Dear editor:

We are thankful for the valuable comments you and both reviewers made for our manuscript. In the following, you can find our point to point reply to all the comments. Since most of the comments are already answered in our published reply during the open discussions. This reply then aims to give the details of what changes we have made during the revision. We hope our revised paper now to be satisfactory for publishing.

Sincerely yours,

Hongxing He

On behalf of all the authors

Interactive comment on "Forests on drained agricultural peatland are potentially large sources of greenhouse gases – insights from a full rotation period simulation" by H. He et al.

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Please amend the soil N2O emission value (0.3 g N m-2 yr-1) in Table 2 for Yamulki et al. (2013) to 0.05 g N m-2 yr-1, as the original value reported by Yamulki for the drained low-land raised peat bog is 0.08 g N2O m-2 yr-1 (see Table 3 in their paper) which equates to 0.05 g N2O-N m-2 yr-1.

- *The N2O emission in Table 3 has now changed to 0.05 g N m-2 year-1 in the revision. Our simulated N2O emission data is still comparable with literature values and ranges of Table 3, and also in line with the IPCC emission factors.*

Interactive comment on "Forests on drained agricultural peatland are potentially large sources of greenhouse gases – insights from a full rotation period simulation" by H. He et al.

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This study addresses a very interesting and important question: how do the carbon and greenhouse gas balances of a drained forested peatland change in the long run, during the whole tree stand rotation. Such long time series of GHG data are not available, which means that modeling is the only relevant method to solve the question. Thus, COUP-model was used to simulate the forest and soil development on a fertile, afforested peatland in southern Sweden. COUP-model is one of the few models that can, to my knowledge, handle organic soil processes, in which the water table dynamics, and the resultant changes in soil chemical and physical conditions, are the key-issues. In the model, soil is divided to layers, the characteristics of which can then be simulated following changes in weather, C input etc. Thus it would seem suitable for the job.

- *The CoupModel has a strong basis in soil physics and the model also use well-known equations. Therefore it is generally applicable for all soil types (Jansson, 2012), including organic soil. Besides, in He et al., (2016), CoupModel was calibrated to described the water, heat, C and N cycling of Skogaryd (the same site as this study). The calibrated model successfully reproduced the measured data during 2007 to 2009. Here our aim was to upscale the calibrated model (He et al., 2016) to simulate the long term dynamics of drained peatlands, mostly GHG fluxes. However, this revealed problems and challenges are discussed in the paper and also commented by you below.*

The model in these simulations, however, seems to have some very serious shortages. According to the manuscript, it cannot simulate changes in the water table, nor changes in the soil physical characteristics. This seems odd, and since water table is an important feature controlling e.g. organic matter decomposition, it is a big lack. Even in their own tests GWL was very important (Table 1), and water table seems to have changed quite a lot during the simulation period (Fig. 5f). A question rises, how is the water level simulated in Fig. 4, if the model cannot simulate water level? And still, water table level was set to constant 50 cm, but no grounds for the 50 cm were given. Maybe it produced results closest to the observed ones?

- *To clarify the drainage depth and GWL, we have now added the explanation of drainage depth "a parameter used for estimation of horizontal flow of water out of the site due to drainage" into section 2.3. We also add the reference He et al. 2016 into the revised paper "*with the drainage depth set to 0.5 m as in He et al., (2016).*" to explain where the 50 cm origin from. Thus it is not the GWL that is set to 50 cm, rather the drainage depth that is set to 50 cm (The GWL is simulated in daily scale, see Figure 4c & 5f). The model of course can simulate the variable GWL, which* *fluctuates over time. By comparing the simulated GWL with the measured data during 2006 to 2011, the model simulates the GWL well, with coefficient of determination R2 of 0.8 and mean error of zero (Figure 4c). The drainage depth (50 cm in vegetation fitted model) was obtained by previous calibration, see Table 3 in He et al. (2016) The drainage depth parameter was calibrated because the drainage system at Skogaryd is quite complex, having both parallel drainage ditches and a major drainage ditch (Fig. 1)*

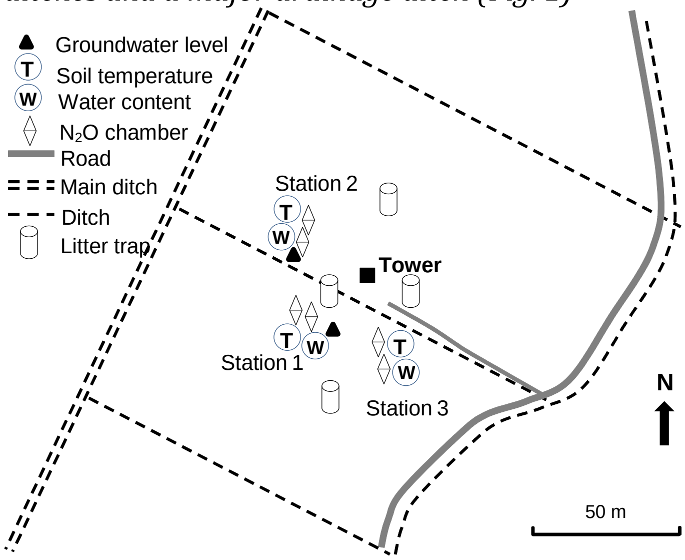

Fig. 1. Brief scheme of Skogaryd site

- *We have now added these texts to motive our assumption on the soil physical properties: "First, the soil layers are assumed the same over the 60 years simulated. And the soil physical characteristics in 1951 are assumed the same as measured in 2006; possibly not fully true but better than introducing uncertain numbers, and could be argued reasonable since 1) this site has been drained for many years (starting in 19th century), why physical soil compaction should not be important during the last 60 years, and 2) soil properties were not found to be the major GHG emission influencing factor, (He et al., 2016)."*

The second phase was to define the initial soil C content in 1951. This was predicted using an IPCC emission factor, calculating backwards from the present soil C pool. Then the COUP-model was used to simulate the peat decomposition from 1951 to the present – producing very similar soil C stock than where started. One might ask: Does this mean that IPCC EF is as good a model as COUP for estimating peat decomposition? But seriously, it is not told WHY the C content is needed in the first place, and HOW is the carbon in peat divided to the soil layers. For decomposition, it is not important only how much carbon there is in peat soil, what is important is that how much carbon is in AEROBIC conditions, i.e. above GWL. If 100 cm peat layer is simulated, and GWL is in 50 cm, a significant part of the C pool is anaerobic and it does not matter if that C pool is increased or not. So please explain: why is the soil C pool important for the fluxes?

- *Since the CoupModel simulates the soil C decomposition based on linear kinetics which is dependent on soil conditions (e.g., temperature and moisture), Peat Decomposition = k f(T)f(θ) Cpeat , Where Peat Decomposition is the decomposition* *rate of soil peat, parameter k, decomposition coefficient, f(θ) and f(T) are the common response functions for soil moisture and temperature, Cpeat is the total C in peat. Therefore the total peat C has strong impact on the peat decomposition. The approach used in this study is the same as in He et al. (2016), therefore we do not repeat these in our revision. The high uncertainty also was the reason why the sensitivity analysis was performed, Table 2, showing a low initial soil C to result in lower peat decomposition, and the opposite, high initial soil C higher decomposition (emissions).*

- *We have added "The back calculated total soil C is assumed uniformly distributed in the soil profile of 1 meter depth, based on the measured data in 2007 (He et al., 2016)." to clarify how the soil C is distributed in the profile. The measured data in 2007 was shown in Table 1 below. The influence of initial soil C on the overall results is discussed based on a sensitivity analysis; see Table 2 in the revised paper.*
- *To make this more clear, we have now added a new table (Table 1 in the revised paper) describing the soil C budget for each modeled soil layer in 1951 and 2011. We also add these texts in the result section, "Table 1 shows the soil C budget of each modeled soil layer (down to 1 m) in 1951 and 2011. The soil C content at the uppermost 5 cm layer increases due to the addition of plant litterfall (Fig. 3), where the modeled C content in the first meter of soil is shown to match the observed data. Except the deepest layer, the other soil layers all lose soil C where losses decrease by depth. This is due to a soil water content increase, where decomposition is zero in the saturated soil (like the 90-100 cm layer) (Table 1)." to further explain the change of soil C pools and also shown that it is soil C in the aerobic layers are important for the fluxes.*

Table 1, measured Skogaryd soil properties

Measured stations	*Measured soil layer/depth (cm)*	*C content (kg/m²)*	*N content (kg/m²)*	*Total C/N*
station 1	*3-13*	*11,51*	*0,48*	*24,09*
	22-32	*12,14*	*0,49*	*24,78*
	42-52	*14,76*	*0,55*	*26,78*
station 2	*5-15*	*11,04*	*0,46*	*24,09*
	30-40	*9,50*	*0,38*	*24,78*
	48-58	*10,68*	*0,40*	*26,78*
station 3	*5-15*	*12,33*	*0,48*	*25,82*
	30-40	*10,58*	*0,44*	*24,09*
	70-80	*6,95*	*0,31*	*22,77*

Are the initial soil layers realistically described? Could you describe them to the readers? It would help if the used soil layers and their physical and chemical characteristics, and their development, were shown (fig or table). IF the original C peat C pool was important, then the present value should be checked: It is given that the original C content in 50 cm layer in soil was 11.6 kg C m-2. This is an unbelievably small value! With bulk density of 230 kg m-3 and and 85% organic matter content (Meyer et al. 2013), C concentration would have to be as low as 12% of OM (230 kg/m3 *0.5m = 115 kg m2; 115*0.85=98 kg OM m2; 98*12%=11.6 kg m-2), while it is usually close to 50% of OM. There must be an error in the C content value, it is way too low.

- *We have now added a new table (Table 1 in the revised paper) describing the soil C budget for each modeled soil layer in 1951 and 2011, shown the soil C development during the simulated 60 years.*
- *Unfortunately the too low C content was an error by us using numbers for 10 cm depths as it was 50 cm, thus too low. By using the measured data from Table 1, the measured C content in the upper 50 cm should be 55.3 kg C m-2. Then the OM concentration should be 57.2%. We have rerun the model with the updated number and updated all the results and figures in the revised paper.*

There are some issues with terminology of soil C fluxes. Soil C balance, which should be the most interesting variable here, is the sum of soil organic matter (peat and litter) decomposition and litter production. It is not always clear what the authors mean by “peat decomposition”. Sometimes “peat decomposition” is given as if it were the soil C balance (e.g. comparison with IPCC EF-values, which are soil C balances). These are two different things and have to be kept separate.

- *We have now define the terminology in the beginning of section 2.3 and adding these texts in the revised paper to make it clear “The CoupModel conceptually divides the soil organic matter (SOM) into two pools called soil litter (fresh plant detritus) and humus, constituting a fast and a slow decomposing pool, respectively (Johnsson et al., 1987). When soil litter decays carbon is either released as CO2, or adds into a resistant fraction, the humus pool (Johnsson et al., 1987). In this study, the soil humus pool was used to represent the old stored soil peat. Thus soil decomposition is composed of both peat decomposition (called humus decomposition in the model) and soil litter decomposition.”*

In results the authors state that “The GHG fluxes are composed of two important quantities, the forest carbon (C) uptake, 405 g C m-2 yr-1 and the decomposition of peat soil, 396 g C m-2 yr-1.”, it is unclear to me what do they mean with the latter – the decomposition of peat, or the soil C balance. Please be more specific with the terms.

- *We have now define the terminology in the beginning of section 2.3 and adding texts in the revised paper to make it clear, see also above*

The simulation itself shows (Fig. 5) that the “peat decomposition” rate in the 100 cm soil layer continuously almost linearly decreases. I guess the authors here observe the initially 100 cm peat layer, which in the end is not anymore 100 cm (or is it?) but 50 cm. This is interesting to see, but as litter and humus are also produced (Fig. 3), and as they form a large part of the soil C balance, they should be presented with the peat decomposition fluxes.

- *We agree with the reviewers and the accumulated litter and humus values are important in the overall soil C balance, thus we have now updated Fig. 3. We also now updated the texts in the results section to better describe the litter and soil humus formation "Over the whole of the simulated 60 years, the accumulated soil litter decomposition almost equaled that of the soil peat (treated as humus in the model), where ca. 80% of the litter is respired and the rest adds into the resistant soil C fraction, the soil peat (called humus formation in the figure). Over the 60 years, the soil litter was close to balance as the accumulated plant litterfall almost equal to the accumulated soil litter decomposition and humus formation (Fig. 3). Thus the total losses of soil C are mostly from decomposition of historical soil peat."*
- *To make this more clear, we have now added a new table (Table 1 in the revised paper) describing the soil C budget for each modeled soil layer in 1951 and 2011. we add the texts "The soil C content at the uppermost 5 cm layer increases due to the addition of plant litterfall (Fig. 3)" to show the importance of plant litterfall. The model do not simulated the surface subsidence therefore the soil layers are the same at the end of the simulation, 100 cm, see section 2.3.*

The conclusion of this study is that more C and other GHG have been lost than has been bound to the growing tree stand and that forestry is not sustainable. This conclusion seems reasonable with the given, measured NEE, forest growth and soil efflux values (Meyer et al. 2013). Does this simulation study add our understanding of the system? Yes, I think it would, but there are still many unclear things in methods, terms etc. mentioned above and in the commented MS (appendix) that should be clarified before this paper be published.

- *We have now added more detail and clear texts in the section 2.3 to define the terms and methods used in this study. And also clarify previous unclear statements now. We hope now with the revision it would be satisfactory.*

References mentioned

He, H., Jansson, P.-E., Svensson, M., Meyer, A., Klemedtsson, L., and Kasimir, Å.: Factors controlling Nitrous Oxide emission from a spruce forest ecosystem on drained organic soil, derived using the CoupModel, Ecological Modelling, 321, 46-63, 10.1016/j.ecolmodel.2015.10.030, 2016.
Jansson, P. E.: CoupModel: model use, calibration, and validation, Transactions of the ASABE, 55, 1335-1344, 2012.

