carbon is liable to be released, the system  
6 having captured C only temporarily and with a cost of disappeared peat, adding  $\text{CO}_2$  to the  
7 atmosphere.

8

## 9 **1 Introduction**

10 Peatlands contain around one third of the carbon (C) stored in global soils, which is  
11 equivalent to almost half that present in the atmosphere (FAO, 2012; IPCC, 2013).  
12 Undisturbed peatlands accumulate C as partially decayed vegetation, and the decay processes  
13 emit C in the form of carbon dioxide ( $\text{CO}_2$ ) and methane ( $\text{CH}_4$ ). Overall, the balance of  
14 photosynthesis and respiration in peatlands means that these systems act as C sinks, acting to  
15 mitigate climatic warming (e.g. Gorham, 1991). However, when peatlands are drained for  
16 intensified land use, i.e. agriculture or forestry, the stored peat starts to decompose  
17 aerobically. The accelerated soil decomposition emits large amounts of  $\text{CO}_2$ , in contrast  $\text{CH}_4$   
18 emissions are greatly reduced, possibly even accounting for a net uptake of atmospheric  $\text{CH}_4$   
19 (Limpens et al., 2008). The decomposition also releases nitrogen, and another powerful GHG,  
20 nitrous oxide ( $\text{N}_2\text{O}$ ), could also be produced, primarily through microbial nitrification and  
21 denitrification processes (Firestone and Davidson, 1989). Globally, peatlands cover only 3%  
22 of the Earth surface, of which in turn 10% - 20% have been drained for agriculture or forestry,  
23 mainly in the boreal and tropical regions (FAO, 2012). However, these drained areas emit  
24 around 6% of the global annual anthropogenic GHG emissions (IPCC, 2013).

25 To date, a number of studies have investigated the size of GHG fluxes from managed  
26 peatlands with different land uses, together with their interactions with environmental factors  
27 (Kasimir Klemedtsson et al., 1997; Von Arnold et al., 2005a; Von Arnold et al., 2005b; Alm  
28 et al., 2007; Beek et al., 2010; Lund et al., 2010; Lohila et al., 2011; Ojanen et al., 2013).  
29 Several factors have been found to influence the size of the emissions, including the  
30 groundwater level (GWL), land use intensity, climate zones, and soil fertility (Klemedtsson et  
31 al., 2005; Drösler et al., 2008; Leppelt et al., 2014). In general, nutrient rich fens with deep  
32 GWL are larger GHG sources than ombrotrophic bogs with shallow GWL, while intensive  
33 land use in tropical/temperate regions have much higher emissions than extensive land use in

1 boreal regions (Byrne et al., 2004). Peatlands in Europe used as grassland, agricultural land,  
2 peat cuts, and abandoned peat are generally found to be net GHG sources (Byrne et al., 2004;  
3 Drösler et al., 2008). However, forested drained peatland can be everything from a source to a  
4 small GHG sink due to the growing forest, where the net primary production (NPP) of trees  
5 and understorey vegetation balances the soil emissions (Drösler et al., 2008; Klemedtsson et  
6 al., 2008; Hommeltenberg et al., 2014). Previous flux measurement studies have also shown  
7 contradictory results. Measurements from Scandinavia and Great Britain have shown the NPP  
8 to compensate for the soil CO<sub>2</sub> release, and thus the forests to act as net sinks (Hargreaves et  
9 al., 2003; Von Arnold et al., 2005a; Von Arnold et al., 2005b; Ojanen et al., 2013).  
10 Hommeltenberg et al., (2014) also reported an afforested drained bog in southern Germany to  
11 be a net GHG sink; however, if the 44-year history of the forest were included in the analysis,  
12 then the so-called ‘long-term carbon balance’, showed the forest to be an overall GHG source.  
13 Von Arnold et al., (2005a) showed that accounting for N<sub>2</sub>O in the greenhouse budget  
14 calculation could shift drained birch peatlands from being minor GHG sinks into sources.  
15 This was also shown by Meyer et al., (2013) for a drained former agricultural peat soil with  
16 spruce forest, where soil N<sub>2</sub>O emissions, in terms of global warming potential (265 times of  
17 CO<sub>2</sub> in a 100-year perspective, IPCC, 2013), offset half the net ecosystem exchange (NEE).  
18 Large N<sub>2</sub>O emissions are most pronounced for fertile soils like former agricultural peatlands  
19 (Klemedtsson et al., 2005). So far most studies have only covered a few years at most.  
20 Consequently we still lack an understanding of the full GHG balance when viewed over the  
21 full forest rotation (Maljanen et al., 2010).

22 In the present study we aim to address this knowledge gap by exploring the GHG balance for  
23 a Norway spruce (*Picea abies*) forest on drained agricultural peatland (Skogaryd Research  
24 Site) over a full rotational time period. Since measurements are mostly short-term, and  
25 because it is not possible to directly upscale the measured fluxes to the entire forest rotation  
26 period (Drösler et al., 2008; Hommeltenberg et al., 2014), we chose a modeling approach  
27 based on emission data over five years and data on forest growth rate over 45 years for a  
28 spruce forest on former agricultural peatland.

29

## 30 **2 Material and methods**

### 31 **2.1 Site description**

1 Data used for the present study were obtained from the Skogaryd research site  
2 (<http://www.fieldsites.se/en/field-research-stations>), located in southwest Sweden (58°23'N,  
3 12°09'E), which is part of the Swedish Infrastructure for Ecosystem Science (SITES,  
4 [www.fieldsites.se](http://www.fieldsites.se)). The drained peat area at Skogaryd was previously a fen, classified as  
5 mesotrophic peat with a peat depth of more than 1 m, according to the soil classification  
6 scheme suggested by Karlsson (1989). It was initially drained by ditches in the 1870s and  
7 then used for agriculture until 1951. Norway spruce (*P. abies*) was then planted and the stand  
8 is now a mature mixed coniferous forest dominated by Norway spruce (95% by stem volume),  
9 with a sparse presence of Scots pine (*Pinus sylvestris*) and Silver birch (*Betula pubescens*)  
10 (Klemedtsson et al., 2010). The site has been intensively measured and monitored since 2006,  
11 providing abiotic and biotic data including CO<sub>2</sub> and N<sub>2</sub>O fluxes that could be used to validate  
12 the long-term model predictions. More detailed site description can be found in He et al.,  
13 (2016), Klemedtsson et al., (2010), Meyer et al. (2013) and Ernfors et al. (2010).

## 14 **2.2 Modelling description**

### 15 **2.2.1 Concept of drained peatland for forestry**

16 When peatlands are drained for forestry or agriculture, resulting in a lower GWL, the aerobic  
17 soil volume increases (Fig. 1a). The previously water-logged peat soil then decomposes  
18 aerobically, losing soil C stock and also causing a lowering of the soil surface (surface  
19 subsidence) (Eggelsmann, 1976; Hooijer et al., 2012). During the first few decades after  
20 planting, the development of plant roots and leaf area cover increases the transpiration rate, so  
21 deepening the GWL (Fig. 1b). In other words, a growing forest will, in part, help to keep the  
22 soil drained. However, drainage becomes less efficient with time due to subsidence and  
23 ditches becoming filled with litter and moss, all of which can lead to an increased GWL (Fig.  
24 1c), which is why ditch maintenance is performed regularly. After ditch maintenance the  
25 forest ecosystem restarts at the well-drained state (Fig. 1d), until the final clear-cutting when  
26 re-drainage has to be conducted. The entire cycle then starts again and can continue until all  
27 the peat is gone.

### 28 **2.2.2 Brief introduction to the CoupModel**

29 The CoupModel (coupled heat and mass transfer model for soil-plant-atmosphere systems) is  
30 an updated version of the previous SOIL and SOILN model (Jansson and Moon, 2001). The

1 main model structure is a one-dimensional, layered soil depth profile, in which the water,  
2 heat, and C and N dynamics are simulated based on detailed descriptions of soil physical and  
3 biogeochemical processes. C and N dynamics are simulated both in the soil and in the plant,  
4 driven by the canopy-intercepted radiation, regulated by multiplicative response functions of  
5 air temperature, and plant availability of water and N. Two vegetation layers are simulated in  
6 the model, the spruce tree and the understorey layer (e.g. grasses and shrubs) (He et al., 2016).  
7 The model is available at <http://www.coupmodel.com/>. A detailed description of the model,  
8 its parameterization and setup is given in He et al., (2016); here only the variables and  
9 parameters with different values are reported.

