Response to referees for paper:

” Forest soil carbon stock estimates in a nationwide inventory: evaluating performance of the ROMULv and Yasso07 models in Finland” by *Lehtonen et al.* *Submitted for publication in Geoscientific Model Development journal.*

Dear Editor,

We acknowledge constructive comments and editorial remarks provided to our manuscript. We find comments useful and addressed them as described below (our reply is given in *italics*), note that page and line numbers refer to version with track changes done:

Comments by Executive Editor:

1. "The main paper must give the model name and version number (or other unique identifier) in the title."

The above statement is part if the requirements for the model description papers. However, model evaluation papers are closely linked to model description papers and therefore it would be beneficial to specify the exact version of the models the evaluation was performed with in the title. Please consider this upon revision of your article.

This was corrected accordingly and ROMUL is now ROMULv, where “v” refers to decomposition rates based on volumetric soil water measures, while Yasso07 is still Yasso07 where “07” refers to the model version in question, this version was developed in 2007 and published by Tuomi et al. (2011). The difference between original ROMUL and ROMULv models was clarified on page 3 lines 23-28.

Major comments by Referee 1:

1. Although some of the these estimations might be afflicted with uncertainty (for example, a spatial extrapolation of understorey vegetation by kriging for total Finland based on only 18 plots is hardly meaningful), I think that a rough estimation of an important but difficult parameter is better than not account for it at all.

Actually, we used much more data, and apologize it was not properly described in the earlier version of the paper. Text was modified on page 6 line 1 and on page 6 line 18 and it was made clear that ***only the biomass vs biomass cover relationship was made*** *using data from 18 stands (a total of 504 of 0.3*0.3 m^2 sample squares), while* ***co-kriging was based on 2501 permanent sample plots*** *with understorey cover measurements.*

2. There is only one important point which is not clear so far, the depth of the SOC estimates. I did not find any information about the depth for which SOC was predicted.

Sections 2.4.2 and 2.4.3 about Yasso07 & ROMULv models were modified in order to describe how soil depth was defined with models. For Biosoil data this information was given in the section 2.5.

3. From my point of view the structure of those models only allows a prediction for topsoils (0- 20 cm), for deeper parts stabilization mechanisms of mineral-associated SOC must be taken into account. At least, model performance should be tested not for the total depth but for different depth increments (e.g. 0-20, 20-40 cm etc.).

We agree that models have their strength in estimation of decomposition of litter with varied quality. Both models still have compartments for stabile carbon, but these carbon pools are not depth-specific. In the Yasso07 model this pool is named as "humus" box, while in the ROMULv model this is named as "stabile humus" box (see fig.1). These boxes integrate stabile carbon accumulation from various processes, including that of mineral association. Both models are used in such applications (greenhouse gas inventories, evaluation of the effects of alternative forest management practices) where estimates for deeper soil layers are needed and the models are parametrized accordingly.

Minor comments by Referee 1:

Title: I would include "Forest soil carbon" and "Finland"

The title was changed accordingly to: "Forest soil carbon stock estimates in a nationwide inventory: evaluating performance of the ROMULv and Yasso07 models in Finland"

P1, L11: generally, the manuscript is well-written, but the first sentence of the abstract is not very good ("We test...weather data are enough..."), please rephrase.

The beginning of the abstract was re-phrased.

P2, L3: References for Sweden and Germany?

References were added

P2, L11: to reproduce

This was corrected

P2, L17: here is becomes clear for the first time that the paper is about forest SOC, however, this could be clarified from the beginning with a clear focus on forest SOC models and references to similar studies.

The abstract of the paper was modified accordingly.

P2, L20: CENTURY model

This was corrected

P5, L31: the kriging approach was only shortly mentioned. Due to its importance the overall performance of this important step should be described in more detail, e.g. by showing variograms.

R code, variograms and cross-variograms of vegetation group coverages are shown in the Supplement.

Major comments by Referee 2:

1. Being able to predict the current inventory is very different than being able to accurately assess changes in carbon stocks due to land use or climate. The authors more or less make this point in the introductory comments but then go on to try to model the current inventory data as a means for improving soil carbon models.

We fully agree with this comment. Estimation of C stock change is very different than estimation of the current soil carbon stocks with these models. However, the initial soil carbon stocks should be at right level in order to predict correct changes of soil carbon in future due to fact that soil C change is relative to stock size. Therefore it is essential to have soil C stock at right level to start with simulations. We added further clarification on page 2 lines 23-25.

2. Given the detailed inventory data already available, a spatial model seems to be the way to go to improve the national inventory. If the authors are trying to develop a model that can predict year-to-year variations in soil carbon stocks then calibrating models on a few sites with really good long-term data seems more powerful than trying to recreate mean latitudinal trends on soil carbon.