Supplement of the comment from K. Minkkinen (Referee)

This is organized in this format: the texts in the manuscript, followed by the comment from the referee and the answers from the author.

1. 164 Mg C ha-1, Comment: the unite

- *We have now made the unites consistent in the revised paper, where all numbers are given in g m-2 or kg g m-2.*

2. Norway Spruce (Picea abies), Comment: italics

- *We have now changed it into Norway Spruce (Picea abies) accordingly.*

3. For instance in Finland, forest peatlands used for timber production normally undergo drainage maintenance every 40 years (Minkkinen et al., 2002). Comment: an assumption for simulation, not statistics.

- *We agree this was a mistake and have now removed this sentence. And since this is a general description we do not need to tell the maintenance intervals just state ditch maintenance is performed regularly.*

4. First, we assume the soil physical characteristics in 1951 to be the same as measured in 2006; the drainage depth to be constant during the simulated 60 years; Comment: how can it be, if a lot of C is lost from peat and a tremendous amount of new litter produced on top and into the soil (roots)?

- *We have now added the following texts to explain this assumption "First, the soil layers are assumed the same over the 60 years simulated. And the soil physical characteristics in 1951 are assumed the same as measured in 2006; possibly not fully true but better than introducing uncertain numbers, and could be argued reasonable since 1) this site has been drained for many years (starting in 19th century), why physical soil compaction should not be important during the last 60 years, and 2) soil properties were not found to be the major GHG emission influencing factor, (He et al., 2016)."*

5. Second, in order to define the initial soil C content in 1951, Comment: in which layer? The aerobic upper 50 cm? Cannot affect similarly, if it is in the catotelm, as part of the C actually must have been.

- *We have now added these texts "The back calculated total soil C is assumed uniformly distributed in the soil profile of 1 meter depth, based on the measured data in 2007 (He et al., 2016)."*
- *Moreover, we also add a new table, Table1, showing the soil C budget of each modeled soil layer (down to 1 m) both for 1951 and 2011.*

6. An extremely large initial soil C is also used, Comment: again: into which soil layers was this allocated?

- *Please see the answer above.*

7. Peat decomposition, Comment: define peat decomposition! Peat decomposition is not the same as peat loss or soil C balance - yet you seem to mean it is. This is confusing. New peat (SOM) is being formed all the time, when new litter decomposes. Thus peat decomposition rate is >> peat soil C loss.

- *We have now added the definition in the beginning section of 2.3 to define the peat decomposition, litter decomposition and soil decomposition, and also make clear the humus decomposition in the model represents peat decomposition, these texts are added in the revised paper: "The CoupModel conceptually divides the soil organic matter (SOM) into two pools called soil litter (fresh plant detritus) and humus, constituting a fast and a slow decomposing pool, respectively (Johnsson et al., 1987). When soil litter decays carbon is either released as CO2, or adds into a resistant fraction, the humus pool (Johnsson et al., 1987). In this study, the soil humus pool was used to represent the old stored soil peat. Thus soil decomposition is composed of both peat decomposition (called humus decomposition in the model) and soil litter decomposition". We thus agree that the humus pool decomposition is larger than peat C loss, described by the model.*

8. 72% of the plant biomass, Comment: that's a lot! Is there natural mortality included in the model? Some of the planted trees might have died before thinning.

- *72% is obtained from the tree ring data and the removed number of trees during the thinning. The model does not have natural mortality therefore the planted tress that died before thinning cannot be simulated. However even if some trees would have died (which we do not know) dead trees also add CO2 into the atmosphere, similarly as the indirect emissions in this case.*

9. That the material removed due to the thinning management in 1979 and the storm harvest in 26 2010 was used for paper production, as is common practice in Sweden (Swedish Forest 27 Agency, 2005). Comment: all of it? No sawwood?

- *The thinned spruces have too small diameter for saw wood. Normally it is the final harvested products that have sawwood. Also the storm harvested woods were assumed used for paper production as 60% in average are, and if a share of the storm harvest was used for timber this would have changed the conclusions very minor.*

10. Kg C m-2, Comment: kg C m-2

- *This has been changed into kg C m-2 for all in the revision.*

11. Total roots, Comment: diameter of?

- *We have now added more texts to tell the total roots including both fines roots (<2 mm) and coarse roots (>2mm).*

12. The total soil C within the top 1 m depth at the end of the simulated period, Comment: 1m at the end, or in the beginning??? See e.g. fig. 1. How is this physically possible? Bulk density in 2006 was 230 kg m-3 (p.15, r.21). Was that only 39% of the 1951 value (i.e. 590 kg m-3). Why would it get smaller? Or are you actually comparing different layers (100 cm vs. 50 cm???).

- *Yes the model soil depth must be the same in the beginning and in the end, thus 1 m. This we try to tell in Fig 1, that the real world and the model world is not the same.*
- *We have delete "The total soil C within the top 1 m depth at the end of the simulated period generally matches the observed data and only accounts for 39% of initial values estimated for 1951 (Fig. 3)" in the revised paper since we made a mistake of the soil C content, which were only 1/5 of what it should have been, we have rerun the model with the corrected number.*
- *Moreover, we also add a new table, Table1, showing the soil C budget of each modeled soil layer (down to 1 m) in 1951 and 2011. Thus the comparison between the beginning and end of the simulated period is now shown by Table 1.*

13. Reference model, Comment: the use of the reference model is unclear to me, as it is obviously not used as the prediction model for the 1951-2011. If the model can predict water levels, why is it not used for the whole period then?

- *The reference model is the prediction model for 1951 to 2011, as described in the end of section 2.3, used for the whole period. We think our naming it the 'reference model' could have caused this problem, and accordingly changed the name into "vegetation fitted model" to make it more clear and easy to understand.*

14. However, this decreased to about 150 g C m^{-2} at the end of the simulated period, Comment: why? Decrease in decomposability - or decrease in the peat layer thickness?

- *The results are updated now and we have added texts to explain the reason of the decreasing trend: "Peat respiration (decomposition) shows a slight decreasing trend during the simulated period, with an annual average of 399 g C m-2 (Fig. 5c). The decreasing trend may be explained by a lower amount of soil peat left in the surface (Table 1 and Fig. 3) and an increasing GWL (Fig. 5f) where inter-annual variations are mainly regulated by the weather".*
- *We also add a new table, Table1, showing the soil C budget of each modeled soil layer (down to 1 m) in 1951 and 2011. The table also shows the decreasing of soil C stock in most of the soil layers.*
- *Peat layer thickness has not been possible to change.*

15. And peat decomposition are the two major components of NEE, Comment: what about litterfall and litter decomposition? In Fig. 3 you show that cumulative litter decomposition has been actually larger than "humus" decomposition (which you elsewhere refer as peat). Litterfall is higher than either of these. NPP of course includes litterfall, but as a flux of organic carbon, it is essentially different from the one that forms tree biomass.

- *We have now updated figure 3 in the revised paper and added the following texts in the results section to describe the other major components "Over the whole of the simulated 60 years, the accumulated soil litter decomposition almost equaled that of the soil peat (treated as humus in the model), where ca. 80% of the litter is respired and the rest adds into the resistant soil C fraction, the soil peat (called humus formation in the figure). Over the 60 years, the soil litter was close to balance as the accumulated plant litterfall almost equal to the accumulated soil litter decomposition and humus formation (Fig. 3). Thus the total losses of soil C are mostly from decomposition of historical soil peat".*

16. From 1953 to 1962, the forest system behaves as a major CO2 source, emitting 343 g C m-2 yr-1. However, during 1963 to 1965 the system switches and acts as a minor CO2 sink with an average flux of 61 g C m-2 yr-1 before it again returns to being a CO2 source from 1966 to 1971, with an average flux of 78 g C m-2 yr-1, except for another brief period as a minor sink of 86 g C m-2 in 1968. From 1972 to 1979, the forest ecosystem acts as a sink of CO2 with an average flux of 172 g C m-2 yr-1. Comment: why? what is driving these changes.

- *We have now deleted these texts in the revised paper, since we think in this paper we are more interested into the 60 year budget than year to year variations.*

17. Instead it predicts most of the N_2O to be emitted from 1966 to 1988, Comment: why?

- *We have now added in the discussion; "The high N2O emission during the period 1966 to 1988 could be explained by the deeper GWL (Fig.5)".*

18. Soon, the whole forest will be harvested releasing a large part of the captured carbon, 16.4 Kg C m^{-2} (Fig. 2d), into the atmosphere again; and if everything were released from these soils, Comment: maybe a large part of the logs would now be made for sawwood, conserving the C pool in them. In addition, this wood product would replace for example concrete or plastic and other products the production of which cause much higher emissions, decreasing the source function, What do you mean by this? All the remaining C? Will that be released in the next 60 years?
please, use the same units, at least in the same sentence.

- *We have now add new discussions on this issue, stating "The harvested wood products over a forest rotation is used for both timber and paper, about 40 and 60% (Sweden CRF table 4.Gs2 for year 2013, submitted to the UNFCC 2015) having a half-life of 30 and 2 years respectively (IPCC 2006). Thus the carbon will soon be released as CO2. However a better alternative would be the use of timber for wooden buildings which otherwise should have been built by using concrete (Gustavsson et al., 2006). The displacement of concrete by wood could according to a meta-analysis by (Sathre and O'Connor, 2010) avoid emissions by 2.1 times the C content of the timber. However, even then, most buildings do not last more than a century and only a few buildings are functional for longer periods. Thus most harvested biomass will soon be burnt releasing the stored C. These indirect emissions following the consumption of wood would shift the system from an overall small sink into a large GHG source (Fig. 6)."*
- *Yes, we have now changed the unit into the same form for the whole paper.*

19. NEE becoming a CO_2 source when using the largest initial soil C, Comment: how does the size of the soil C pool affect the decomposition rate? It could, if there were more C in the oxic zone. But did you mean this when you changed the original soil C pool? Or is this just the impact of generating larger original soil C pool with greater emissions, which then, of course, means greater emissions? It is difficult to tell, what is the result and what is the cause.

- *We have now updated the Table 2 by adding a column of results from the vegetation fitted model in the revised paper to make it easier to understand. The initial C was assumed distributed over the whole 1m soil horizon, however we agree the largest decompositions take place in the oxic layers, also see Table 1.*
- *The sensitivity analysis here is generating larger original soil C pool with greater emissions. We have rewritten some of the texts in 3.3 model sensitivity section to make it more clear.*

20. Our simulated peat decomposition rate of 396 g C m^{-2} yr^{-1}, Comment: is this really peat decomposition rate, or soil C balance (thus including litter input and litter decomposition)?

- *We have now made this clear and added the definition in the beginning of section 2.3 to define the peat decomposition, litter decomposition and soil decomposition. Thus the humus decomposition in the model represents peat decomposition, therefore, according to the definition, the peat decomposition is the decomposition of old stored peat. Also see question 7 above.*

21. However, when compared with the IPCC EF's, Comment: IPCC EF's are soil C balance values, not peat decomposition values!

- *The IPCC EF's is the heterotrophic soil respiration which is in our case, peat decomposition. This could be found at the Figure 2.1, summary of fluxes from drained organic soils, pp28 in "IPCC 2014, 2013 supplement to the 2006 Guidelines: wetlands". In addition, at Annex 2A.1 pp 81 in the same document, under dark chamber measurements, it states "To obtain organic soil CO2 emissions, the observed flux (Rt) must be adjusted for contributions from other carbon pools (e.g. litter) and autotrophic (plant root) respiration needs to be subtracted (Ojanen et al., 2012). For these calculations, the proportion of Rh to Rt was estimated from a limited number of studies." which further tells that the IPCC EF's are only for the peat decomposition.*
- *Besides, our results also indicate that the soil litter pool is almost balanced over the rotation period since the plant litterfall almost equal to the litter decomposition and humus formation (Fig. 3). Therefore the soil C balance is almost only composed by peat decomposition.*
- *Also see question 7 above.*

22. Due to deep and long-lasting drainage, Comment: is Fig. 5f measured or simulated data? If it is measured, put cite to Fig. 5 here. But during the last years it has been fluctuating between 5 and 50 cm (Fig. 4), which is not very deep at all.

- *Figure 5f is simulated data. We have now added that in the figure texts to make it clear.*
- *When we take the average during the simulated 60 years, the average GWL is 0.52m, which could be compared with sites used to compile IPCC EF, where the deepest GWL was around 0.40 m. This justifies our statement of "deep and long-*

lasting drainage". For the last years, the decreasing GWL was mainly due to the increase of the precipitation that is shown in the Figure 5a.

23. There are some issues which still need to be more explicitly accounted for when simulating organic soils, Comment: which issues?

- *This followed in the coming text, and we agree it was a lack here, to just say there are some issues. We explain this in the text that follows but have now also added "These are the nature of the soil organic matter and physical changes of a peat soil." into revised paper to make it clear.*

24. Assuming the same bulk soil density of 0.23 g cm^{-3} as measured in 2006 and analogizing the measured total soil C in the upper 0.5 m in 2007, which was 11.6 (±1.6) 22 Kg C m^{-2} (Meyer et al., 2013), Comment: 230 kg/m3 *0.5 = 115 kg/ 0.5 m3. OM content was 0.85, i.e. 98 kg OM/0.5m3. To have only 11.6 kg C/m2 gives a C% of 12% of OM, while it is generally about 50-60% in peat. There must be an error in the C content of 11.6 kg/m2, it is much too low. This is too small a value

- *We agree this was not possible, and have checked this thoroughly. This was an error by us using numbers for 10 cm depths as it was 50 cm, thus too low. Now I have rerun the model with the updated soil C content (being about 5 times larger in 2007). By the measured C content in the upper 50 cm, 55.3 kg C m-2 instead of 11.6. Then the OM concentration should be 57.2% in 2007. We have now rerun the model with the new C content and revise all the results, figures and tables in the revised paper.*

25. And thus the wood products produced on peat soil cannot be regarded as renewable products. Comment: you are forgetting the substitution factor, i.e. the substitution of non-wood products with wood products (Sathre and Connor 2010). The effect is the same magnitude as the initial C pool in the products themselves (1 in sawwood, 0.7 in pulp) and it is cumulative.