### 10 **2.2.3 Model approach and design**

11 The CoupModel conceptually divides the soil organic matter (SOM) into two pools called soil  
12 litter (fresh plant detritus) and humus, constituting a fast and a slow decomposing pool,  
13 respectively (Johnsson et al., 1987). When soil litter decays, carbon is either released as CO<sub>2</sub>,  
14 or added into a resistant fraction, the humus pool (Johnsson et al., 1987). In this study, the soil  
15 humus pool was used to represent the old stored soil peat. Thus soil decomposition is  
16 composed of both peat decomposition (called humus decomposition in the model) and soil  
17 litter decomposition. Besides, CoupModel conceptualizes the soil profile into a number of soil  
18 layers, where the soil's physical structure (defined by the measured water retention  
19 characteristics) and the drainage depth (a parameter used for estimation of horizontal flow of  
20 water out of the site due to drainage) is assumed to be fixed over time (Figs 1e and 1f), with  
21 the drainage depth set to 0.5 m as in He et al., (2016). Though the drainage depth is a very  
22 important parameter for the simulated GWL, a fixed drainage level is not to be confused with  
23 a fixed GWL as the latter is simulated (see Fig 5f). The subsidence of the soil surface and any  
24 variation in drainage (Figs 1a, 1b, 1c and 1d) during the plant development years (1951 to  
25 2011) cannot explicitly be simulated. We thus make the following assumptions to simplify the  
26 system:

27 First, the soil layers are assumed the same over the 60 years simulated, and the soil physical  
28 characteristics in 1951 are assumed the same as measured in 2006. Whilst this assumption  
29 may not hold in detail, we consider any changes minor as 1) this site has been drained for  
30 many years (starting in 19th century), why physical soil compaction should not be important  
31 during the last 60 years, and 2) soil properties were not found to be the major GHG emission  
32 influencing factor (He et al., 2016). A range of drainage depth was used to quantify the

1 model's sensitivity. The lower end of the range was chosen to be a drainage depth of 0.3 m,  
2 since this has been suggested to be the minimum requirement to sustain forest productivity on  
3 drained peatlands (Sarkkola et al., 2010; Ojanen et al., 2013). The higher drainage level of  
4 0.8 m was set according to general forest management practices, also taking into  
5 consideration the maximum simulated soil depth 1 m.

6 Second, in order to define the initial soil C content in 1951, we use the soil C measurements  
7 made at Skogaryd in 2007, back-calculated to 1951 by assuming an annual peat loss of 260 g  
8 C m<sup>-2</sup> yr<sup>-1</sup> from 1951 to 2007. This annual loss was taken from the recent IPCC wetland  
9 supplement (IPCC, 2014), where it represents the emission factor for forest on drained  
10 nutrient-rich peatlands in the temperate region. The model's sensitivity to this initial condition  
11 was assessed by varying IPCC emission factors (EF's) between 200 and 330 g C m<sup>-2</sup> yr<sup>-1</sup>  
12 when calculating total soil C in 1951. In addition, an extremely large initial soil C is also used  
13 in the sensitivity analysis which was back-calculated using the highest peat decomposition  
14 rate of 630 g C m<sup>-2</sup> yr<sup>-1</sup> (Meyer et al., 2013) measured at Skogaryd during 2008. The back  
15 calculated total soil C is assumed uniformly distributed in the soil profile of 1 meter depth,  
16 based on the measured data in 2007 (He et al., 2016).

17 Third, the soil C / N ratio in 1951 is assumed to be the same as measured in 2006, and the N  
18 deposition rate was also assumed to be constant as in He et al., (2016) during the entire  
19 simulated period. The model's sensitivity to this was tested by varying the initial soil C / N  
20 ratio between 20 and 45, the latter being a value measured at a nearby un-drained peatland  
21 near Skogaryd.

22 Fourth, the model only simulates the C and N dynamics in the uppermost 1 m depth of soil.

23 The model was initially run with the calibrated single parameter representation using the same  
24 mean parameter values as used by He et al., (2016). However, each calibrated parameter has a  
25 range of possible values, its so-called posterior distribution, which we varied in order to fit the  
26 model results to the 45 year (1966 to 2011) tree-ring-derived biomass data and extended  
27 abiotic data (2006 to 2011). We call the model parameterized to fit those data the 'vegetation  
28 fitted' model, used for sensitivity analysis by varying the drainage depth, initial soil C, as well  
29 as the initial soil C / N ratio.

### 30 **2.3 Tree ring sampling and data processing**

1 The previous calibration of the CoupModel mainly focused on the soil processes while plant  
2 development was less emphasized (He et al., 2016). In order to calibrate the model results of  
3 the plant biomass development, we acquired incremental core samples from the spruce trees  
4 in Skogaryd during spring 2013, to estimate forest biomass. In total, 25 samples were  
5 obtained from randomly chosen trees. The cores were taken at breast height (1.3 m above  
6 ground). The annual growth rings in the tree cores were cross-dated according to standard  
7 dendrochronological methods (Stokes and Smiley, 1968) to assign an exact calendar year of  
8 formation to each ring. Tree ring width data were obtained by analysis of scanned images of  
9 carefully surfaced cores using the software CooRecorder (cybis.se). The annual variation in  
10 height growth was modeled with the Korf's function using cumulative radial growth during  
11 the previous years, calibrated by extensive inventory data, collected in 2010 (Meyer et al.,  
12 2013). Since the inventory data lacked information concerning trees with a diameter smaller  
13 than 10 cm, and because the sample depth of trees decreases back in time, the forest biomass  
14 calculations were only considered to be valid from 1966 (a date when all trees had a diameter  
15 above 10 cm and the sample replication was complete). The forest biomass was calculated for  
16 stem, living branches, dead branches, stumps and roots including fine roots, following the  
17 allometric equations (Marklund, 1988) for spruce in Minkkinen et al., (2001) and Meyer et al.,  
18 (2013), using the inputs of measured annually resolved radial growth and modeled annual  
19 longitudinal growth. The total biomass of the tree stands was calculated as a sum of the  
20 average biomass of the individual trees, where the planting density was assumed to be 3000  
21 trees ha<sup>-1</sup>, which was a typical planting density during the 1950s in Sweden (Drossler et al.,  
22 2013). A thinning was conducted by the land owner in 1979 when the number of trees was  
23 reduced to ca. 1000 trees ha<sup>-1</sup>, according to the survey data presented in Meyer et al. (2013).  
24 Using these tree ring biomass data, the thinning management was estimated to have removed  
25 72% of the spruce biomass. The forest thinning practices was assumed and made according to  
26 general Swedish forest management guidelines (Svensson et al., 2008). In addition, a heavy  
27 storm hit Skogaryd forest in 2010 and blew down 10% of the tree biomass. The fallen trees  
28 were removed from the experimental site after the storm event. Therefore an additional  
29 harvest was included in the CoupModel to simulate this removal of storm-fallen biomass.

## 30 **2.4 Data for model forcing**

31 To drive the model, we used daily mean meteorological data (1961 to 2011) from the Swedish  
32 Meteorological and Hydrological Institute (SMHI) Sätenäs station (58°44'N, 12°71'E),  
33 (www.smhi.se) situated approximately 60 km east of Skogaryd. Precipitation, air temperature,

1 wind speed and relative humidity data from Såtenäs were strongly correlated ( $R^2 > 0.8$ ) with  
2 those from Skogaryd from 2006 to 2011, and were of similar magnitude. Another driving  
3 variable needed in CoupModel is the global short wave radiation. As these data are not  
4 available from Såtenäs station, they were deduced by the model from the potential global  
5 radiation and atmospheric turbidity, using the measured total cloud-cover fraction (for more  
6 details see <http://www.coupmodel.com>). Since meteorological data were only available from  
7 1961, the meteorological data from 1961 to 1971 were duplicated to represent the climate  
8 between 1951 and 1961.

## 9 **2.5 GHG budget compilation**

10 For a total GHG budget of the system we include harvest removal and products. We assume  
11 that the biomass removed by thinning management in 1979 and the storm harvest in 2010 was  
12 mainly used for paper production, as is common practice in Sweden (Swedish Forest Agency,  
13 2005). We therefore use the emission factors suggested in the IPCC guidelines (IPCC, 2006),  
14 in which paper is assumed to decay exponentially with a half-life of 2 years.