- *We have now added a new text in discussions on this issue, stating "The harvested wood products over a forest rotation is used for both timber and paper, about 40 and 60% (Sweden CRF table 4.Gs2 for year 2013, submitted to the UNFCC 2015) having a half-life of 30 and 2 years respectively (IPCC 2006). Thus the carbon will soon be released as CO2. However a better alternative would be the use of timber for wooden buildings which otherwise should have been built by using concrete (Gustavsson et al., 2006). The displacement of concrete by wood could according to a meta-analysis by (Sathre and O'Connor, 2010) avoid emissions by 2.1 times the C content of the timber. However, even then, most buildings do not last more than a century and only a few buildings are functional for longer periods. Thus most harvested biomass will soon be burnt releasing the stored C. These indirect emissions following the consumption of wood would shift the system from an overall small sink into a large GHG source (Fig. 6).", also see question 18.*

26. Table 1, Comment: explain: during which time period (2006-2011?) and define peat decomposition

- *We have now added 1951-2012 into the table to make it clear.*
- *Peat decomposition is now defined at the beginning of section 2.3.*

27. Table 2, Comment: again, what do you mean by soil peat CO2 emissions. The emissions from decomposition, or soil C balance?

- *We have now defined peat decomposition at the beginning of section 2.3 and make it clear.*

28. Figure 1, Comment: what are the grounds for 50 cm subsidence in 56 years? Has this been measured? Or does the 56*EF produce the amount of peat in 50 cm?

- *We never say there is a 50 cm subsidence during 56 years. Figure 1e and f (now updated) do not consider subsidence. Back-calculation for an initial soil C assumes C addition to the full 1 m soil profile, also see answer to question 5.*

29. Figure 3, Comment: so the simulation concerns only the original 100 cm layer? So that it is 50 cm in 2007? This should be mentioned in the caption, it is not self-evident. In addition, the C pool is given at 11.6 kg m-2 in 50 cm layer. This is unbelievably small value. With bulk density of 230 kg m-3 and and 85% organic matter content, C concentration would have to be 12% of OM. It is usually close to 50%.

- *Yes, we have now added that in the caption stating we model 1 m soil depth, and this depth holds for the full period.*
- *Yes unbelievable small, we agree and have checked this thoroughly, see above. This was an error by us using numbers for 10 cm depths as it was 50 cm, thus too low. Now I have rerun the model with the updated soil C content (being about 5 times larger in 2007). By the measured C content in the upper 50 cm, 55.3 kg C m-2 instead of 11.6. Then the OM concentration should be 57.2% in 2007. We have now rerun the model with the new C content and revise all the results and figure and tables in the revised paper.*

30. Figure 4. Comment: how could you simulate GWL here, when you have stated that COUP can not simulate GWL

- *In our previous manuscript, GWL and drainage depth might be confusing. To clarify the drainage depth and GWL, we have now added the explanation of drainage depth "a parameter used for estimation of horizontal flow of water out of the site due to drainage" into section 2.3. We also add the reference He et al. 2016 into the revised paper "*with the drainage depth set to 0.5 m as in He et al., (2016).*" to explain where the 50 cm origin from. Thus it is not the GWL that is set to 50 cm, rather the drainage depth that is set to 50 cm (The GWL is simulated in daily scale, see Figure 4c & 5f). The model of course can simulate the variable GWL, which fluctuates over time. By comparing the simulated GWL with the measured data during 2006 to 2011, the model simulates the GWL well, with coefficient of determination R2 of 0.8 and mean error of zero (Figure 4c).*

31. Figure 5. Comment: is this only the original peat layer of 100 cm (which gets thinner)?
Please add other fluxes (litter, humus formation, from Fig. 3). Show the soil C balance (peat+litter decomposition - litterfall). Why does GWL rise, although stand volume gets bigger and transpiration increases?
Is this measured or simulated. You earlier mention that GWL cannot be used in the model. This is confusing!

- *We have now updated Fig. 3. We also now updated the texts in the results section to better describe the litter and soil humus formation "Over the whole of the simulated 60 years, the accumulated soil litter decomposition almost equaled that of the soil peat (treated as humus in the model), where ca. 80% of the litter is respired and the rest adds into the resistant soil C fraction, the soil peat (called humus formation in the figure). Over the 60 years, the soil litter was close to balance as the accumulated plant litterfall almost equal to the accumulated soil litter decomposition and humus formation (Fig. 3). Thus the total losses of soil C are mostly from decomposition of historical soil peat."*
- *To make this more clear, we have now added a new table (Table 1 in the revised paper) describing the soil C budget for each modeled soil layer in 1951 and 2011, also see above. we add the texts "The soil C content at the uppermost 5 cm layer increases due to the addition of plant litterfall (Fig. 3)" to show the importance of plant litterfall.*
  The model do not simulated the surface subsidence therefore the soil layers are the same at the end of the simulation, 100 cm, see section 2.3.
- *Figure 5f is simulated data. We have now added that in the figure texts to make it clear.*
- *The GWL increase is mainly due the increase of precipitation in the later years (Fig 5a).*

Reference

IPCC 2014, 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: wetlands, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Jamsranjav, B., Fukuda, M. and Troxler, T. G. (eds). Published: IPCC, Switzerland.

Interactive comment on “Forests on drained agricultural peatland are potentially large sources of greenhouse gases – insights from a full rotation period simulation” by H. He et al.

Anonymous Referee#1

Received and published: 1 Feb 2016

I thoroughly enjoyed reading this manuscript which describes a modelling study the impact of land-use change from peatlands to forests on the GHG balance in Sweden. It is clear there has been a considerable amount of work in both the simulations and the manuscript which is well written. The figures are clear and self-explanatory with only one or two mistakes. Below are my comments and questions.

1) Figure 2c maybe it would have been better if it was a scatterplot. It will make clearer the under/over estimation of the model. My question here is that although on average the model is closer to the data how significant is the slope and intercept of the comparison. Maybe then put the scatterplot of the evaluation of the model against data (plant & tree growth) separately and show significance of slopes/intercepts

- *Yes a scatterplot is another way to show the data. However, we think our plotting against time shows the biases over time better. The bias is also shown by: 1) the mean error (ME) given in the plot indicates an overestimation compared to measured data. 2) The significance of a scatter plot slope is also given in the figure with a high correlation coefficient (R^2=0.84) between the model and data. We have discovered the plot can be misunderstood as a carbon stock content, where it actually is a rate, why we updated the unit on the y-axis to g C m^{-2} yr^{-1}.*

2) Page 19683 lines 16-17. I cannot see where there is any data shown to support your suggestion that understorey layer is over predicted by the model. I see that both plant growth AND tree growth is underestimated by the model in 0-20 years (Fig 2c & 2d). Now I assume here that tree growth is included with plant growth so I don’t see how understorey layer could have been overpredicted. Needs more explanation within the text and maybe more clear graphs

- *We have now added “Two vegetation layers are simulated in the model, the Spruce tree and the understorey layer (e.g. grasses and shrubs) (He et al., 2016).” into section 2.2 to clarify the terms used by the model. Figure 2c and 2d only show the Spruce tree growth, and we now use consistent and clear terminology in the revised paper, where the “Spruce tree growth” means Spruce tree only and “plant growth including understorey layer” means the total plant growth. The underestimation of Spruce tree growth in the first 20 years is probably due to competition with understorey vegetation (Fig 2e), mainly grass, which is now added into the section 3.1.1. However after this initial period the understorey vegetation is suppressed by the spruce and in the 60 year forest the ground vegetation is very sparse composed mainly of patches with mosses. Overall the understorey vegetation has little impact on the results.*

- *We have now added more colors in the Figure 2e to make it more clear and easy to read.*

3) Page 19683 lines 17-18. As far as I understand the works of the CoupModel there are different ways of doing photosynthesis by either using simple light use efficiency model or the most complicated root of Farquhar model which usually comes with light attenuation mechanisms within the plant canopy. The authors have not made clear which version of the model have used. This is important since in the case of the first (i.e, light use efficiency) the relationship between LAI and NPP with radiation is stronger since photosynthesis is more directly driven by it. So the statement here does not necessarily consist of a success of the model's ability to simulation NPP.

- *We have now added "C and N dynamics are simulated both in the soil and in the plant, driven by the canopy-intercepted radiation, regulated by multiplicative response functions of air temperature, and plant availability of water and N." into the section 2.2 to clarify the radiation use efficiency method is used for photosynthesis simulation. However details can be found in He et al. (2016), where all equations, parameters and methods used for modeling Skogaryd forest are reported (this reference is also added now). We there found the model able to describe the C cycling (including NPP) quite well. Also the fairly well agreement between the modelled spruce biomass obtained in this study and the tree ring data further suggest the NPP was well described.*

4) Figure 3. Lines are not very clear in the graph for accumulated humus respiration and plant litter. Consider improving graph.

- *We have now changed the thickness of the lines and make the graph looks more clear, see Figure 3.*

5) Figure 4 and Page 19684 Line 25, Page 19685 line 1. I agree the seasonality was captured by the model but I disagree that the magnitude was capture. In the case of solar radiation 2007 magnitude was not successfully simulated and for NEE 2008. In particular the maximum of NEE from observations were around 10 gC m-2 day-1 (Please check the units on the graph) where as the model peaked closer to 18 (?) gC m-2 day-1.

- *By rerun the model with the updated soil C content, the soil abiotic properties generally do not change so much compare to earlier results. The figure 4 has now been updated with new model results. Similarly, the model overestimates the radiation (shown by a positive mean error) and also the NEE compared with measured data. However, the magnitude of the overestimation is small compare to the data (10^5 compared with 10^7 for radiation). With the updated results, the simulated discrepancies of NEE during the summer of 2008 have also been reduced (Fig. 4d), as also shown by the small mean error.*
- *We have also corrected the unit for NEE in figure 4d to be g C m^{-2} day^{-1}.*

6) It is likely that the over-prediction of NEE is associated with underestimation of soil respiration. But if we assume that soil respiration is strongly driven by soil temperature then soil respiration should have also be overpredicted since predicted soil temperatures is higher than observed (Figure 4b). So the question is how the model has can have higher respiration but with higher temperatures. There is a big uncertainty here which I believe is related to the decomposition parameters and how respiration is produced which I believe needs further exploration. Furthermore, data from 60km away were used to drive the model. In micro-

meteorological terms, topography and climate between the site for which simulations were done using met data and the site were CO_2 measurements took place with eddy covariance can not be assumed the same. All these and the fact that a fitting with a single point value of soil total C was done to represent soil processes reduces my confidence to the model. In the end the high uncertainty over soil fluxes has an impact on the final conclusion. The authors should have addressed the uncertainty arising from the lack of data with a data-model fusion such as a Bayesian calibration with MCMC or a Kalman filter.

- *We have now updated all the results and figures with corrected initial soil C content data. The updated results have shown an increased soil respiration compared with earlier results thus a better simulation of the NEE (Fig. 4d), as shown by the small mean error. Further discussion on this could be found at He et al., (2016).*
- *We fully agree that micro-meteorological conditions at the climate Såtenäs station could be different with Skogaryd site. However, we needed this data for the long term simulation and we have checked this data with data from the Skogaryd site between 2006 and 2011 and the Såtenäs data showed high correlations and similar magnitude with the measured Skogaryd data, see Section 2.5.*
- *We also fully agree that it would have been be good to have more soil C data during the 60 years to validate our simulated soil C dynamics. Unfortunately that's not the case. The best we could do was to use the calibrated CoupModel, He et al., (2016,) using Generalized Likelihood Uncertainty Estimation method. In addition we in this study calibrate the model with respects to plant growth (tree ring data) over the period 1966 to 2011, plus extend with new available data, both abiotic and soil gas fluxes, so called "vegetation fitted model". One source of uncertainty is of course the soil C content in the planting year (which is hopelessly unknown). To overcome this we conducted a sensitivity analysis spanning a soil C variation, shown in the revised paper. We have further included and updated the sensitivity analysis results in our revision. Taken together we believe the model is able to give a realistic description of the 60 year dynamics of soil and plant development.*

7) By assuming a constant N deposition rate using the authors have ignored increases to global pollution levels over the recent years and the combined combination it has with increasing temperature over the higher latitude forests. It was shown that nitrogen deposition creates an extra added feedback to tree growth which should not be ignored. The authors suggest that from the sensitivity analysis any extra nutrients would have no impact on the result of the model which might be true since the relationship between nitrogen and growth as model could have reached an asymptote although some times there might be a hidden-non linear relationship only and further increase would have shown. But, by assuming a constant N deposition, failed to answer the critical questions of how N deposition will affect the balance of GHG and in this case N_2O, and what feedback exist between production of carbon GHG and non-carbon GHG due to extra nitrogen. These are questions which experiments can deliver with difficulty.

- *The site simulated in this study was drained peat soil, a former fen used for agriculture during a few decades before planting spruce. The soil is fertile and in our model simulation the soil N availability was mostly not limiting the forest growth. In He et al., (2016) we did a complete N budget for the forest and found the peat soil to deliver most of the N needed (118 kg N ha-1 year-1) for* *the forest growth and the N deposition only contribute a small amount (12 kg N ha-1 year-1). This suggests that in this type of ecosystem the N deposition is not very important. Moreover the N deposition has decreased in this area during the last decades, and is now smaller than 12 kg N ha^{-1} year^{-1}.*

8) I agree with the authors that until know models have been simulating SOM decomposition with the same rates through out a prolonged simulation period based on linear kinetics which are dependent only on soil conditions (e.g., temperature and moisture) but with no consideration both on the microbial community that drives decomposition and the quality of litter that may affect how fast decomposition is happening. and modelling studies have shown that the fate of SOM is highly dependent on the quality of litter and how it is consumed by microbes. Good quality of litter which is easy to decompose is usually preferred by microbes thus accelerating the decomposition of fast pool to such rates that it only becomes an intermediate pool and starting to reduce faster the old, "slow" pool. Grass litter is a good example. On the other hand introducing spruce litter, which is lignin rich, will reduce decomposition of old "stable" pool by microbes since it becomes more difficult to decompose. This switch in quality of litter can associated with the change in land-use from peat to forest can make a difference to the carbon stocks and they should be included in the author's model

- *We have now added how CoupModel handles SOM for organic soil at the beginning of Section 2.3: "The CoupModel conceptually divides the soil organic matter (SOM) into two pools called soil litter (fresh plant detritus) and humus, constituting a fast and a slow decomposing pool, respectively (Johnsson et al., 1987). When soil litter decays carbon is either released as CO2, or adds into a resistant fraction, the humus pool (Johnsson et al., 1987). In this study, the soil humus pool was used to represent the old stored soil peat. Thus soil decomposition is composed of both peat decomposition (called humus decomposition in the model) and soil litter decomposition."*
- *We further revised the discussion section 4.2.1. To better show and illustrate the processes that the decomposition of litter over time will add a resistant fraction into the humus pool, we now added a new table, Table 1 where litter addition results in accumulation of soil C in the uppermost soil layer.*

9) I agree with the other reviewer that changes to soil physical properties is important when you considering trees and how their root system changes over the years. In a peat environment there should be a bias introduced to soil dynamics and feedback because of tree growth.

- *We have now added the texts "First, the soil layers are assumed the same over the 60 years simulated. And the soil physical characteristics in 1951 are assumed the same as measured in 2006; possibly not fully true but better than introducing uncertain numbers, and could be argued reasonable since 1) this site has been drained for many years (starting in 19th century), why physical soil compaction should not be important during the last 60 years, and 2) soil properties were not found to be the major GHG emission influencing factor, (He et al., 2016)." in the revised paper to explain the first assumption.*
- *We have also deleted "root development also follows a simple static approach. The disappearance of the soil and the deepening of the root system are therefore not considered in the simulation as it is currently configured." in our revised paper. As the model simulates the development (growth, respiration and turnover) of plant roots (both for fine roots and coarse roots) well, shown*

by Fig 2e. And CoupModel has already included the feedbacks to the soil physical properties (e.g. water content, temperature) due to the growth of the trees through plant interception, shading, and transpiration etc. The growth of the trees also impacts the soil chemistry through plant litterfall (Fig. 3). Therefore the soil dynamics and feedbacks from tree growth are already considered in our study.

References mentioned

He, H., Jansson, P.-E., Svensson, M., Meyer, A., Klemedtsson, L., and Kasimir, Å.: Factors controlling Nitrous Oxide emission from a spruce forest ecosystem on drained organic soil, derived using the CoupModel, Ecological Modelling, 321, 46-63, 10.1016/j.ecolmodel.2015.10.030, 2016.

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

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Abstract

The CoupModel was used to simulate a Norway Spruce forest on fertile drained peat over 60-years, from planting in 1951 until 2011, describing abiotic, biotic and greenhouse gas (GHG) emissions (CO_2 and N_2O). By calibrating the model against tree ring data we obtained a '~~reference'~~ vegetation fitted' model by which we were able to describe the fluxes and controlling factors over the 60 years. We discuss some conceptual issues relevant to improving the model in order to better understand peat soil simulations. However, the present model was able to describe the most important ecosystem dynamics such as the plant biomass development and GHG emissions. The GHG fluxes are composed of two important quantities, the Spruce ~~tree~~ forest carbon (C) uptake, ~~405~~ 413 g C m^{-2} yr^{-1} and the decomposition of peat soil, ~~396~~ 399 g C m^{-2} yr^{-1}. N_2O emissions contribute to the GHG emissions by 0.~~5~~ 7 g N m^{-2}

yr^{-1}, corresponding to ~~56.8~~76 g C m^{-2} yr^{-1}. The 60-year-old Spruce forest has an accumulated biomass of 16.~~4~~ 0 ~~Mg~~ kg C ~~ha~~m^{-}~~^{1}~~^{2}. However, over this period~~,~~ ~~20~~26.~~8~~ 4 ~~Mg~~ kg C ~~ha~~m^{-}~~^{1}~~ ^{2} GHG has been added to the atmosphere, which means a net addition of GHG emissions. The main losses are from the peat soil and, indirectly, from forest thinning products, which we assume have a short lifetime. We conclude that after harvest at an age of 80 years, most of the stored biomass carbon is liable to be released, the system having captured C only temporarily and with a cost of disappeared peat, adding CO_2 to the atmosphere.

1 Introduction

Peatlands contain around one third of the carbon (C) stored in global soils, which is equivalent to almost half that present in the atmosphere (FAO, 2012; IPCC, 2013). Undisturbed peatlands accumulate C as partially decayed vegetation, and the decay processes emit C in the form of carbon dioxide (CO_2) and methane (CH_4). Overall, the net greenhouse gas (GHG) balance of the ecosystem photosynthesis and ~~decomposition~~ respiration is generally positive, thus peatlands are considered to be C sinks contributing to an attenuation of climate change (Gorham, 1991). However, when peatlands are drained for intensified land use, i.e. agriculture or forestry, the stored peat starts to decompose aerobically. The accelerated soil decomposition emits large amounts of CO_2, ~~and,~~ in contrast ~~to~~ CH_4 emissions~~,~~ are greatly reduced, possibly even accounting for a net uptake of atmospheric CH_4 (Limpens et al., 2008). The decomposition also releases nitrogen, ~~while~~ and another powerful GHG, nitrous oxide (N_2O), could also be produced, primarily through microbial nitrification and denitrification processes (Firestone and Davidson, 1989). Globally, peatlands cover only 3% of the Earth surface among which 10% - 20% of the total peatlands have been drained for agriculture or forestry, mainly in the boreal and tropical regions (FAO, 2012). However, these small areas emit around 6% of the global annual anthropogenic GHG emissions (IPCC, 2013).

To date, a number of studies have investigated the size of GHG fluxes from managed peatlands with different land uses, together with their interactions with environmental factors e.g. (Kasimir Klemedtsson et al., 1997; Von Arnold et al., 2005a; Von Arnold et al., 2005b; Alm et al., 2007; Beek et al., 2010; Lund et al., 2010; Lohila et al., 2011; Ojanen et al., 2013). Several factors have been found to influence the size of the emissions, including the groundwater level (GWL), land use intensity, climate zones, and soil fertility (Klemedtsson et al., 2005; Drösler et al., 2008; Leppelt et al., 2014). In general, nutrient rich fens with deep GWL are larger GHG sources than ombrotrophic bogs with shallow GWL, while intensive land use in tropical/temperate regions have much higher emissions than extensive land use in boreal regions (Byrne et al., 2004). Peatlands in Europe used as grassland, agricultural land, peat cuts, and abandoned peat are generally found to be net GHG sources (Byrne et al., 2004; Drösler et al., 2008). However, forested drained peatland can be everything from a source to a small GHG sink due to the growing forest, where the net primary production (NPP) of trees and understorey vegetation balances the soil emissions (Drösler et al., 2008; Klemedtsson et al., 2008; Hommeltenberg et al., 2014). Previous flux measurement studies have also shown contradictory results. Measurements from Scandinavia and Great Britain have shown the NPP to compensate for the soil CO_2 release, and thus the forests to act as net sinks (Hargreaves et al., 2003; Von Arnold et al., 2005a; Von Arnold et al., 2005b; Ojanen et al., 2013). Hommeltenberg et al., (2014) also reported an afforested drained bog in southern Germany to be a net GHG sink; however, if the 44-year history of the forest were included in the analysis, then the so-called 'long-term carbon balance', showed the forest to be an overall GHG source. Von Arnold et al., (2005a) showed that accounting for N_2O in the greenhouse budget calculation could shift drained birch peatlands from being minor GHG sinks into sources. This was also shown by Meyer et al., (2013) for a drained former agricultural peat soil with spruce forest, where soil N_2O emissions, in terms of global warming potential (265 times of CO_2 in a 100-year perspective, IPCC, 2013), offset half the net ecosystem exchange (NEE). Large N_2O emissions are most pronounced for fertile soils like former agricultural peatlands (Klemedtsson et al., 2005). So far most studies have only covered a few years at most. Consequently we still lack an understanding of the full GHG balance when viewed over the full forest rotation (Maljanen et al., 2010).

In the present study we aim to address this knowledge gap by exploring the GHG balance for a Norway Spruce (*Picea abies*) forest on drained agricultural peatland (Skogaryd Research Site: http://www.fieldsites.se/en/field-research-stations) over a full rotational time period. Since measurements are mostly short-term, and because it is not possible to directly upscale the measured fluxes to the entire forest rotation period (Drösler et al., 2008; Hommeltenberg et al., 2014), we chose a modeling approach based on emission data over five years and data on forest growth rate over 45 years for a Spruce forest on former agricultural peatland. This study forms a continuation of that by He et al., (2016), in which the process-based model 'CoupModel' (Jansson, 2012) was calibrated to simulate the water, heat, and major C and N processes for the Skogaryd Research Site.

1.1 Conceptual model of drained peatland for forestry

When peatlands are drained for forestry or agriculture, resulting in a lower GWL, the aerobic soil volume increases (Fig. 1a). The previously water-logged peat soil then decomposes aerobically, losing soil C stock and also causing a lowering of the soil surface (surface subsidence) (Eggelsmann, 1976; Hooijer et al., 2012). During the first few decades after planting, the development of plant roots and leaf area cover increases the transpiration rate, so deepening the GWL (Fig. 1b). In other words, a growing forest will, in part, help to keep the soil drained. However, drainage becomes less efficient with time due to subsidence and ditches becoming filled with litter and moss, all of which can lead to an increased GWL (Fig. 1c), which is why ditch maintenance is performed regularly. For instance in Finland, forest peatlands used for timber production are assumed to normally undergo drainage maintenance every 40 years (Minkkinen et al., 2002). After ditch maintenance the forest ecosystem restarts at the well-drained state (Fig. 1d), until the final clear-cutting when re-drainage has to be conducted. The entire cycle then starts again and can continue until all the peat is gone.

2 Material and methods

2.1 Site description

Data used for the present study were obtained from the Skogaryd research site, located in southwest Sweden (58°23′N, 12°09′E), which is part of the Swedish Infrastructure for Ecosystem Science (SITES, www.fieldsites.se). The drained peat area at Skogaryd was previously a fen, classified as mesotrophic peat with a peat depth of more than 1 m, according to the soil classification scheme suggested by Karlsson (1989). It was initially drained by ditches in the 1870s and then used for agriculture until 1951. Norway Spruce (*P. abies*) was then planted and the stand is now a mature mixed coniferous forest dominated by Norway Spruce (95% by stem volume), with a sparse presence of Scots pine (*Pinus sylvestris*) and Silver birch (*Betula pubescens*) (Klemedtsson et al., 2010). The site has been intensively measured and monitored since 2006, providing abiotic and biotic data including CO_2 and N_2O fluxes that could be used to validate the long-term model predictions. More detailed site description can be found in He et al., (2016), Klemedtsson et al., (2010), Meyer et al. (2013) and Ernfors et al. (2010).

2.2 Brief introduction to the CoupModel

The CoupModel (coupled heat and mass transfer model for soil-plant-atmosphere systems) is an updated version of the previous SOIL and SOILN model (Jansson and Moon, 2001). The main model structure is a one-dimensional, layered soil depth profile, in which the water, heat, and C and N dynamics are simulated based on detailed descriptions of soil physical and biogeochemical processes. C and N dynamics are simulated both in the soil and in the plant, driven by the canopy-intercepted radiation, regulated by multiplicative response functions of air temperature, and plant availability of water and N. Two vegetation layers are simulated in the model, the Spruce tree and the understorey layer (e.g. grasses and shrubs) (He et al., 2016). The model is available at http://www.coupmodel.com/. A detailed description of the model, its parameterization and setup is given in He et al., (2016); here only the variables and parameters with different values are reported.

2.3 Model approach and design

The CoupModel conceptually divides the soil organic matter (SOM) into two pools called soil litter (fresh plant detritus) and humus, ~~which~~ constitut~~e~~ing a fast and a slow decomposing pool, respectively (Johnsson et al., 1987). ~~The model assumes~~When soil litter ~~to~~ decays~~,~~ carbon~~so producing both~~ ~~this~~ is either released as CO_2 ~~and~~, or adds~~ing~~ into a resistant fraction ~~into~~, the humus pool (Johnsson et al., 1987). In this study, the soil humus pool ~~in the model~~ was used to represent the ~~historical~~old stored soil peat ~~in reality~~. Thus ~~e~~ soil decomposition ~~thus~~ is composed of both ~~soil~~ peat decomposition (~~or~~called humus decomposition in the model) and soil litter decomposition. ~~The~~ Besides, CoupModel conceptualizes the soil profile into a number of soil layers, where the soil's physical structure (defined by the measured water retention characteristics) and the drainage depth (a parameter used for estimation of horizontal flow of water out of the site due to drainage) ~~are~~ is assumed to be fixed over time (Figs 1e and 1f), with the drainage depth set to 0.5 m as in He et al., (2016). Though the drainage depth is a very important parameter for the simulated GWL, a fixed drainage level is not to be confused with a fixed GWL as the latter is simulated (see Fig 5f). The subsidence of the soil surface and any variation in drainage (Figs 1a, 1b, 1c and 1d) during the plant development years (1951 to 2011) cannot ~~therefore be~~ explicitly be simulated. We thus make the following assumptions to simplify the system:

First, the soil layers are assumed the same over the 60 years simulated. ~~First, we assume t~~And the soil physical characteristics in 1951 are~~to be~~ assumed the same as measured in 2006; possibly not fully true but better than introducing uncertain numbers, and could be argued reasonable since 1) this site has been drained for many years (starting in 19th century), why physical soil compaction might not be largeshould not be important during the last 60 years, and 2) soil properties were not found to be the major GHG emission influencing factor, (He et al., 2016). As the results of sensitivity analysis in He et al., (2016) shows the drainage depth determines the GWL, thus regulates GHG fluxes and also possibly the plant growth. TThe drainage depth is assumed to be constant during the simulated 60 years; and there to have been a continuous lowering of drainage ditch depth as the soil subsides, so keeping the distance between soil surface and GWL constant (Figs 1e and 1f), with the drainage depth set to 0.5 m as in He et al., (2016). However, a range between 0.3 m and 0.8 m was used to assess the model's sensitivity to long-term processes (Fig. 1e, see also Table 1). A range of drainage depth was used to quantify the model's sensitivity. The lower end of the range was chosen to be a drainage depth of 0.3 m, since this has been suggested to be the minimum requirement to sustain forest productivity on drained peatlands (Sarkkola et al., 2010; Ojanen et al., 2013). The higher drainage level, 0.8 m, was set according to general forest management practices and also took into consideration the fact that our simulated soil depth only reaches a maximum of 1 m.