15

## 16 **3 Results**

### 17 **3.1 Model performance**

#### 18 **3.1.1 Plant and soil development from 1951 to 2011**

19 The simulated tree biomass dynamics during the 60 years agrees well with the estimated tree  
20 biomass from radial growth observations beginning in 1966. After an initial phase of slow  
21 growth during the establishment of the spruce trees' leaf area, growth increased almost  
22 linearly (Fig. 2d). The spruce trees gradually increased their leaf (needles) cover until a closed  
23 canopy formed in the 1980s with a maximum leaf area index (LAI) of around 6, which was  
24 similar to field measurements (Fig. 2b). The simulated annual average spruce tree growth over  
25 the whole period is  $413 \text{ g C m}^{-2} \text{ yr}^{-1}$  with the maximum growth rate of  $848 \text{ g C m}^{-2} \text{ yr}^{-1}$  in 1974  
26 (Fig. 2c). However, the 'vegetation fitted' model showed a slow establishment of the spruce  
27 in the first decade due to a modelled competition from grasses and other field vegetation, thus  
28 underestimating the spruce growth before 1970, mainly caused by lack of information on  
29 initial stages. The LAI and the NPP of spruce generally follow the dynamics of the plant's  
30 ability to intercept radiation (Fig. 2a); however, the model slightly overestimates annual



1 spruce tree growth from the 1970s to the 1990s, and underestimates it from 1996 until 2011  
2 (Fig. 2c). Furthermore, the large increase of simulated plant growth observed in 2006 was not  
3 observed in the tree ring data. The total tree biomass in 2011 is modeled to be  $16.0 \text{ kg C m}^{-2}$ ,  
4 which is very similar to the biomass estimated from the tree ring data,  $16.2 \text{ kg C m}^{-2}$  (Fig. 2d).  
5 The thinning conducted in 1979 removed  $6.8 \text{ kg C m}^{-2}$  plant biomass, and the storm in 2010  
6 caused an additional removal of  $1.8 \text{ kg C m}^{-2}$ ; these quantities were used for indirect emission  
7 calculations (Fig. 2d). The modeled amounts of leaf and root biomass in 2007 also match  
8 estimations using allometric equations reported by Meyer et al., (2013). The modeled and  
9 estimated values for leaf biomass were  $0.95$  and  $1.06 \text{ kg C m}^{-2}$ , respectively, and the values  
10 for total roots (both coarse roots ( $> 2 \text{ mm}$ ) and fine roots ( $< 2 \text{ mm}$ )) were  $2.9$  and  $3.0 \text{ kg C m}^{-2}$ ,  
11 respectively. The modeled value for spruce stem biomass was  $12.8 \text{ kg C m}^{-2}$ , which was  
12 higher than the estimated  $11.2 \text{ kg C m}^{-2}$ . This discrepancy may be explained by the estimated  
13 total spruce tree biomass by Meyer et al. (2013) being smaller than that estimated from tree  
14 ring data. The maximum biomass of understorey vegetation was simulated to be around  $2 \text{ kg C m}^{-2}$   
15 10 years after planting, but it decreased gradually thereafter (Fig. 2e).

16 Table 1 shows the soil C budget of each modeled soil layer (down to 1 m) in 1951 and 2011.  
17 The soil C content at the uppermost 5 cm layer increases due to the addition of plant litterfall  
18 (Fig. 3), where the modeled C content in the first meter of soil is shown to match the observed  
19 data. Except the deepest layer, the other soil layers all lose soil C where losses decrease by  
20 depth. This is due to a soil water content increase, where decomposition is zero in the  
21 saturated soil (like the 90-100 cm layer) (Table 1). Over the whole of the simulated 60 years,  
22 the accumulated soil litter decomposition almost equaled that of the soil peat (treated as  
23 humus in the model), where *ca.* 80% of the litter is respired and the rest added into the  
24 resistant soil C fraction, the soil peat (called humus formation in the figure). Over the 60  
25 years, the soil litter was close to balance as the accumulated plant litterfall almost equal to the  
26 accumulated soil litter decomposition and humus formation (Fig. 3). Thus the total losses of  
27 soil C are mostly from decomposition of historical soil peat.

### 28 **3.1.2 Comparing vegetation fitted model output with observational data** 29 **from 2006 to 2011**

30 The simulation beginning in 1951 using the ‘vegetation fitted’ model showed a good fit with  
31 data collected during 2006 until 2011 of GWL, total net radiation and soil temperature data.  
32 The linear correlations ( $R^2$ ) between the simulated and measured data were all above 0.8 with

1 the mean errors close to zero (Fig. 4). Discrepancies were found in May 2010, when the  
2 measured GWL peaked (high GWL) which by the model was underestimated (Fig. 4c), and  
3 during summers and autumns when the model overestimated both radiation and soil  
4 temperature (Figs 4a, 4b). Besides showing reasonable description of abiotic factors, the  
5 model results were also similar to observed data between 2007 and 2008 on NEE flux, both in  
6 terms of seasonal pattern and magnitude (Fig. 4d). However, the simulations seem to slightly  
7 underestimate the CO<sub>2</sub> uptake during summertime and overestimate the respiration flux in the  
8 autumn (Fig. 4). The model performance for N<sub>2</sub>O emissions during 2006 to 2011 was  
9 generally similar as in the previous calibration study (He et al., 2016), where the annual  
10 emission size was reasonably simulated but the model had some difficulties in capturing every  
11 measured emission peak.

## 12 **3.2 GHG balance**

### 13 **3.2.1 Annual NEE and N<sub>2</sub>O from 1951 to 2011**

14 The annual 60-year NPP for the spruce forest, including biomass and litter, was on average  
15 673 g C m<sup>-2</sup> with less than 100 g C m<sup>-2</sup> during the first 10 years after planting, and with a  
16 value that fluctuates around 1000 g C m<sup>-2</sup> yr<sup>-1</sup> over the last 40 years (Fig. 5b). Peat respiration  
17 (decomposition) shows a slight decreasing trend during the simulated period, with an annual  
18 average of 399 g C m<sup>-2</sup> (Fig. 5c). The decreasing trend may be explained by a lower amount  
19 of soil peat left in the surface (Table 1 and Fig. 3) and an increasing GWL (Fig. 5f) where  
20 inter-annual variations are mainly regulated by the weather (Fig. 5a). NPP and peat  
21 decomposition are the two major components of NEE, in which the system showed itself to be  
22 both a sink and a source during the first 19 years (1951 to 1970), but thereafter to be a  
23 continuous CO<sub>2</sub> sink, except for 1980 and 2002 (Fig. 5d). The thinning management in 1979  
24 had a large impact on the NEE which changed the system to that of a source of 820 g C m<sup>-2</sup> yr<sup>-1</sup>  
25 for the following year. After 1981, the forest ecosystem was a continuous sink of CO<sub>2</sub> with  
26 an average NEE of 217 g C m<sup>-2</sup> yr<sup>-1</sup> except for being a minor source of 82 g C m<sup>-2</sup> yr<sup>-1</sup> for 2002  
27 (Fig. 5d).

28 The model predicts low N<sub>2</sub>O emissions for the initial 10 years. Instead it predicts most of the  
29 N<sub>2</sub>O to be emitted from 1966 to 1988, a period when the understorey vegetation becomes  
30 sparse and the spruce trees are still small. Three years (1969, 1973 and 1977) of extreme  
31 emissions were due to very high precipitation events in summer. The last 30 years the  
32 emissions were lower again, due to a closed canopy and high N uptake by trees and a more

1 shallow GWL. Over the 60 years, the simulated annual N<sub>2</sub>O emission varied from a minimum  
2 of 0.01 to a maximum 7 g N m<sup>-2</sup> yr<sup>-1</sup>, with an average of 0.7 g N m<sup>-2</sup> yr<sup>-1</sup> (Fig. 5e).

### 3 **3.2.2 Overall GHG balance from 1951 to 2011**

4 Over the full 60-year time period the forest trees acted as a C sink and the soil as a source, of  
5 fairly similar size (Fig. 6). This could be viewed as a relocation of C from the soil to the trees,  
6 since our model predicts the total soil C loss to be 75 kg CO<sub>2</sub> m<sup>-2</sup> over the 60 years, while  
7 total plant biomass (including spruce forest and understorey vegetation) sequesters 58 kg CO<sub>2</sub>  
8 m<sup>-2</sup>. The accumulated NEE shows the young forest ecosystem to be a net CO<sub>2</sub> source, and it is  
9 not until 1990, 39 years after the forestation, that the ecosystem uptake balances previous  
10 cumulative emissions and it reaches zero CO<sub>2</sub> emission before becoming an overall carbon  
11 sink. If including the N<sub>2</sub>O emissions during the 60-year rotation period, taking the most  
12 commonly used 100-year time horizon global warming potential from the IPCC (1 g N<sub>2</sub>O =  
13 265 g CO<sub>2</sub>eq, IPCC, (2013)), the source strength of the forest ecosystem increases and the  
14 system switch to an overall small GHG source.

15 However, if including the fate of the biomass removed as thinnings, usually used for paper  
16 production, resulting in indirect CO<sub>2</sub> emissions from consumed paper makes this extended  
17 system (from the production site to the fate of the products) a large GHG source of 38 kg CO<sub>2</sub>  
18 m<sup>-2</sup> by the end of the simulation (Fig. 6). Soon, the whole forest will be harvested releasing  
19 most of the captured carbon into the atmosphere again, 16 kg C m<sup>-2</sup> (Fig. 2d), and if  
20 everything were released from these soils there would be 96.9 kg CO<sub>2</sub> m<sup>-2</sup> released over a  
21 period of 60 years.

### 22 **3.3 Model sensitivity**

23 Accumulated plant biomass is most sensitive to a higher soil C / N ratio or a shallower  
24 drainage depth (Table 2). The peat decomposition is instead more sensitive than the  
25 accumulated plant biomass to larger initial soil C or increasing drainage depth (Table 2).  
26 Also, magnitudes of NEE and N<sub>2</sub>O fluxes are very sensitive to these variations, the NEE  
27 becoming a CO<sub>2</sub> source at larger initial soil C, since peat decomposition rate becomes larger  
28 than the accumulated plant biomass. The model sensitivity also shows higher N<sub>2</sub>O emissions  
29 under shallower rather than deeper drainage (Table 2). When these various factors were  
30 combined, the peat decomposition varied by -38% to +33%, being largest when the  
31 combination was deep drainage with the largest initial soil C, and a low initial soil C / N ratio.