Second, in order to define the initial soil C content in 1951, we use the soil C measurements made at Skogaryd in 2007, and back-calculated to 1951 by adding assuming an annual peat loss of 2.60 Mg C ham^{-1-2} yr^{-1} from 1951 to 2007, Table 1. This annual loss was taken from the recent IPCC wetland supplement (IPCC, 2014), where it represents the emission factor for forest on drained nutrient-rich peatlands in the temperate region. The model's sensitivity to this initial condition can bewas assessed by varying IPCC emission factors (EF's) between 200 and 3.30 Mg C ham^{-1-2} yr^{-1} when calculating total soil C in 1951, Table 2. In addition, an extremely large initial soil C is also used in the sensitivity analysis which was back-calculated using the highest peat decomposition rate of 6.30 Mg C ham^{-1-2} yr^{-1} (Meyer et al., 2013) measured at Skogaryd during 2008 (Table 1). The back calculated total soil C is thenassumed uniformly distributed in the soil profile of 1 meter depth, based on the measured data in 2007 (He et al., 2016).

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

Fourth, similarly to the previous calibration study, the model only simulates the C and N dynamics in the uppermost 1 m depth of soil.

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

2.4 Tree ring sampling and data processing

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

2.5 Data for model forcing

To drive the model, we used daily mean meteorological data (1961 to 2011) from the Swedish Meteorological and Hydrological Institute (SMHI) Såtenäs station (58°44′N, 12°71′E), (www.smhi.se) situated approximately 60 km east of Skogaryd. Precipitation, air temperature, wind speed and relative humidity data from Såtenäs were strongly correlated ($R^2 > 0.8$) with those from Skogaryd from 2006 to 2011, and were of similar magnitude. Another driving variable needed in CoupModel is the global short wave radiation. As these data are not available from Såtenäs station, they were deduced by the model from the potential global radiation and atmospheric turbidity, using the measured total cloud-cover fraction (for more details see http://www.coupmodel.com). Since meteorological data were only available from 1961, the meteorological data from 1961 to 1971 were duplicated to represent the climate between 1951 and 1961.

2.6 GHG budget compilation

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

3 Results

3.1 Model performance

3.1.1 Plant and soil development from 1951 to 2011

The simulated tree biomass dynamics during the 60 years agrees well with the estimated tree biomass from radial growth observations beginning in 1966. After an initial phase of slow growth during the establishment of the Spruce trees' leaf area, growth increased almost linearly (Fig. 2d). The slow establishment of the Spruce in the first decade was probably due to competition from grasses and other field vegetation. The Spruce's~~ plants~~ gradually increased their leaf (needles) cover until a closed canopy formed in the 1980s with a maximum leaf area index (LAI) of around 6, which was similar to field measurements (Fig. 2b). The simulated annual average Spruce tree~~plant~~ growth over the whole period is ~~405~~ 413 g C m^{-2} yr^{-1} with the maximum growth rate of ~~820~~ 848 g C m^{-2} yr^{-1} in 1974 (Fig. 2c). However, the ~~reference model~~'vegetation fitted model' generally shows underestimation of the plant growth ~~during the first 20 years~~before 1970s, which is probably due to the model's difficulty ~~in precisely simulating the competition between the~~to distribute the importance of the Spruce tree ~~layer~~ and the understorey layer. The underestimation of Spruce tree growth for the first 20 years suggests an overestimation of the model~~l~~ed understorey layer~~ in the reference model.~~. –The LAI and the NPP of Spruce generally follow the dynamics of the plant's ability to intercept radiation (Fig. 2a); however, the model slightly overestimates annual Spruce tree growth from the 1970s to the 1990s, and underestimates it from 1996 until 2011 (Fig. 2c). Furthermore, the large increase of simulated plant growth observed in 2006 was not observed in the tree ring data. The total tree biomass in 2011 is modeled to be 16.~~4~~0 ~~Kg~~ kg C m^{-2}, which is very similar to the biomass estimated from the tree ring data, 16.2 ~~Kg~~ kg C m^{-2} (Fig. 2d). The thinning conducted in 1979 removed 6.8 ~~Kg~~ kg C m^{-2} plant biomass, and the storm in 2010 caused an additional removal of 1.8 ~~Kg~~ kg C m^{-2}; these quantities were used for indirect emission calculations (Fig. 2d). The modeled amounts of leaf and root biomass in 2007 also match estimations using allometric equations reported by Meyer et al., (2013). The modeled and estimated values for leaf biomass were 0.95 and 1.06 ~~Kg~~ kg C m^{-2}, respectively, and the values for total roots (both coarse roots (> 2 mm) and fine roots (< 2 mm)) were 2.9 and 3.0 ~~Kg~~ kg C m^{-2}, respectively. The modeled value for Spruce stem biomass was ~~13~~12.~~1~~ 8 ~~Kg~~ kg C m^{-2}, which was higher than the estimated 11.2 ~~Kg~~ kg C m^{-2}. This discrepancy may be explained by the estimated total ~~plant~~ Spruce tree biomass by Meyer et al. (2013) being smaller than that estimated from tree ring data. The maximum biomass of understorey vegetation was simulated to be around 2 ~~Kg~~ kg C m^{-2} 10 years after planting, but it decreased gradually thereafter (Fig. 2e).

~~The total soil C within the top 1 m depth at the end of the simulated period generally matches the observed data and only accounts for 39% of initial values estimated for 1951 (Fig. 3).~~ Table 1 shows the soil C budget of each modeled soil layer~~s~~ (down to 1 m) ~~from~~in 1951 ~~to~~and 2011. The soil C content at the uppermost 5 cm layer increases due to the addition of plant litterfall (Fig. 3), where the model~~l~~ed C content in the first meter of soil is shown to match the observed data. Except the deepest layer, t~~T~~he other soil layers all lose soil C ~~and the amount of~~where losses ~~during the 60 years shows a~~ decrease~~ing trend~~ by depth. This is due to a soil water content increase, where~~and~~ decomposition is zero in the ~~when the soil is~~ saturated soil (like the 90-100 cm layer) ~~the decomposition is zero~~ (Table 1). Over the whole of the simulated 60 years, the accumulated soil litter ~~respiration~~ decomposition almost equaled that of the soil peat (~~which was~~ treated as humus in the model), where *ca.* 80% of the litter is respired and the rest adds~~.~~ ~~Decomposition of soil litter adds The~~ into the resistant soil C fraction, the ~~of litter into historical~~ soil peat (called humus formation in the figure) ~~and this only accounts for *ca.* 20% of the total plant litter input to the soil,~~. Over the 60 years, the soil litter was close to balance as the accumulated plant litterfall almost equal to the accumulated soil litter decomposition and humus formation (Fig. 3). ~~and~~ Thus the total losses of ~~the~~ soil C are mostly ~~due to losses~~ from ~~respiration~~ decomposition of historical soil peat.~~. Before 1965, the total soil C losses are mainly through soil peat respiration~~decomposition~~, which is larger than the total plant litter input, indicating there to be a large soil C imbalance at the beginning of the rotation (Fig. 3).~~

3.1.2 Comparing ~~reference model~~vegetation fitted model output with observational data from 2006 to 2011

The simulation beginning in 1951 using the ~~reference~~ ‘vegetation fitted model’~~, fitted to the tree ring data,~~ showed a good fit with data collected during~~for the period~~ 2006 until 2011 ~~when comparing simulated and measured~~of GWL, total net radiation and soil temperature data. The linear correlations between the simulated and measured data were all above 0.~~7~~8 with the mean errors close to zero (Fig. 4). Discrepancies were found in May 2010, when the measured GWL peaked (high GWL) ~~and~~ which by the model was underestimated (Fig. 4c), and during summers and autumns when the model overestimated both radiation and soil temperature (Figs 4a, 4b). Besides ~~being a~~showing reasonable description of abiotic factors, the model results were also similar to observed data ~~from~~ between 2007 ~~to~~ and 2008 on NEE flux, both in terms of seasonal pattern and magnitude (Fig. 4d). However, the simulations seem~~ed~~ to slightly underestimate the CO_2 uptake during summertime and overestimate the respiration flux in the autumn (Fig. 4). The model performance for N_2O emissions was generally similar as in the previous calibration study (He et al., 2016), where the annual emission size was reasonably simulated but the model had some difficulties in capturing every measured emission peak.

3.2 GHG balance

3.2.1 Annual NEE and N_2O from 1951 to 2011

The annual 60-year NPP for the Spruce forest, including biomass and litter, was on average ~~683~~ 673 g C m^{-2} with less than 100 g C m^{-2} during the first 10 years after planting, and with a value that fluctuates around 1000 g C m^{-2} yr^{-1} over the last 40 years (Fig. 5b). ~~In the first decade the peat decomposed at its maximum rate of around 700 g C m^{-2}. However, this~~Peat respiration (decomposition) shows a slight~~ly~~ decreas~~e~~ing trend during the simulated period ~~decreased to about 150 g C m^{-2} at the end of the simulated period~~, with an annual average of ~~396~~ 399 g C m^{-2} (Fig. 5c). The decreasing trend ~~could~~may be explained by ~~the~~a ~~decreasing~~lower amount of soil peat left in the surface (Table 1 and Fig. 3) and an increasing ~~of~~ GWL (Fig. 5f) ~~with the~~where inter-annual variations are mainly regulated by the ~~climate~~weather (Fig. 5a). NPP and peat decomposition are the two major components of NEE, in which the system showed itself to be both a sink and a source during the first ~~29~~ 19 years (1951 to ~~1980~~1970), but thereafter to be a continuous CO_2 sink, except for 1980 and 2002 (Fig. 5d).

~~According to our simulation, the forest and soil system emits 316~~ ~~138 g C m^{-2} CO_2 to the atmosphere in the first year after planting, quickly changing to an uptake of 150~~ ~~223 g C m^{-2} in the following year, which coincides with the colonization of the understorey vegetation as shown by the modeled biomass development (Fig. 2e). From 1953 to 1962, the forest system behaves as a major CO_2 source, emitting 343~~ ~~229 g C m^{-2} yr^{-1}. However, during 1963 to 1965~~ ~~1964 the system switches and acts as a minor CO_2 sink with an average flux of 61~~ ~~62 g C m^{-2} yr^{-1} before it again returns to being a CO_2 source from 1966~~ ~~1965 to 1971~~~~1970, with an average flux of 78~~ ~~46 g C m^{-2} yr^{-1}, except for another brief period as a minor sink of 86~~ ~~29 g C m^{-2} in 1968~~~~1967. From 1972~~ ~~1971 to 1979, the forest ecosystem acts as a sink of CO_2 with an average flux of 172~~ ~~222 g C m^{-2} yr^{-1}.~~ The thinning management in 1979 had a large impact on the NEE which changed the system to that of a source of ~~825~~ 820 g C m^{-2} yr^{-1} for the following year. After 1981, the forest ecosystem was a continuous sink of CO_2 with an average NEE of ~~327~~ 217 g C m^{-2} yr^{-1} except for being a minor source of 82 g C m^{-2} yr^{-1} for 2002 (Fig. 5d).

Surprisingly, the model does not predict the largest N_2O emissions to occur in the early period when the peat decomposition was high. Instead it predicts most of the N_2O to be emitted from 1966 to 1988, a period concomitant with the rapid increase of Spruce NPP, and ~~the period of~~at thinning. Over the 60 years, the simulated annual N_2O emission varied ~~between~~ from less than 0.01 to ~~4~~ 7 g N m^{-2} yr^{-1}, with an average of 0.~~5~~ 7 g N m^{-2} yr^{-1} (Fig. 5e).

3.2.2 Overall GHG balance from 1951 to 2011

Over the full 60-year time period the forest trees acted as a C sink and the soil as a source, of fairly similar size (Fig. 6). This could be viewed as a relocation of C from the soil to the trees, since our model predicts the total soil C loss to be ~~590~~ 75~~0~~20 ~~M~~kg CO_2 ~~ha~~m^{-1} $^{-2}$ over the 60 years, while total plant ~~growth~~ biomass (including spruce forest and understorey vegetation) sequesters ~~602~~ 58~~5~~12 ~~Mg~~ kg CO_2 ~~ha~~m^{-12}. The accumulated NEE shows the young forest ecosystem to be a net CO_2 source, and it is not until 1990, 39 years after the forestation, that the ecosystem uptake balances hitherto emissions and it reaches zero CO_2 emission before becoming an overall ~~continuous~~ carbon sink. If including the N_2O emissions during the 60-year rotation period ~~are included~~, ~~and we take~~ taking the most commonly used 100-year time horizon global warming potential from the IPCC ~~for calculating N_2O greenhouse gas potential~~ (1 g N_2O = 265 g CO_2 eq~~uivalent global warming potential~~, IPCC, (2013)), the source strength of the forest ecosystem increases and the system ~~first reaches GHG neutrality in 1998~~switch to an overall small GHG source.