1 The accumulated biomass varied between -69% and +6%, being smallest when the  
2 combination was shallow drainage with a low initial soil C and a large soil C / N ratio.  
3 However, the overall total GHG emissions, including the thinning and storm harvested  
4 biomass and its associated CO<sub>2</sub> losses, the emissions increased by 11% to 57% (Table 2),  
5 suggesting that the total GHG balance was still a source to the atmosphere.

6

## 7 **4 Discussion**

### 8 **4.1 Comparison of our simulated results with observational and published data**

9 The GHG balance over a rotational period for forestry on drained peatland is mainly  
10 determined by two large fluxes viz. plant C assimilation and peat decomposition. We  
11 therefore first discuss the validity of these two variables by comparing our simulated results  
12 with values published in the literature.

#### 13 **4.1.1 Plant growth**

14 Our simulated spruce growth at 413 g C m<sup>-2</sup> yr<sup>-1</sup> was higher than the normal growth rate of  
15 162 to 270 g C m<sup>-2</sup> yr<sup>-1</sup> in southwest Sweden, but lower than the potential growth rate of 472  
16 to 607 g C m<sup>-2</sup> yr<sup>-1</sup> under experimentally optimal nutrient conditions (Bergh et al., 2005). This  
17 high growth rate can be explained by the fertile soil at the Skogaryd site, which was a drained  
18 fen before it was used for agriculture, and then forestry. The high rate of nitrate leaching,  
19 estimated at 4.3 g N m<sup>-2</sup> yr<sup>-1</sup> also suggests that nutrients are not likely to be limiting. That the  
20 forest growth at this site is close to maximum has also been demonstrated in a modeling study  
21 by Tarvainen et al., (2013) who showed that if canopy N content was increased by 30%,  
22 canopy C uptake would only increase by only 2% - 4% and none of the 37 nutrients tested  
23 would directly limit photosynthesis. The very small increase of plant growth (+6%) in our  
24 model sensitivity analysis (Table 2), obtained when more deeply drained soil plus a larger  
25 initial soil C and a lower C / N ratio assumed, can also be explained by the already high  
26 fertility at the site, so any extra nutrient availability would have a negligible impact. Our  
27 simulated understorey vegetation was small during most of the simulated years; however, it  
28 dominated the organic matter dynamics and GHG fluxes in the first two decades after  
29 plantation, a finding similar to that of Laiho et al., (2003).

#### 30 **4.1.2 Soil CO<sub>2</sub> and N<sub>2</sub>O fluxes**

1 Our simulated average peat decomposition rate of  $399 \text{ g C m}^{-2} \text{ yr}^{-1}$  during the period 1951 to  
2 2011 is lower than the value measured in 2008, which was  $630 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Meyer et al.,  
3 2013). However, this high peat decomposition rate could be attributed to an inter-annual  
4 weather variation, which is corroborated by the high plant growth measured in 2008,  $830 (\pm$   
5  $390) \text{ g C m}^{-2} \text{ yr}^{-1}$ . Our simulated  $\text{N}_2\text{O}$  emission,  $0.52 (\pm 0.1) \text{ g N m}^{-2} \text{ yr}^{-1}$  during 2007 to 2009  
6 is similar to the observed data collected these years,  $0.71 (\pm 0.59) \text{ g N m}^{-2} \text{ yr}^{-1}$  and  
7 measurements 2006 to 2011,  $0.38 (\pm 0.12) \text{ g N m}^{-2} \text{ yr}^{-1}$  (Holz et al., 2015). Only during these  
8 years, our predicted level of emissions was  $0.50 (\pm 0.12) \text{ g N m}^{-2} \text{ yr}^{-1}$ . Our simulated  $\text{CO}_2$  and  
9  $\text{N}_2\text{O}$  fluxes are therefore generally comparable with the measured data.

10 Our simulated peat decomposition and  $\text{N}_2\text{O}$  emissions are generally comparable in size with  
11 measured flux data from afforested drained peatland published in the literature (Table 3).  
12 However, when compared with the IPCC EF's for temperate drained nutrient-rich forest soil,  
13 which are given as  $260 (200 \text{ to } 330) \text{ g C m}^{-2} \text{ yr}^{-1}$  for  $\text{CO}_2$  and  $0.28 (-0.06 \text{ to } 0.61) \text{ g N m}^{-2} \text{ yr}^{-1}$   
14 for  $\text{N}_2\text{O}$  (IPCC, 2014), our simulated values were found to be larger. This could be explained  
15 by the higher soil fertility at the Skogaryd site and also a deeper GWL (mean of 0.52 m during  
16 the simulated 60 years), compared to what pertained at those sites used for constructing the  
17 IPCC EF's. That the GWL is of crucial importance for emission levels for drained peat soils  
18 has also been shown by Couwenberg et al., (2011) and Leppelt et al., (2014). This could  
19 justify our assumption that our somewhat high estimates were due to deep and long-lasting  
20 drainage.

21 The unexpectedly low simulated  $\text{N}_2\text{O}$  emission in the first years after planting was mainly  
22 caused by a high N uptake by the understorey vegetation, probably dominated by grasses,  
23 making less N available for nitrification and denitrification. From 1960 the understorey  
24 vegetation decreases and in 1966 the spruce trees are more dominant but still rather small,  
25 thus the model shows total N plant uptake to be smaller than in both the earlier and later  
26 periods and more inorganic N available in the soil (supplementary Figure 1). During this  
27 period, the GWL was also deep (Fig. 5), resulting in high peat mineralisation rates and a net  
28 release of inorganic N. Both vegetation and GWL could thus explain the high  $\text{N}_2\text{O}$  emission  
29 during the period 1966 to 1988. Besides, a high soil N availability also accounts for the  
30 'vegetation fitted' model consistently overestimating spruce growth during this period (Fig.  
31 2c). However, our model also predicts some extreme annual  $\text{N}_2\text{O}$  emissions, i.e. in 1969, 1973  
32 and 1977 (Fig. 5e), modelled to occur simultaneously with large precipitation events lasting  
33 several days in summer. Since the model shows  $\text{N}_2\text{O}$  to be produced close to the GWL at 50-

1 70 cm depth and the model simply assumes the N gases to be directly emitted into the  
2 atmosphere after production thus no further reduction into N<sub>2</sub> is simulated. If a vertical gas  
3 transport process and further processing during transport was considered as performed by  
4 Stolk et al., (2011), this could further have converted N<sub>2</sub>O into N<sub>2</sub> thus simulating lower  
5 emissions. This is corroborated by gas profile measurements in Skogaryd where the soil N<sub>2</sub>O  
6 gas concentration increases with soil depth (He et al., 2016). If we remove the extreme annual  
7 emissions (1969, 1973 and 1977) in our calculations, the annual average N<sub>2</sub>O emission would  
8 change from 0.7 to 0.5 g N m<sup>-2</sup> (thus 30% lower). The accumulated CO<sub>2</sub> and N<sub>2</sub>O fluxes  
9 (NEE+N<sub>2</sub>O in Fig. 6) would in 2012 be 1000 g CO<sub>2</sub> equ m<sup>-2</sup> instead of 7000 g CO<sub>2</sub> equ m<sup>-2</sup>.  
10 However the forest ecosystem would still be a GHG source to the atmosphere.

## 11 **4.2 Challenges of modeling long-term dynamics of an organic soil**

12 Overall our modeling application indicates, given a few assumptions, that the CoupModel is  
13 generally able to simulate the decadal-scale dynamics of the drained organic soils used for  
14 forestry. However, our modeling exercise also reveals that there are some issues which still  
15 need to be more explicitly accounted for when simulating organic soils and which require  
16 further model development. These are the nature of the soil organic matter and physical  
17 changes of a peat soil.

### 18 **4.2.1 A need for explicitly specifying the nature of soil organic matter**

19 A multi-pool approach was developed for modeling SOM dynamics from mineral soils and  
20 has been shown to work well for forest mineral soils e.g. (Svensson et al., 2008; Wu, 2013).  
21 However, for organic soils, because there is no explicit peat pool in the model, we have had to  
22 assume the peat to comprise an unknown mixture of the fast and the slow pool. In the present  
23 study we have assumed the initial values of SOM as only representative of the slow pool. The  
24 decomposition coefficients for the fast and slow pool were obtained by calibrating the model  
25 coefficient against the measured fluxes as we did in our previous study (He et al., 2016).  
26 However in this long term simulation there is a continuous addition of spruce litter leading to  
27 resistant soil organic matter and a change in substrate quality over the simulation period for  
28 the slow pool. Although most existing models do not explicitly specify the nature of the  
29 organic matter (Smith et al., 1997), they can still simulate the total organic matter dynamics  
30 fairly well over a relatively short period. Metzger et al., (2015) found that the CoupModel  
31 could capture major C fluxes and the ecosystem dynamics when applied to five European  
32 treeless peatlands, where they pointed out that the total C flux was mainly determined by the

1 decomposition coefficients of the total SOM. Continuous addition of organic matter into the  
2 slow pool from litter decomposition must also change the decomposition coefficient for the  
3 slow pool over time. However, this is seldom accounted for. In order to understand the long-  
4 term dynamics of organic matter, which might differ in origin and components, a more  
5 precise consideration of the changes of soil organic matter characteristics would be helpful.