However, if including the fate of the biomass removed as thinnings, ~~which~~ usually ~~goes into~~used for paper production~~, is included~~, resulting in ~~these~~ indirect CO_2 emissions from consumed paper ~~switch constitute 42% of the total soil C losses~~ makes this extended system (from the production site to the fate of the products) ~~from a GHG sink to~~ a large GHG source of ~~162~~ 38~~2~~60 ~~M~~kg CO_2 ~~ha~~m^{-1} $^{-2}$ by the end of the simulation (Fig. 6). Soon, the whole forest will be harvested releasing ~~a large part~~most of the captured carbon into the atmosphere again, 16~~.4~~ 0 k~~K~~g C m^{-2} (Fig. 2d)~~, with the possibility to use some of the timber (10 kg C m^{-2}) for long lasting buildings, into the atmosphere again;~~ and if everything were released from these soils there would be ~~763~~ 96.9 ~~M~~kg CO_2 ~~ha~~m^{-1} $^{-2}$ released over a period of 60 years.

3.3 Model sensitivity

Accumulated plant biomass is most sensitive to ~~changes~~a higher ~~in the~~ soil C / N ratio or a shallower drainage depth (Table 2). The ~~simulated soil~~ peat decomposition is instead ~~generally~~ more sensitive than the accumulated plant biomass ~~if only the single factor of either~~to ~~the~~ larger initial soil C or increasing drainage depth ~~is changed~~ (Table ~~1~~2). ~~On the other hand, the accumulated plant biomass is more sensitive to changes in the soil C / N ratio or shallower drainage depth (Table 12).~~ Also t~~T~~he NEE and N_2O sizes are ~~also~~ very sensitive to these variations, the NEE becoming a CO_2 source ~~when using~~at ~~the~~ large~~r~~st initial soil C, ~~when the~~since peat decomposition rate becomes larger than the accumulated plant biomass. The model sensitivity also shows higher N_2O emissions under shallower rather than deeper drainage (Table ~~1~~2).~~ ~~When these various factors were combined, the peat decomposition varied by -~~53~~38% to +~~74~~33%, being largest when the combination was deep drainage with the largest initial soil C, and a low initial soil C / N ratio. The accumulated biomass varied between -~~63~~69% and +~~9~~6%, being smallest when the combination was shallow drainage with a low initial soil C and a large soil C / N ratio. However, the overall total GHG emissions, including the thinning and storm harvested biomass and its associated CO_2 losses, ~~when compared to the reference model,~~ the emissions increased by ~~88~~11% to ~~267~~57% (Table ~~1~~2), suggesting that the total GHG balance was still a source to the atmosphere.

4 Discussion

4.1 Comparison of our simulated results with observational and published data

The GHG balance over a rotational period for forestry on drained peatland is mainly determined by two large ~~numbers~~ values *viz.* those important quantities relating to plant growth and peat decomposition. We therefore first discuss the validity of these two variables by comparing our simulated results with values published in the literature.

4.1.1 Plant growth

Our simulated Spruce growth at ~~405~~ 413 g C m^{-2} yr^{-1} was higher than the normal growth rate of 162 to 270 g C m^{-2} yr^{-1} in southwest Sweden, but lower than the potential growth rate of 472 to 607 g C m^{-2} yr^{-1} under experimentally optimal nutrient conditions (Bergh et al., 2005). This high growth rate can be explained by the fertile soil at the Skogaryd site, which was a drained fen before it ~~had been~~was used for agriculture, and then forestry. The high rate of nitrate leaching, estimated at ~~3~~4.~~6~~3 g N m^{-2} yr^{-1} also suggests that nutrients are not likely to be limiting. That the forest growth at this site is close to maximum has also been demonstrated in a modeling study by Tarvainen et al., (2013) who showed that if canopy N content was increased by 30%, canopy C uptake would only increase by only 2% - 4% and none of the 37 nutrients tested would directly limit photosynthesis. The very small increase of plant growth (+~~9~~6%) in our model sensitivity analysis (Table 2), ~~which~~ obtained when more deeply drained soil plus~~,~~ a larger initial soil C~~,~~ and a ~~small~~ lower C / N ratio ~~were~~ assumed, can also be explained by the already high fertility at the site, so any extra nutrient availability would have a negligible impact. Our simulated understorey vegetation was small during most of the simulated years; however, it dominated the organic matter dynamics and GHG fluxes in the first two decades after plantation, a finding similar to that of Laiho et al., (2003).

4.1.2 Soil CO_2 and N_2O fluxes

Our simulated average peat decomposition rate of ~~396~~ 399 g C m^{-2} yr^{-1} during the period 1951 to 2011 is lower than the value measured in 2008, which was 630 g C m^{-2} yr^{-1} (Meyer et al., 2013). However, this high peat decomposition rate could be attributed to an inter-annual weather variation, which is corroborated by the high plant growth measured in 2008, ~~at~~ 830 (± 390) g C m^{-2} yr^{-1}. Our simulated N_2O emission, 0.~~65~~52 (±0.1) g N m^{-2} yr^{-1} during 2007 to 2009 is similar to the observed data, ~~at~~ 0.71 (±0.59) g N m^{-2} yr^{-1}~~. However, an extended~~ and measurements~~ period at Skogaryd (~~2006 to 2011~~) reveals the possibility of lower annual N_2O emissions of~~ 0.38 (±0.12) g N m^{-2} yr^{-1} (Holz et al., 2015~~ submitted~~). Only d~~D~~uring these years, our predicted level of emissions was 0.50 (±0.~~17~~12) g N m^{-2} yr^{-1}. Our simulated CO_2 and N_2O fluxes are therefore generally comparable with the measured data.

~~When we compare o~~Our simulated peat decomposition and N_2O emissions are generally comparable in size with measured flux data from afforested drained peatland published in the literature~~, they are generally within the reported ranges~~ (Table ~~2~~3). However, when compared with the IPCC EF's for temperate drained nutrient-rich forest soil, which are given as 260 (200 to 330) g C m^{-2} yr^{-1} for CO_2 and 0.28 (-0.06 to 0.61) g N m^{-2} yr^{-1} for N_2O (IPCC, 2014), our simulated values were found to be larger. This could be explained by the higher soil fertility at the Skogaryd site and also a deeper GWL (mean of 0.~~55~~52 m during the simulated 60 years), compared to what pertained at those sites used for constructing the IPCC EF's. That the GWL is of crucial importance for emission levels for drained peat soils has also been shown by Couwenberg et al., (2011) and Leppelt et al., (2014). This could justify our assumption that our somewhat high estimates were due to deep and long-lasting drainage. The high N_2O emission during the period 1966 to 1988 could be explained by the deep GWL (Fig.5). However, the unexpectedly low simulated N_2O emission in the first years after planting could ~~maybe~~ be explained by a high N uptake by the understorey vegetation, probably dominated by grasses, making less N available for nitrification and denitrification.

4.2 Challenges of modeling long-term dynamics of an organic soil

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

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

~~The CoupModel conceptually divides the soil organic matter (SOM) into two pools called soil litter (fresh plant detritus) and humus, which constitute a fast and a slow decomposing pool, respectively (Johnsson et al., 1987). The model assumes soil litter to decay, so producing both CO_2 and adding a resistant fraction into the humus pool (Johnsson et al., 1987). This~~A m~~M~~ulti-pool approach was developed ~~conceptual model~~for modeling SOM dynamics ~~was developed~~ from mineral soils and has been shown to work well for forest mineral soils e.g. (Svensson et al., 2008; Wu, 2013). However, for organic soils, because there is no explicit peat pool in the model, we have had to assume the peat to comprise an unknown mixture of the fast and the slow pool. ~~-~~In the present study we have assumed the initial values of SOM as only representative of the slow pool. The decomposition coefficients for the fast and slow pool were obtained by calibrating the model coefficient against the measured fluxes as we did in our previous study (He et al., 2016). However in this long term simulation there is a continuous addition of Spruce litter leading to resistant soil organic matter and a change in substrate quality over the simulation period for the~~Thus our simulated~~ slow pool~~ may be composed differently at the end of the simulation compared to that at the beginning when the Spruce was planted, since there is a continuous addition of resistant organic matter in the form of Spruce litter, which changes the substrate quality over the simulation period~~. ~~However, the quality of a resistant litter fraction differs from that of historically stored peat, both in terms of quality of the organic matter and the decomposition kinetics.~~ Although most existing models do not explicitly specify the nature of the organic matter (Smith et al., 1997), they can still simulate the total organic matter dynamics fairly well over a relatively short period~~, a situation which we also found here (Fig. 3)~~. Metzger et al., (2015) found that the CoupModel could capture major C fluxes and the ecosystem dynamics when applied to five European treeless peatlands, where~~. However,~~ they ~~also~~ pointed out that the total C flux was mainly determined by the decomposition coefficients of the total SOM. ~~The decomposition coefficients for the fast and slow pool can be obtained by calibrating the model coefficient against the measured fluxes as we did in our previous study (He et al., 2016). However, if the decomposability of the substrates, i.e. the humus, changes over time due to~~

C~~the c~~ontinuous addition of organic matter into the slow pool from ~~resistant~~ litter decomposition~~,~~ must also change~~then~~ the decomposition coefficient for the slow pool ~~must also change~~ over time~~ accordingly~~. However, this is seldom accounted for. In order to understand the long-term dynamics of organic matter, which might differ in origin and components, a more precise consideration of the changes of soil organic matter characteristics would be helpful.

4.2.2 Modeling physical changes of peat soil

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

Root development also follows a simple static approach. The disappearance of the soil and the deepening of the root system are therefore not considered in the simulation as it is currently configured. All these processes remain a major challenge when applying the CoupModel to the long-term dynamics of a forest ecosystem on drained peatland. In To quantify the uncertainty from surface subsidence, in the present study, the system has beenwas simplified by assuming a fixed drainage depth, whereas a range of values was used to quantify the model's sensitivity. The lower end of the range was chosen to be a drainage depth of 0.3 m, since this has been suggested to be the minimum requirement to sustain forest productivity on drained peatlands (Sarkkola et al., 2010; Ojanen et al., 2013). The higher drainage level, 0.8 m, was set according to general forest management practices and also took into consideration the fact that our simulated soil depth only reaches a maximum of 1 m. The variation of the drainage depth had a considerable impact on the soil peat decomposition, as shown by the model sensitivity analysis (Table 2), which in turn highlights the need, when developing future models, to explicitly account for these processes when performing long-term simulations.

4.2.3 Initial soil C, N and soil C / N ratio

A major difficulty in the simulation was the unknown initial soil conditions. We chose to use the EF's 260 (200 to 330) g C m^{-2} yr^{-1} for CO_2 from the IPCC wetland supplement (IPCC, 2014), which compiles up-to-date observational data from similar sites under temperate climate conditions. Another alternative could be to use the subsidence rate to calculate the soil C losses, which has been applied in other published studies e.g. (Leifeld et al., 2011; Hommeltenberg et al., 2014). By taking the measured subsidence, rate of 0.22 m (ranging from -0.15 m to 1.03 m) during ca. 60 year post-drainage period 0.01 m yr^{-1},for Finnish drained afforested fens (Minkkinen and Laine, 1998), analogizing the measured total soil C in the upper 0.5 m in 2007, which was 55.3 kg C m^{-2} (Meyer et al., 2013), the estimated soil losses during the 60 year period would be 24.3 kg C m^{-2}, which is equivalent to a loss of 405 g C m^{-2} yr^{-1}, close to current modeling estimates, 399 g C m^{-2} yr^{-1}. suggested for German and Swedish drained fens (Berglund and Berglund, 2010; Leifeld et al., 2011; Hommeltenberg et al., 2014), the subsidence from 1951 to 2007 is 0.56 m. Assuming the same bulk soil density of 0.23 g cm^{-3} as measured in 2006 and aAnalogizing the measured total soil C in the upper

0.5 m in 2007, which was 11.6 (±1.6) Kg C m^{-2} (Meyer et al., 2013), the estimated soil losses during the period from 1951 to 2007 would be 13 Kg C m^{-2}, which is equivalent to a loss of 230 .kg C m^{-2} yr^{-1}, and falls within the range of the IPCC EF's. is probably due to the Smay yThe convergence of the C losses calculated by these two methods suggests the back-calculated initial C in the present study to have been acceptable. However, tThe variation of theIncreased initial soil C in our sensitivity analysis shows there to be a direct impact both on peat decomposition and on plant growth to increase (Table 2). Compared to the reference 'vegetation fitted model'model, the combination of a small initial soil C, a large soil C / N ratio, and a shallow drainage, gives a larger reduction in plant growth than in peat decomposition, which is why the overall emissions of GHG increase. These initial settings can probably be attributed to a smaller N availability than in the reference model, resulting in a lower rate of plant growth.

4.3 GHG balance for the forest ecosystem

Our modeling indicates forest on drained agricultural peatland to be a strong net CO_2 source for the first 39 years of the forest rotation which changes into a CO_2 sink thereafter due to a large amount of tree growth (Fig. 6). This means that, despite soil respiration decomposition being high, the high growth rate of forest over 60 years compensates for most C losses. Meyer et al., (2013) also showed the forest ecosystem in Skogaryd to be an overall GHG sink (4.10 Mg CO_2eq ha^{-1} yrm^{-12}) in 2008, a year when the plant growth rate was at its maximum, thus offsetting the high rate of peat decomposition. Our findings are also generally in line with the few previous field investigations conducted on afforested drained agricultural peatlands where Mäkiranta et al., (2007) and Lohila et al., (2007) found a 30-year-old Scots pine forest on drained agricultural bog to be, overall, a small source of CO_2 (50 g C m^{-2} yr^{-1}), which was explained by a small leaf area index (varying between 0.7 and 2 during the observational period). Another study by Hommeltenberg et al., (2014), reported an afforested drained bog in Germany, previously used for agriculture, to emit 500 g C m^{-2} yr^{-1}. By combining eddy covariance measurements and biometric estimation, they concluded it to be a major CO_2 source, emitting a total of 13.4 Mg kg C ham^{-1} $^{-2}$ over the last 44 years. However, their short-term measurements (2010 to 2012) also indicated that forest growth offsets peat decomposition, a result similar to our own reported in the present study. However, since they found a higher rate of peat decomposition, their site was a C source over a longer period (44 years) than our study (39 years).

Growing forests on drained peat is done at the cost of the soil peat, which has generally accumulated slowly during the last millennia (the last four thousand years in Skogaryd).~~ The soil loss and the forest gain can be viewed as a 'relocation' of the peat carbon into timber carbon, and w~~When the forest growth ~~term is~~has been larger than the soil loss, the system has been interpreted as being an overall sink (Meyer et al., 2013; Hommeltenberg et al., 2014). However the soil loss and the forest gain can be viewed as a 'relocation' of the peat carbon into timber carbon. Where can we expect this carbon to be found in the future? The simulated NEE ~~in~~ (figure 6) tells that the system ~~to keep~~remains a sink ~~status~~ for two decades but ~~probably result in a declined~~ growth rate probably declines over time, as shown in the simulated period from 2011 to 2031. To keep the forest will eventually turn the system into a source again since the peat soil will continue to decompose as long as it is kept aerated by a living transpiring forest. Sudden fires would also be a risk releasing the forest biomass C. However the forest in Skogaryd is not a nature reserve but a managed forest already mature for harvesting, ~~otherwise~~ commonly done at 80 years of age in southern Sweden.~~However, when we combine our simulation with the fate of the forest products, we can show the forest system to be a net GHG emitter during a 60-year period, and more so if the full standard forest rotation period is considered, which in this part of Sweden extends to 80 years (Fig. 6). After 80 years, there are only two options: either continue to keep the land forested or harvest it. Keeping the forest will probably result in a declined growth rate over time, as has already been shown in the simulated period from 2011 to 2031 (Fig. 6) and the carbon stock would keep increasing, albeit slowly, but certainly not for thousands of year, as it does during the formation of peat. Sudden fires would also release the C stored in the forest biomass into the atmosphere. The peat soil will continually decompose as long as it is kept aerated by a living transpiring forest.~~ The harvested wood products over a forest rotation is used for both timber and paper, about 40 and 60% (Sweden CRF table 4.Gs2 for year 2013, submitted to the UNFCC 2015) having a half-life of 30 and 2 years respectively (IPCC 2006 ~~guidelines~~). Thus the carbon will soon be released as CO_2. ~~If, h~~However~~, the forest is harvested, the bulk biomass will soon release its C when burnt as fuel for energy production. A~~ a better alternative would be the use ~~of the~~ of timber for~~to construct~~ wooden buildings which otherwise should have been built by using concrete (Gustavsson et al., 2006). The displacement of concrete by wood could according to a meta-analysis by (Sathre and O'Connor, 2010) avoid emissions by 2.1 times the C content of the timber. However, even then, most buildings do not last more than a century and only a few buildings are functional for longer periods. Thus m~~M~~ost ~~of the~~ harvested biomass ~~products~~ will ~~also~~ soon be burnt~~,~~

similarly releasing their stored C as we have shown occurs with paper products. These larger indirect emissions following the consumption of wood would shift the system from an overall small sink into a largeof GHG into a large source (Fig. 6). AnotherOne alternative use of the biomass could be as biochar in agricultural soils (Ojanen et al., 2013), which potentially could shift the system into an overall GHG sink. However, we think this alternative to be somewhat peculiar, since it is just moving C around, releasing it from peat and storing it in agricultural soils, and it is not clear for how long time the char-carbon persists. Additionally, there are some other direct and indirect GHG sources that become apparent during the full forest rotation period which we have not accounted for, such as methane emissions in drainage ditches and loss of dissolved organic C or particulate organic C. However, these contributions to the overall GHG balance are in general of minor importance and thus not likely to alter the overall picture (Meyer et al., 2013; Hommeltenberg et al., 2014). In summary, the overall message is that a forest rotation on fertile drained peat soil has a long-term GHG cost, never reaching a balance, and thus the wood products produced on peat soil cannot be regarded as renewable products.

In Sweden, forests on drained peatland cover 1.7 Mha (Maljanen et al., 2010; Von Arnold et al., 2005a) of which 0.4 Mha has high fertility, comparable to the soil in the present study. According to our simulations, Tthese forests emit around 1.074 kg CO_2eq m^{-2} yr^{-1} (.peat decomposition and N_2O emissions). Thus these fertile drained peat soils in Sweden emit 7 Mtonnes CO_2eq annually, which is equivalent to 127.5% of the emissions coming from all other sectors in Sweden when excluding LULUCF. From a climate change perspective, forested drained peatlands should be highlighted for actions, especially following forest clear-cut. Instead of digging the ditches deeper for replanting a new forest, making the soil wetter would reduce the soil decomposition, as shown by our sensitivity analysis and other studies (refse.g. Karki et al., 2014). However, these measures need support from policy makers since landowners often only recognize revenues from forest production, not the cost of GHG emissions.

5 Conclusion

Our simulation study shows that the GHG fluxes in a forested drained peatland are composed of two important quantities: C uptake by forest growth, and C losses from the soil. By fitting the CoupModel to the Spruce growth in tree biomass, up-scaled from radial tree-growth observations, we obtained a ‘vegetation fittedreference’ model by which we were able to describe the C and N fluxes over 60 years. We show that the forest C growth is tightly coupled to soil C losses, and if the forest is harvested and used, there will be only be losses over time. Our model sensitivity conducted by this study also provides evidence that a wide range of drainage depth, site fertility and initial soil C does not change the results. Of course, there are many other factors not considered in our study, which could potentially further influence the results. Thus, forests on drained agricultural peatlands are potentially large sources of GHG to the atmosphere. The model sensitivity analysis conducted provides evidence that a wide range of drainage depths, site fertilitiesy and initial soil C contents does not changelead to similar the overall results. This conclusion, however, comes with some caveats regarding the model configuration and its need for further improvementFurther model developments are however needed to better simulate the drained peat soil over forest rotation period.

In Sweden, forests on drained peatland cover 1.7 Mha (Maljanen et al., 2010; Von Arnold et al., 2005a) of which 0.4 Mha has a level of fertility comparable to the soil in the present study. These forests emit around 1.0 Mg kg CO_2eq ham^{-1} $^{-2}$ yr^{-1}. Thus these fertile, drained peat soils emit 4 Mtonnes CO_2eq annually, which is equivalent to 10% of the emissions coming from all other sectors in Sweden except LULUCF sources. From a climate change perspective, forested drained peatlands can be seen to play an important role, so highlighting the need for alternative actions, such as the rewetting of peatlands or other nature conservation measures. However, these measures need support from policy makers since landowners often only recognize revenues from forest production, not the cost of GHG emissions.

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

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Table 1. Soil C content in the soil profile during 1951 to 2011 estimated by the ~~V~~vegetation fitted model, kg C m^{-2}.

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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[1]
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

Note: [1] negative change means an increase of soil C

Table 12. Model sensitivity: comparisons with thechange compared with reference model’vegetation fitted model’ during 1951 to 2011.

Variables	Vegetation fitted model	Drainage depth (m)		Initial soil C (kg C m^{-2})			Initial C/N ratio (-)		Combi-nation 1	Combi-nation 2
		-0.3	-0.8	121.7[1]	129.0[2]	145.8[3]	20	45		
Alternative No		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(1)+(3)+(7)	(2)+(5)+(6)
Accumulated plant biomass (kg C m^{-2})	16.0	-35%	3%	-0.4%	1%	4%	4%	-48%	-69%	6%
Peat decomposition (g C m^{-2} day^{-1})	1.09	-25%	13%	-3%	3%	17%	2%	-14%	-38%	33%
NEE (g C m^{-2} day^{-1}) [4]	-0.12	-52%	-130%	22%	-23%	-125%	42%	-441%	-388%	-257%
N_2O emission (g N m^{-2} day^{-1})	0.0018	33%	-68%	-6%	3%	22%	58%	-84%	-63%	-25%
Indirect CO_2 emission (kg CO_2equ m^{-2})	34.5	-21%	1%	-1%	0.5%	0.3%	2%	-47%	-70%	3%
NEE+N_2O+indirect CO_2 emissions (kg CO_2equ m^{-2})	44.1	18%	6%	-3%	14%	46%	25%	31%	11%	57%

[1;2;3]: Back-calculated initial soil C using the reported range of IPCC EF’s 2200; 3.3330 and 6.3630 Mg C ham^{-1-2} yr^{-1} respectively.

[4]: positive change of NEE means the forest ecosystem sequesters more atmospheric CO_2 than the reference model’vegetation fitted model’; negative change means sequesteringncing less atmospheric CO_2 or a possible source to the atmosphere.

Table ~~2~~3. A comparison of soil peat CO_2 and N_2O emissions in the present study with values published in the literature.

Soil CO_2 flux ($g\ C\ m^{-2}\ yr^{-1}$)	Soil N_2O emissions ($g\ N\ m^{-2}\ yr^{-1}$)	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 [1]		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~~3~~	Afforested drained lowland raised peat bog	UK	Yamulki et al., (2013)
123 to 259 [1]	0.02 to 0.57	Drained organic soils for deciduous and coniferous forests	Sweden	Von Arnold et al., (2005a; 2005b)
~~396~~ 399	0.~~5~~7	Drained forested agricultural peatland	Sweden	This study

[1]: Calculated by assuming 50% of measured soil respiration to have originated from root-based activity.

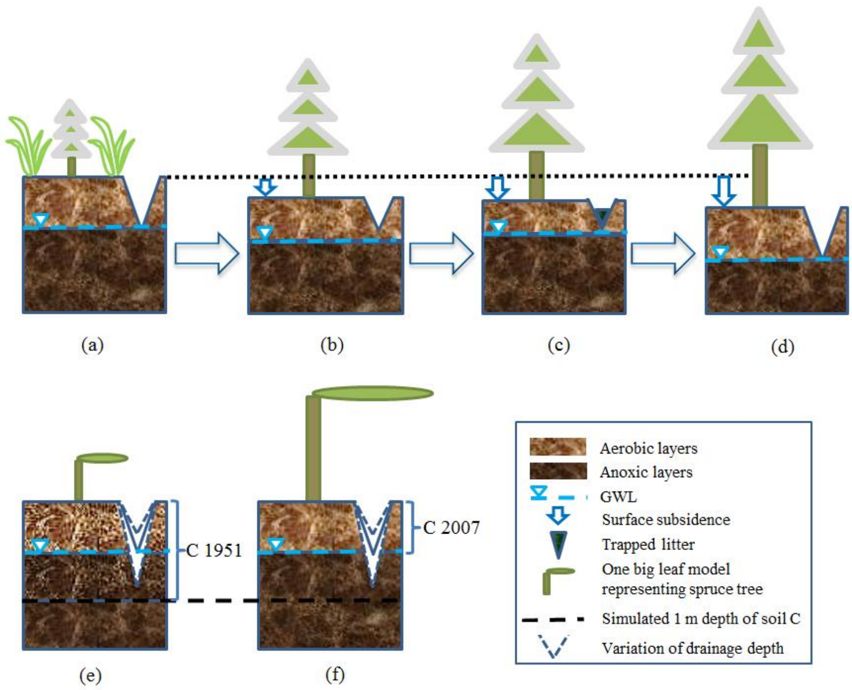
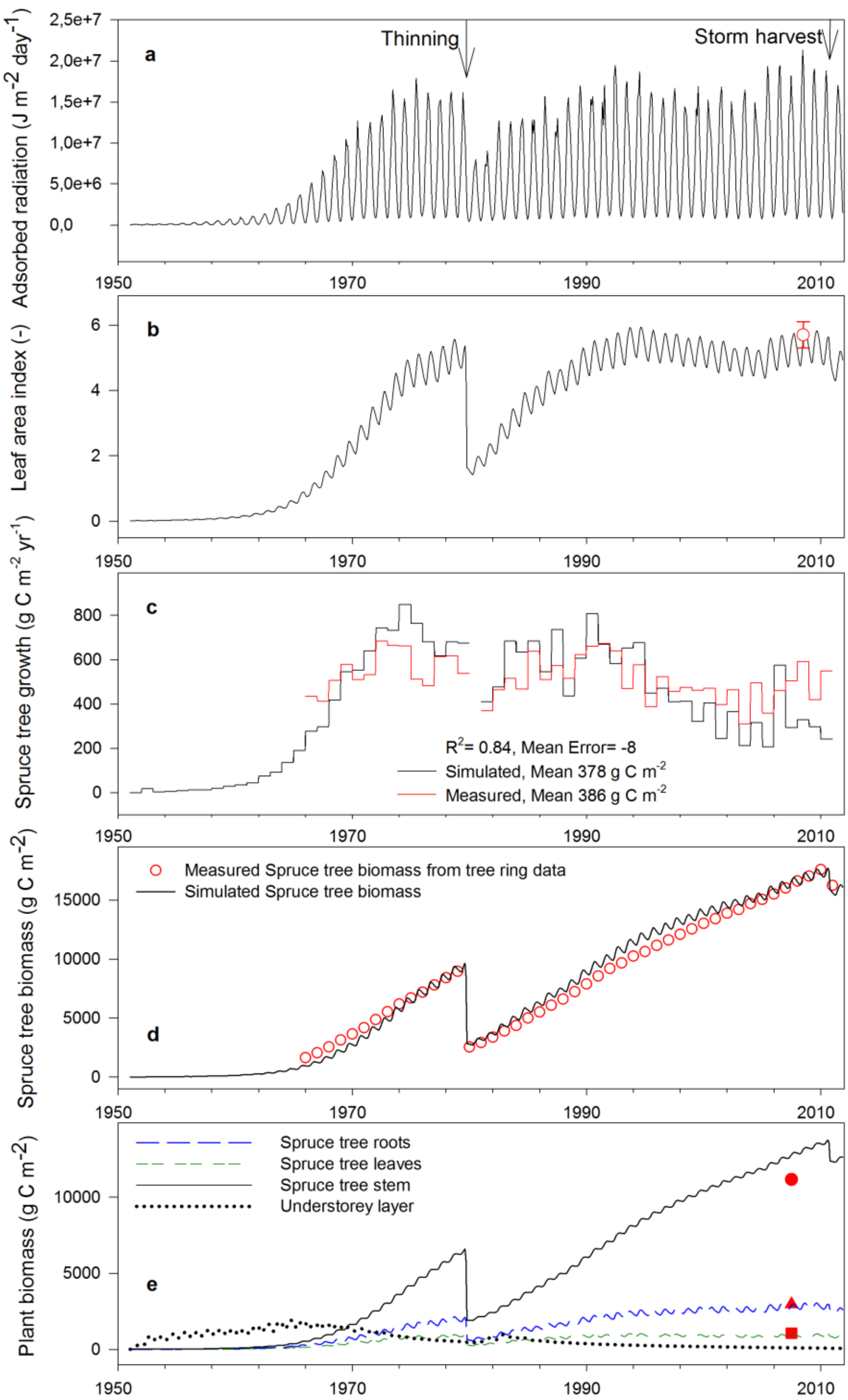