#### 6 **4.2.2 Modeling physical changes of peat soil**

7 For mineral soils in which the physical structure of the soil does not normally change over  
8 time, the CoupModel works well by assuming the soil layer profile to be fixed over time  
9 (Jansson and Karlberg, 2011; Jansson, 2012). However, this is not the case for organic soils  
10 where the soil structure is mainly built by soil organic matter, which gradually disappears  
11 through decomposition. Thus the soil's physical characteristics change over time, e.g. the pore  
12 structure, which could change the soil hydraulic conductivity and preferential flows  
13 (Kechavarzi et al., 2010). Moreover, decomposition makes the top soil to disappear during a  
14 forest rotation, resulting in surface subsidence (Minkkinen and Laine, 1998; Leifeld et al.,  
15 2011; Hooijer et al., 2012). This causes the GWL to come closer to the soil surface, which in  
16 the normal case requires further drainage or ditch management. This process has not so far  
17 been implemented in the CoupModel, which currently is not able to account for surface  
18 subsidence, mainly due to lack of feedback coupling between the soil's biological and  
19 physical properties in the model. The model physical subroutine simulates the water and heat  
20 flow and then links this to the biochemical processes by response functions of water moisture  
21 and soil temperature. While there is no feedback to the soil physical processes arising from  
22 organic matter decomposition or other changes of the soil.

23 All these processes remain a major challenge when applying the CoupModel to the long-term  
24 dynamics of a forest ecosystem on drained peatland. To quantify the uncertainty from surface  
25 subsidence, in the present study, the system was simplified by assuming a fixed drainage  
26 depth, whereas a range of values was used to quantify the model's sensitivity. The variation of  
27 the drainage depth had a considerable impact on the soil peat decomposition, as shown by the  
28 model sensitivity analysis (Table 2), which in turn highlights the need, when developing  
29 future models, to explicitly account for these processes when performing long-term  
30 simulations.

#### 31 **4.2.3 Initial soil C, N and soil C / N ratio**

1 A major difficulty in the simulation was the unknown initial soil conditions. We chose to use  
2 the EF's 260 (200 to 330)  $\text{g C m}^{-2} \text{ yr}^{-1}$  for  $\text{CO}_2$  from the IPCC wetland supplement (IPCC,  
3 2014), which compiles up-to-date observational data from similar sites under temperate  
4 climate conditions. Another alternative could be to use the subsidence rate to calculate the soil  
5 C losses, which has been applied in other published studies e.g. (Leifeld et al., 2011;  
6 Hommeltenberg et al., 2014). By taking the measured subsidence, 0.22 m (ranging from -0.15  
7 m to 1.03 m) during ca. 60 year post-drainage period for Finnish drained afforested fens  
8 (Minkinen and Laine, 1998), analogizing the measured total soil C in the upper 0.5 m in  
9 2007, which was 55.3  $\text{kg C m}^{-2}$  (Meyer et al., 2013), the estimated soil losses during the 60  
10 year period would be 24.3  $\text{kg C m}^{-2}$ , which is equivalent to a loss of 405  $\text{g C m}^{-2} \text{ yr}^{-1}$ , close to  
11 current modeling estimates, 399  $\text{g C m}^{-2} \text{ yr}^{-1}$ . Increased initial soil C in our sensitivity analysis  
12 show both peat decomposition and plant growth to increase (Table 2). Compared to the  
13 'vegetation fitted' model, the combination of a small initial soil C, a large soil C / N ratio, and  
14 a shallow drainage, gives a larger reduction in plant growth than in peat decomposition, which  
15 is why the overall emissions of GHG increase.

#### 16 **4.3 GHG balance for the forest ecosystem**

17 Our modeling indicates forest on drained agricultural peatland to be a strong net  $\text{CO}_2$  source  
18 for the first 39 years of the forest rotation which changes into a  $\text{CO}_2$  sink thereafter due to  
19 strong tree growth (Fig. 6). This means that, despite soil decomposition being high, the high  
20 growth rate of forest over 60 years compensates for most C losses. Meyer et al., (2013) also  
21 showed the forest ecosystem in Skogaryd to be an overall GHG sink (410  $\text{g CO}_2\text{eq ha}^{-1} \text{ m}^{-2}$ ) in  
22 2008, a year when the plant growth rate was at its maximum, thus offsetting the high rate of  
23 peat decomposition. Our findings are also generally in line with the few previous field  
24 investigations conducted on afforested drained agricultural peatlands where Mäkiranta et al.,  
25 (2007) and Lohila et al., (2007) found a 30-year-old Scots pine forest on drained agricultural  
26 bog to be, overall, a small source of  $\text{CO}_2$  (50  $\text{g C m}^{-2} \text{ yr}^{-1}$ ), which was explained by a small  
27 leaf area index (varying between 0.7 and 2 during the observational period). Another study by  
28 Hommeltenberg et al., (2014), reported an afforested drained bog in Germany, previously  
29 used for agriculture, to emit 500  $\text{g C m}^{-2} \text{ yr}^{-1}$ . By combining eddy covariance measurements  
30 and biometric estimation, they concluded it to be a major  $\text{CO}_2$  source, emitting a total of 13.4  
31  $\text{kg C m}^{-2}$  over the last 44 years. However, their short-term measurements (2010 to 2012) also  
32 indicated that forest growth offsets peat decomposition, a result similar to our study.



1 Growing forests on drained peat is done at the cost of the soil peat, which has generally  
2 accumulated slowly during the last millennia (the last four thousand years in Skogaryd).  
3 When the forest growth has been larger than the soil loss, the system has been interpreted as  
4 being an overall sink (Meyer et al., 2013; Hommeltenberg et al., 2014). However the soil loss  
5 and the forest gain can be viewed as a 'relocation' of the peat carbon into timber carbon. The  
6 simulated NEE (figure 6) shows that the system remains a sink for two decades but growth  
7 rate probably declines over time, as shown in the simulated period from 2011 to 2031. After  
8 2031, to continue keeping forest on these lands, a lower growth (Luyssaert et al., 2008) will  
9 further decline the sink strength while the peat soil will continue to decompose as long as it is  
10 kept aerated by a living transpiring forest. Sudden fires would also be a risk releasing the  
11 forest biomass C. However the forest in Skogaryd is not a nature reserve but a managed forest  
12 already mature for harvesting, commonly done at 80 years of age in southern Sweden. The  
13 harvested wood products over a forest rotation is used for both timber and paper, about 40 and  
14 60% (Sweden CRF table 4.Gs2 for year 2013, submitted to the UNFCCC 2015) having a half-  
15 life of 30 and 2 years respectively (IPCC 2006). Thus the carbon will soon be released as  
16 CO<sub>2</sub>. The best alternative would be the use timber for wooden buildings which otherwise  
17 should have been built by using concrete (Gustavsson et al., 2006). The displacement of  
18 concrete by wood could according to a meta-analysis by (Sathre and O'Connor, 2010) avoid  
19 emissions by 2.1 times the C content of the timber. However, even then, most buildings do  
20 not last more than a century and only a few buildings are functional for longer periods. Thus  
21 most harvested biomass will soon be burnt releasing the stored C. These indirect emissions  
22 following the consumption of wood would shift the system from an overall small sink into a  
23 large GHG source (Fig. 6). Another alternative use of the biomass could be as biochar in  
24 agricultural soils (Ojanen et al., 2013), which potentially could shift the system into an overall  
25 GHG sink. However, this is equivalent to releasing C from peat and storing it in agricultural  
26 soils, and it is not clear for how long time the char-carbon persists. Additionally, there are  
27 some other direct and indirect GHG sources that become apparent during the full forest  
28 rotation period which we have not accounted for, such as methane emissions in drainage  
29 ditches and loss of dissolved organic C or particulate organic C. However, these contributions  
30 to the overall GHG balance are in general of minor importance and thus not likely to alter the  
31 overall picture (Meyer et al., 2013; Hommeltenberg et al., 2014). In summary, the overall  
32 message is that a forest rotation on fertile drained peat soil has a long-term GHG cost, never  
33 reaching a balance, and thus the wood products produced on peat soil cannot be regarded as  
34 renewable products.

1 In Sweden, forests on drained peatland cover 1.7 Mha (Maljanen et al., 2010; Von Arnold et  
2 al., 2005a) of which 0.4 Mha has high fertility, comparable to the soil in the present study.  
3 According to our simulations, these forests emit around 1.74 kg CO<sub>2</sub>eq m<sup>-2</sup> yr<sup>-1</sup> (peat  
4 decomposition and N<sub>2</sub>O emissions). Thus these fertile drained peat soils in Sweden emit 7  
5 Mtonnes CO<sub>2</sub>eq annually, which is equivalent to 12% of the emissions coming from all other  
6 sectors in Sweden when excluding LULUCF (Land use, land-use change and forestry). From  
7 a climate change perspective, forested drained peatlands should be highlighted for actions,  
8 especially following forest clear-cut. Instead of digging the ditches deeper for replanting a  
9 new forest, making the soil wetter would reduce the soil decomposition, as shown by our  
10 sensitivity analysis and other studies (e.g. Karki et al., 2014). However, these measures need  
11 support from policy makers since landowners often only recognize revenues from forest  
12 production, not the cost of GHG emissions.

13

## 14 **5 Conclusion**

15 Our simulation study shows that the GHG fluxes in a forested drained peatland are composed  
16 of two important quantities: C uptake by forest growth, and C losses from the soil. By fitting  
17 the CoupModel to the spruce growth, up-scaled from radial tree-growth observations, we  
18 obtained a ‘vegetation fitted’ model by which we were able to describe the C and N fluxes  
19 over 60 years. We show that the forest C growth is tightly coupled to soil C losses, and if the  
20 forest is harvested and used, there will only be losses over time. The model sensitivity  
21 analysis conducted provides evidence that a wide range of drainage depths, site fertilities and  
22 initial soil C contents lead to similar overall results. Further model developments are however  
23 needed to better simulate the drained peat soil over a forest rotation period.

24

25 Author contributions: HH, ÅK, PEJ and LK planned and initialized the study. HH conducted  
26 the data analysis and modeling under supervision from ÅK, MS and PEJ. JB and LT helped  
27 HH with the tree ring data collection and analysis. HH and ÅK wrote the paper with all  
28 authors commenting and participating in the interpretation of the results and contributing to  
29 the discussions.

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- 7

- 1 Table 1. Soil C content in the soil profile during 1951 to 2011 estimated by the vegetation  
 2 fitted model, kg C m<sup>-2</sup>.

Soil layers (cm)	Layer thickness (cm)	Soil C 1951	Soil C 2011	Losses in soil C
0-5	5	6.3	7.8	- 1.5 <sup>1</sup>
5-15	10	12.5	7.5	5.0
15-25	10	12.5	7.7	4.8
25-35	10	12.5	7.9	4.6
35-50	15	18.8	14.7	4.1
50-70	20	25.0	22.1	2.9
70-90	20	25.0	24.3	0.7
90-100	10	12.5	12.5	0

- 3 Note: <sup>1</sup> negative change means an increase of soil C

1 Table 2. Model sensitivity: change compared with 'vegetation fitted' model during 1951 to  
2 2011.

Variables	Vegetation fitted model	Drainage depth (m)		Initial soil C (kg C m <sup>-2</sup> )			Initial C/N ratio (-)		Combination 1	Combination 2
		(1)	(2)	(3)	(4)	(5)	(6)	(7)		
		-0.3	-0.8	121.7 <sup>1</sup>	129.0 <sup>2</sup>	145.8 <sup>3</sup>	20	45		
Alternative No		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(1)+(3)+(7)	(2)+(5)+(6)
Accumulated plant biomass (kg C m <sup>-2</sup> )	16.0	-35%	3%	-0.4%	1%	4%	4%	-48%	-69%	6%
Peat decomposition (g C m <sup>-2</sup> day <sup>-1</sup> )	1.09	-25%	13%	-3%	3%	17%	2%	-14%	-38%	33%
NEE (g C m <sup>-2</sup> day <sup>-1</sup> ) <sup>4</sup>	-0.12	-52%	-130%	22%	-23%	-125%	42%	-441%	-388%	-257%
N <sub>2</sub> O emission (g N m <sup>-2</sup> day <sup>-1</sup> )	0.0018	33%	-68%	-6%	3%	22%	58%	-84%	-63%	-25%
Indirect CO <sub>2</sub> emission (kg CO <sub>2</sub> equ m <sup>-2</sup> )	34.5	-21%	1%	-1%	0.5%	0.3%	2%	-47%	-70%	3%
NEE+N <sub>2</sub> O+indirect CO <sub>2</sub> emissions (kg CO <sub>2</sub> equ m <sup>-2</sup> )	44.1	18%	6%	-3%	14%	46%	25%	31%	11%	57%

3 <sup>1;2;3</sup>: Back-calculated initial soil C using the reported range of IPCC EF's 200; 330 and 630 g C m<sup>-2</sup> yr<sup>-1</sup>  
4 respectively.

5 <sup>4</sup>: positive change of NEE means the forest ecosystem sequesters more atmospheric CO<sub>2</sub> than the  
6 'vegetation fitted' model; negative change means sequestering less atmospheric CO<sub>2</sub> or a possible  
7 source to the atmosphere.

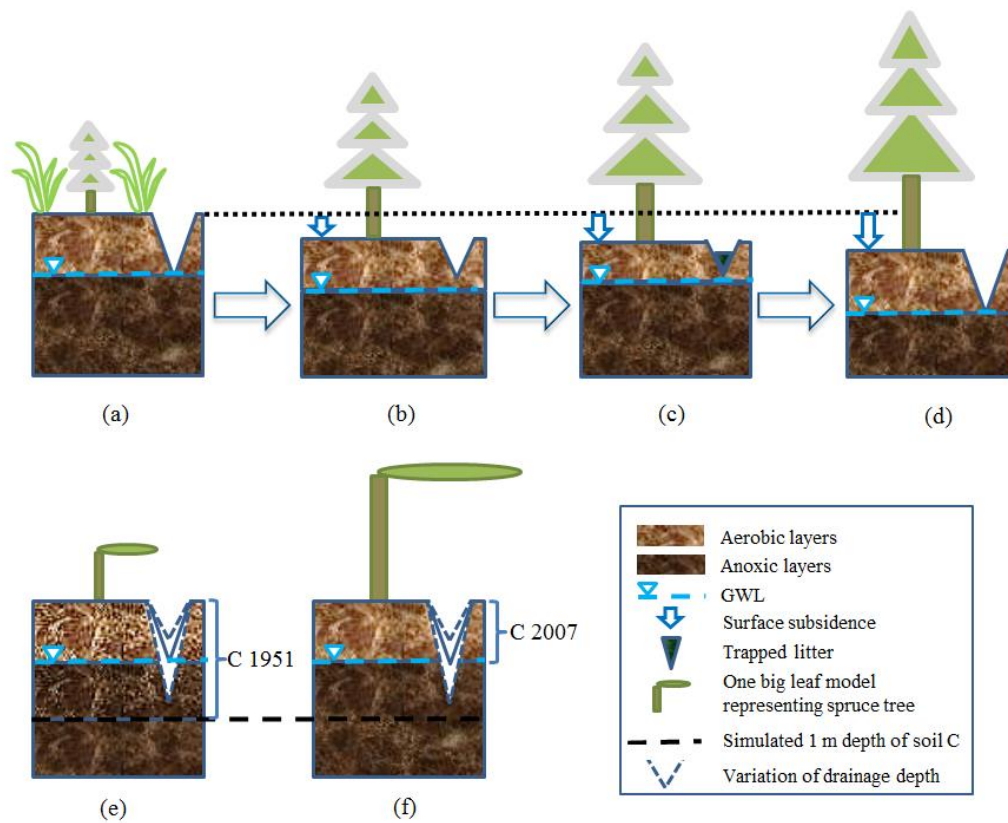
1 Table 3. A comparison of soil peat CO<sub>2</sub> and N<sub>2</sub>O emissions in the present study with values  
 2 published in the literature.

Soil CO <sub>2</sub> flux (g C m <sup>-2</sup> yr <sup>-1</sup> )	Soil N <sub>2</sub> O emissions (g N m <sup>-2</sup> yr <sup>-1</sup> )	Ecosystem type	Country	References
190 to 1000		Forestry-drained boreal peatland	Finland	Ojanen et al., (2013)
109 to 1200	0 to 1.9	Forest soils and other vegetated sites on deep peat	UK and other European Countries	Morison et al., (2012)
125 to 260 <sup>1</sup>		Forestry-drained peatland	Finland	Minkkinen et al., (2007)
700		Grassland on agricultural fen peat	Germany	Kluge et al., (2008)
1405	1.94 (0.67)	Highly fertile drained peatland for forestry with low soil pH	Sweden	Weslien et al., (2009)
452	0.05	Afforested drained lowland raised peat bog	UK	Yamulki et al., (2013)
123 to 259 <sup>1</sup>	0.02 to 0.57	Drained organic soils for deciduous and coniferous forests	Sweden	Von Arnold et al., (2005a; 2005b)
399	0.7	Drained forested agricultural peatland	Sweden	This study

3 <sup>1</sup>: Calculated by assuming 50% of measured soil respiration to have originated from root-based  
 4 activity.