Figure 1. Conceptual representation of the dynamics of plants and peat soil development over a forest rotation period. The upper figures (1a, 1b, 1c, 1d) represent the conceived reality and 1e and 1f represent the CoupModel conceptualization. For all the figures, Spruce tree and understorey vegetation,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



Adsorbed radiation (J m-2 day-1)
Thinning
Storm harvest
a
Leaf area index (-)
b
Spruce tree growth (g C m-2 yr-1)
c
R2= 0.84, Mean Error= -8
Simulated, Mean 378 g C m-2
Measured, Mean 386 g C m-2
Spruce tree biomass (g C m-2)
Measured Spruce tree biomass from tree ring data
Simulated Spruce tree biomass
d
Plant biomass (g C m-2)
Spruce tree roots
Spruce tree leaves
Spruce tree stem
Understorey layer
e

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

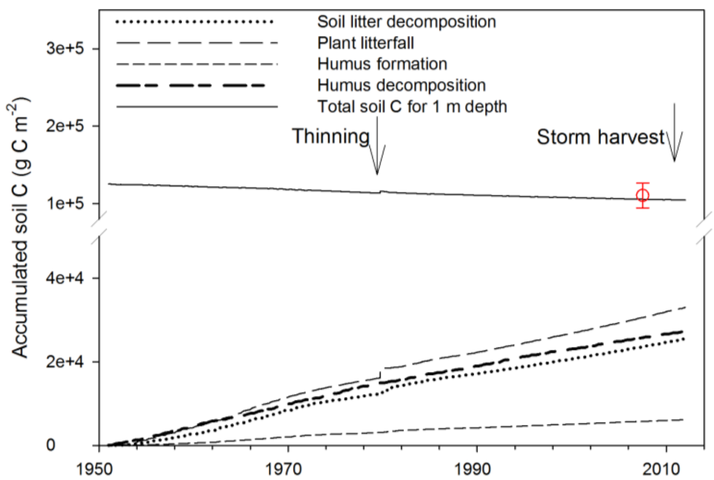


Figure 3. Simulated development of major soil C pools ~~development~~ in the first meter of soil, from 1951 to 2011. The red circle shows the measured total soil C in 2007 (+/- 95% confidence intervals) by Meyer et al., (2013).

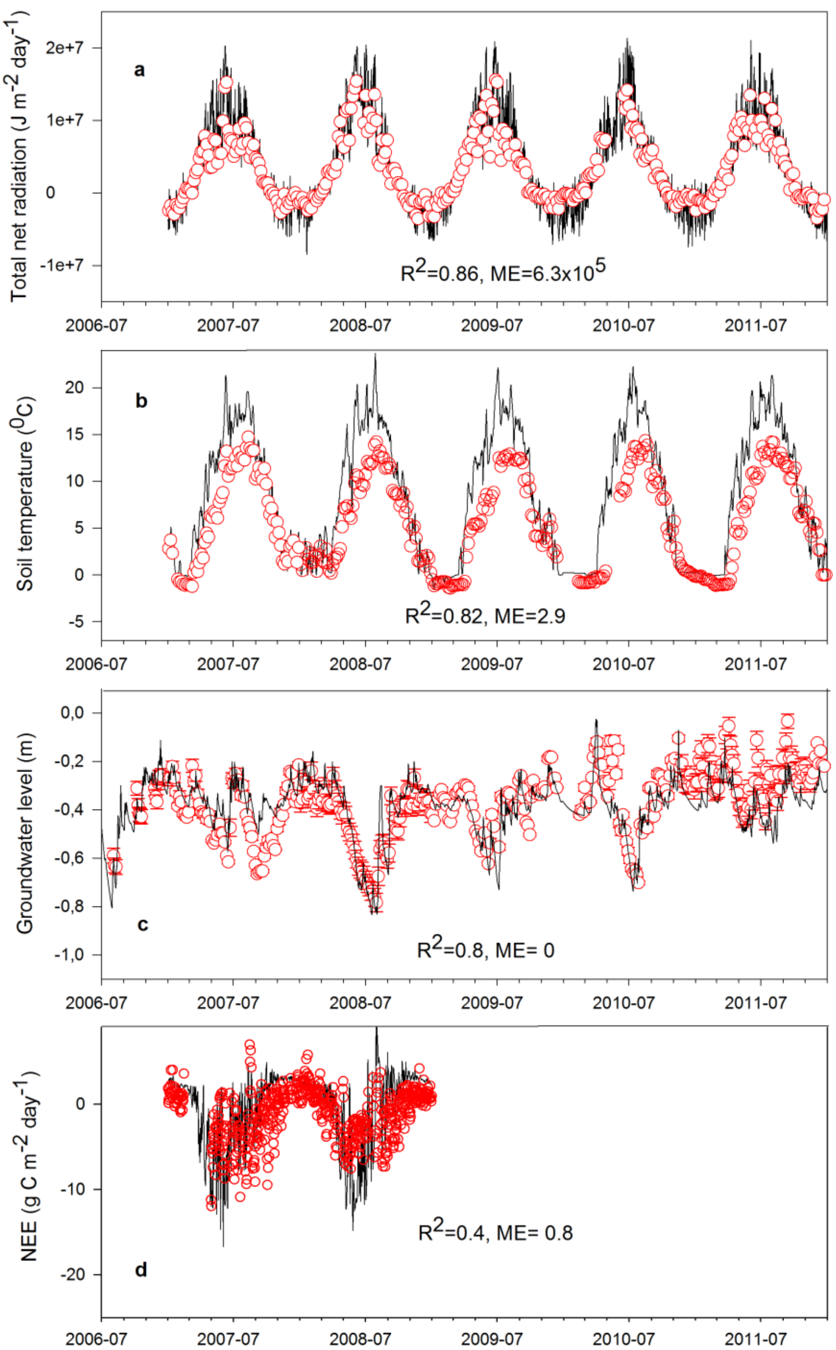

Total net radiation (J m-2 day-1)
2e+7
1e+7
0
-1e+7
a
R2=0.86, ME=6.3x105
Soil temperature (0C)
20
15
10
5
0
-5
b
R2=0.82, ME=2.9
Groundwater level (m)
0,0
-0,2
-0,4
-0,6
-0,8
-1,0
c
R2=0.8, ME= 0
NEE (g C m-2 day-1)
0
-10
-20
d
R2=0.4, ME= 0.8
2006-07
2007-07
2008-07
2009-07
2010-07
2011-07

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

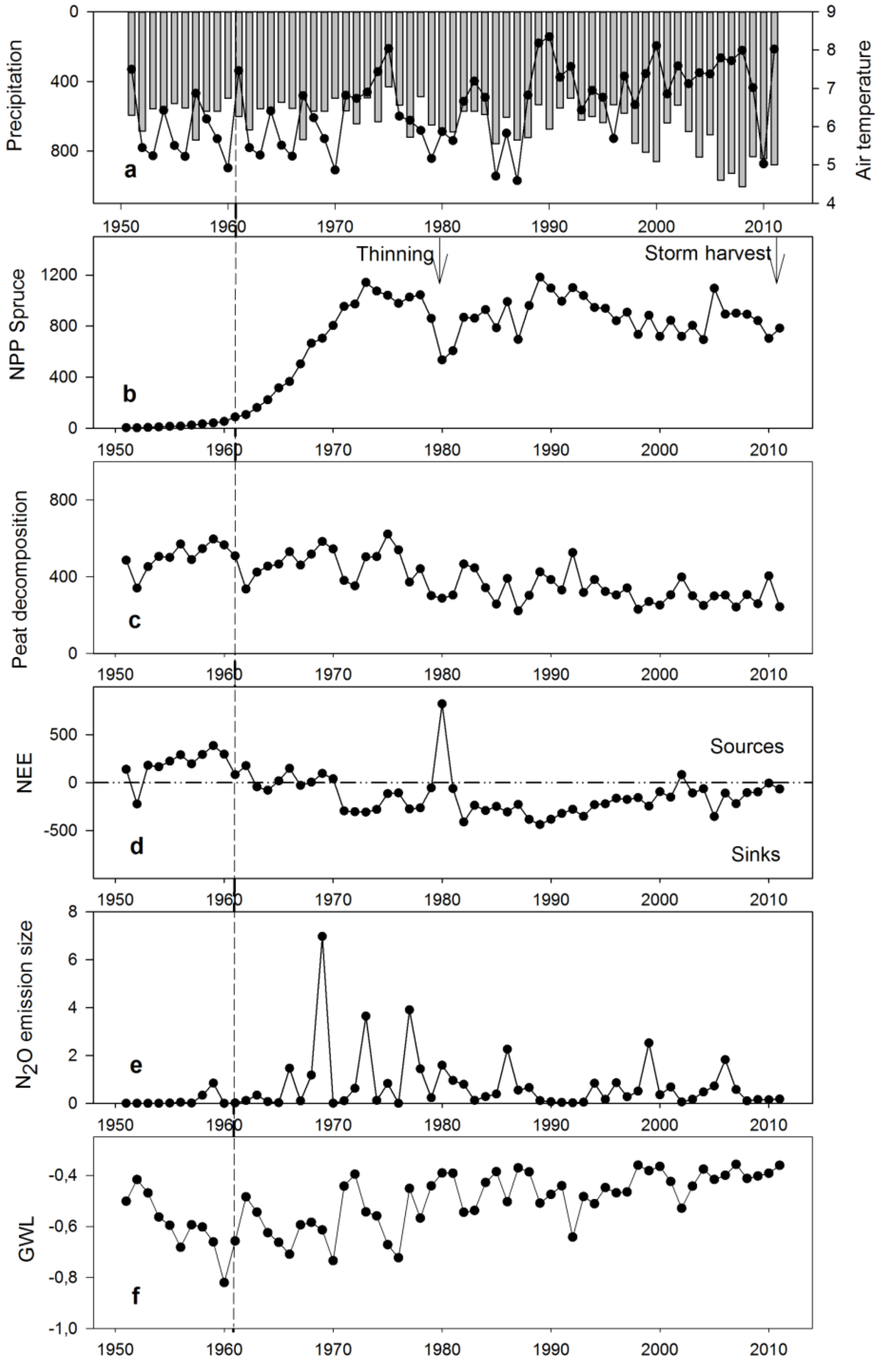

Precipitation
Air temperature
a
Thinning
Storm harvest
NPP Spruce
b
Peat decomposition
c
NEE
Sources
Sinks
d
N2O emission size
e
GWL
f

Figure 5. For the period 1951 to 2011: a) Annual precipitation (mm yr^{-1}) and air temperature (^{0}C); b) the simulated annual NPP of Spruce trees (g C m^{-2} yr^{-1}); c) simulated annual peat decomposition rate (g C m^{-2} yr^{-1}); d) simulated annual NEE (g C m^{-2} yr^{-1}); e) simulated annual N_2O emissions (g N m^{-2} yr^{-1}); f) simulated annual GWL (m). The dashed reference line separates the duplicated 1951 to 1961 and real climate 1961 to 2011. The source or sink is based on the atmospheric perspective, e.g. the soil emissions are sources, and plant uptakes are sinks.

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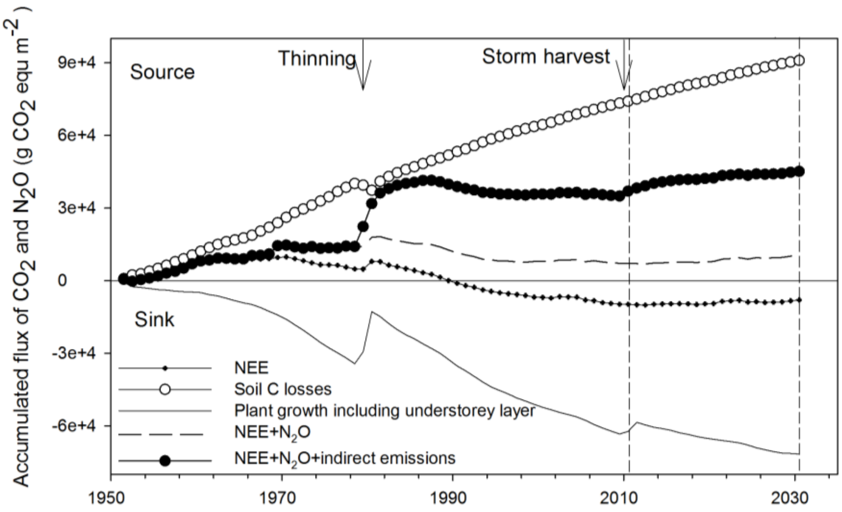

Figure 6. Simulated total GHG balance for the forest ecosystem from 1951 to 2011 and extended to 2031. The simulated results of 2011 to 2031 are obtained by running the ~~reference model~~'vegetation fitted model' with ~~extended~~ meteorological ~~files using meteorological~~ data from 1991 to 2011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