5

6

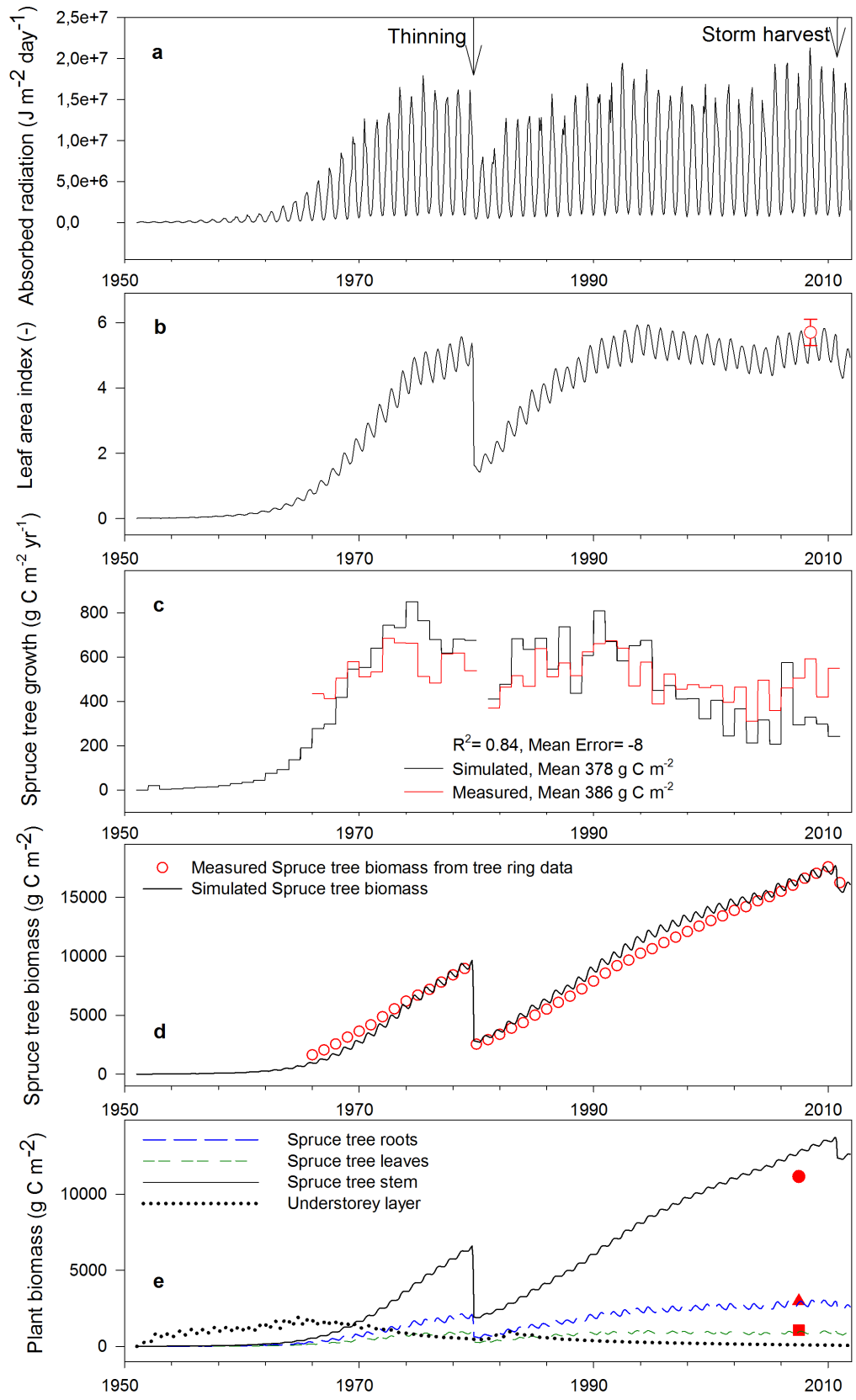


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2 Figure 1. Conceptual representation of the dynamics of plants and peat soil development over  
 3 a forest rotation period. The upper figures (1a, 1b, 1c, 1d) represent the conceived reality and  
 4 1e and 1f represent the CoupModel conceptualization. For all the figures, spruce tree and  
 5 understorey vegetation, e.g. grasses are considered but for clarity, understorey vegetation is  
 6 only shown in Fig. 1a. 'C 2007' in Figure 1f represents the measured total soil C in the upper  
 7 0.5 m of the soil profile in 2007, and 'C 1951' is the total soil C in the upper 1 m of the soil  
 8 profile, as back-calculated from the equation:  $2 \times 'C 2007' + (2007-1951) \times IPCC\ EF's$ . Any  
 9 variation of climate during the forest development in this conceptual figure is not considered.

10

11



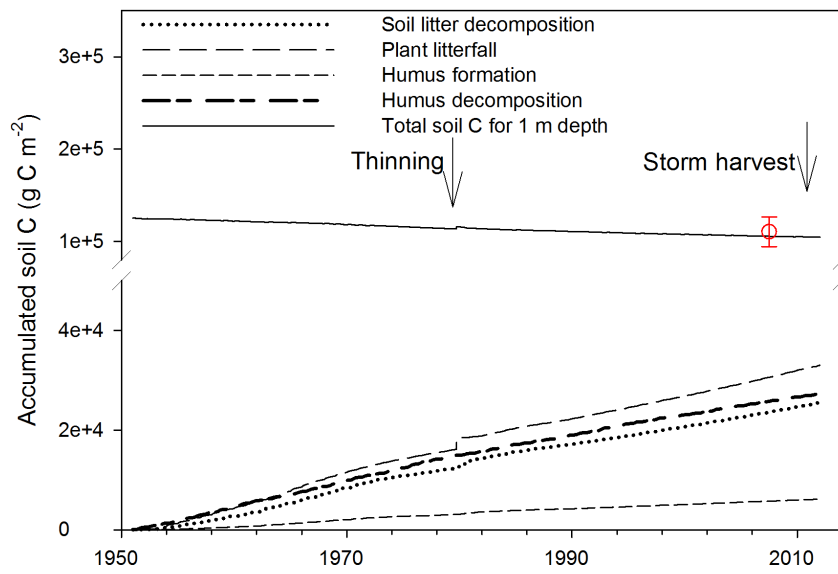
1  
2



1 Figure 2. a) Simulated (black line) spruce absorbed radiation; b) simulated and measured (red  
2 hollow circle) leaf area index; c) annual spruce tree growth rate; d) total spruce tree biomass;  
3 e) spruce tree biomass for different components. In Fig. 2e, the solid red symbols show the  
4 calculated plant biomass of leaf biomass, root and stem biomass using the allometric function  
5 given by Meyer et al., (2013).

6

7

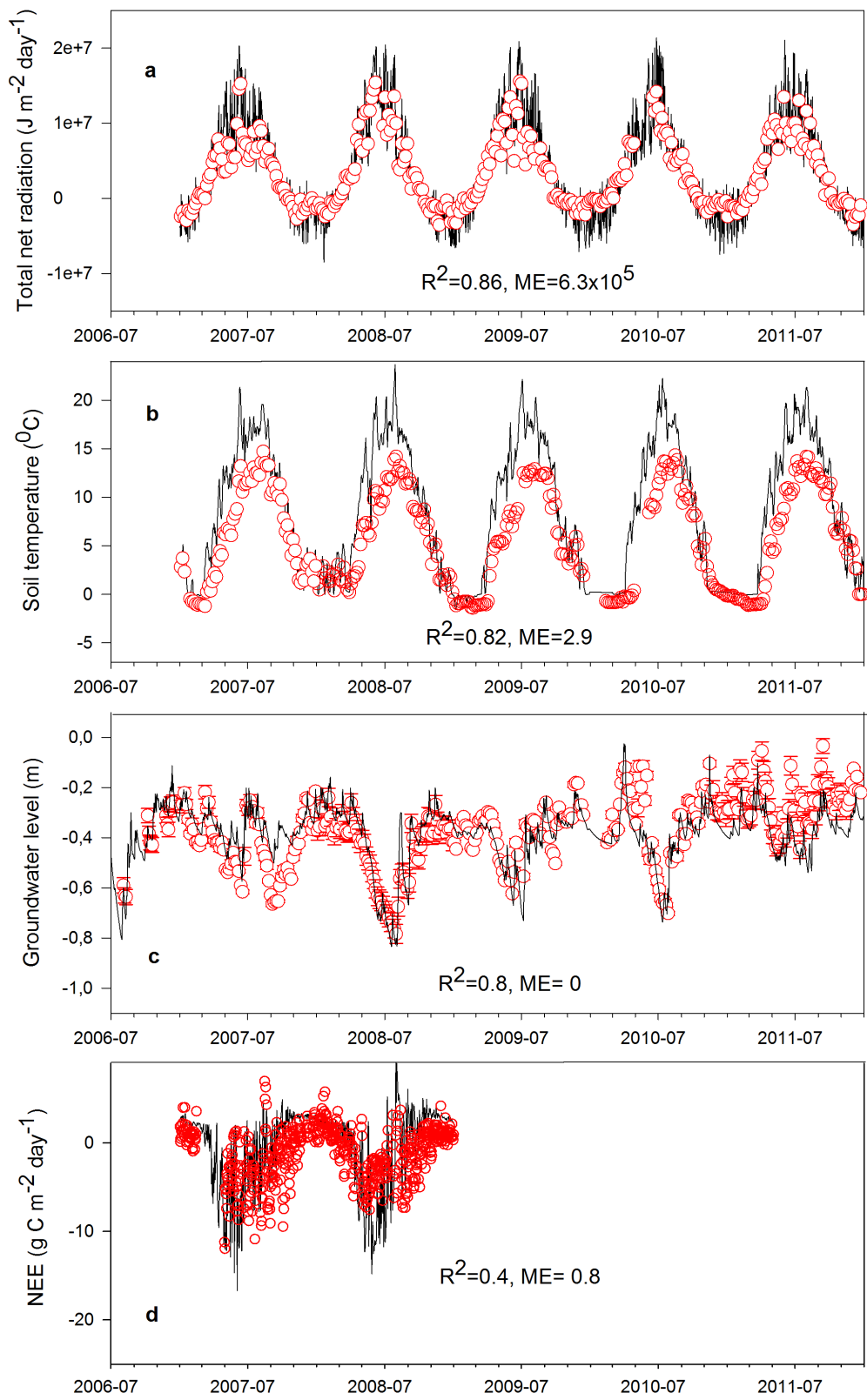


1

2 Figure 3. Simulated development of major soil C pools in the first meter of soil, from 1951 to  
 3 2011. The red circle shows the measured total soil C in 2007 (+/- 95% confidence intervals)  
 4 by Meyer et al., (2013).

5

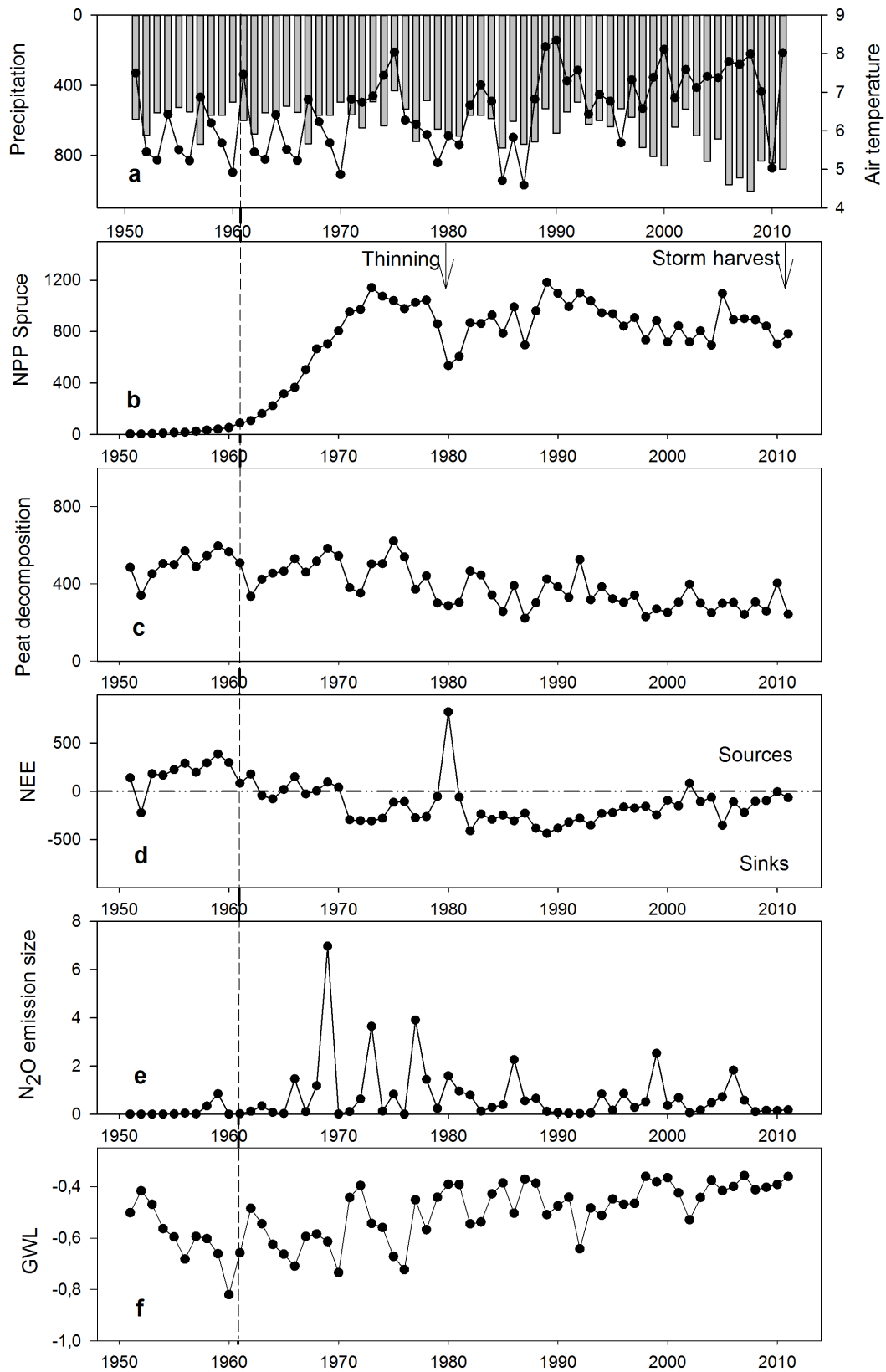
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1 Figure 4. a) Simulated (black line) and measured (red hollow circle) total net radiation; b) soil  
2 surface temperature (0-5 cm depth; c) GWL; d) NEE. Measured data used to create these plots  
3 are 5-day averages, except for NEE where daily averages have been used.

4

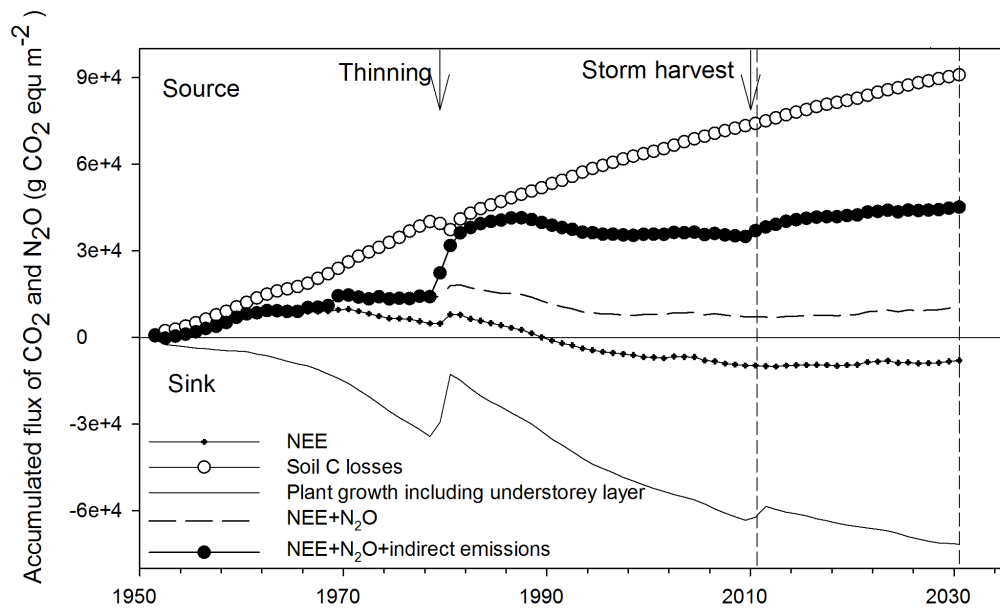
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1 Figure 5. For the period 1951 to 2011: a) Annual precipitation ( $\text{mm yr}^{-1}$ ) and air temperature  
2 ( $^{\circ}\text{C}$ ); b) the simulated annual NPP of spruce trees ( $\text{g C m}^{-2} \text{yr}^{-1}$ ); c) simulated annual peat  
3 decomposition rate ( $\text{g C m}^{-2} \text{yr}^{-1}$ ); d) simulated annual NEE ( $\text{g C m}^{-2} \text{yr}^{-1}$ ); e) simulated annual  
4  $\text{N}_2\text{O}$  emissions ( $\text{g N m}^{-2} \text{yr}^{-1}$ ); f) simulated annual GWL (m). The dashed reference line  
5 separates the duplicated 1951 to 1961 and real climate 1961 to 2011. The source or sink is  
6 based on the atmospheric perspective, e.g. the soil emissions are sources, and plant uptakes  
7 are sinks.

8



1

2 Figure 6. Simulated total GHG balance for the forest ecosystem from 1951 to 2011 and  
 3 extended to 2031. The simulated results of 2011 to 2031 are obtained by running the  
 4 'vegetation fitted model' with meteorological data from 1991 to 2011 extended to represent  
 5 the climate of 2011 to 2031. It should be noted that the GHG balance presented in this figure  
 6 assumes no final harvest.

7

8