Yes, we agree, and this is what we are aiming at, i.e. providing understanding on spatial representativeness of models by using wide spatially representative datasets. The reviewer also mentions 'year-to-year' development aspects of models. However, we're not developing a model to predict year-to-year variability of stocks, but rather evaluating models from the perspective how well they are able to replicate latitudinal patterns of soil C. The *performance of the models in the south – north gradients of vegetation productivity and climate is central for their wider applicability (e.g. for national GHG inventories), and implies whether the decomposition rates are at correct levels, and correctly sensitive to local mean climates. The idea of the paper is to identify locations and conditions where model performances are reduced, and if there are simple yet useful additional drivers that could be incorporated in future models based on these data. We modified objectives of the paper to be more clear, see page 3 from line 27.*

3. Additionally, most of the year-to-year change in soil carbon is going to come from land use and management decisions which have essentially been ignored here because this MS only focuses on established forests on upland soils.

This is correct; our aim in the manuscript is to test how well these models are able to model soil carbon stocks. The ability of models to estimate C stocks at right level is a prerequisite for models to be able to model changes in soil carbon stock due to land-use changes and management events. Especially, estimates of C exchange fail on the land use conversions from forests to other uses, if original forest soil carbon stocks are systematically wrong by models. This was made clearer on page 2 lines 23-25.

4. I really struggled with this paper. It seems that two separate ideas on model testing ending up getting merged together in this MS along with some new measurements on understory biomass and litter turnover. Given the goals of the paper, I would have thought that one model needed to be used that could have different levels of complexity added or removed. Given the fundamental differences between the Yasso07 and ROMUL models I do not see how it is possible to test the hypothesis that "accounting for soil properties" would improve model performance and then go on to say that time step (annual v. daily) might matter. The second hypothesis is only related to the ROMUL model. Since most of the hypothesis testing relates to the ROMUL model, why not just try to add a better litter module onto the ROMUL model and see if this matters?

We agree with this point. Therefore we modified objectives of the paper and in the current version we clarify that the impact of soil texture and water holding capacity to soil carbon stock accumulation was evaluated primarily by comparing ROMULv model with and without soil water content data. We also wanted to include Yasso07 into the comparison due to fact that its decay parameters have been estimated from extensive database and mainly from Nordic countries. Comparing and seeing results of these two models in parallel is useful for GHG experts of many countries using Yasso07 for forest soils and land surface modelers (e.g. Yasso07 is implemented in JSBACH), but it lacks nitrogen dynamics rendering it incapable of simulating vegetation-soil dynamics under climate change. Text was modified on page 3 line 23-30.

5. Model success was never really defined. The author's suggest that the ROMUL model with some information on soil water holding capacity is the superior model but based better

representation of southern soil carbon data but the goodness-of-fit statistics presented in Fig 6 are equivocal on this point.

Text was clarified at the end of the material and methods section on page 10 line 21->. There we justify the use RMSE as a measure of model performance.

Minor comments by Referee 2:

1. Abstract: need to emphasize that these models and model developments are only applicable to northern forests on upland soils. This probably goes for changing the title as well.

Agree. The title was changed to: "Forest soil carbon stock estimates in a nationwide inventory: evaluating performance of the ROMULv and Yasso07 models in Finland". Also text in the abstract was updated.

2. page 1. L25: "However, the significance of different drivers of soil carbon stocks is still unknown", this statement is a bit belittling to the soil carbon science community - we know a lot about what controls SOC levels.

This is a valid point. We reformulated this sentence to be more precise and now we discuss about long term soil carbon accumulation, see page 2 line 2.

3. page 1. L25: "On the other hand …", this sentence is not a logical juxtaposition to the previous sentence.

Text was corrected, see from page 2 line 6.

4. page 2, beginning: "of these inventories is usually not adequate for national-level soil carbon stock change assessment", inventories aren't meant for this purpose but many nations have or are now conducting re-sampling campaigns for this purpose.

We agree with this comment

5. page 2. Line 15 "The majority of countries apply soil carbon 5 models, like Yasso07 (Tuomi et al. 2011) and CENTURY (Parton et al. 1987) to estimate soil carbon stock changes. The scientific community is also aiming to predict future soil–climate change feedbacks on a global level using Earth system models (ESMs).", there is a big difference between biogeochemical models developed for plot level investigations and ESMs running at large grid scales. I'd prefer the two not be lumped into the same discussion in this paragraph. There are severe limitations in data availability globally that ESMs have to deal with.

We agree and in the current version GHG inventory models and ESM models are introduced in separate paragraphs on page 2, lines 13-31.

6. page 2. L10. "Individual soil carbon models are tested against repeated soil inventories and it is found that models are able to estimate soil carbon stock change of the same magnitude as was measured." , please give few citations for example

References were added on page 2, line 27.

7. page 2. L20. "add model between CENTURY and clay"

This was implemented, page 3 line 3.

8. page 3. L10. "ROMUL including the impact of nitrogen and soil water holding capacity to decomposition).", according to below you are not testing nitrogen but only water in ROMUL v. Yasso?

This has been misleadingly reported in the manuscript. A sentence was added under 2.3 (page 7 line 18) to describe that we used constant N fractions by species and by biomass compartment. Also those nitrogen fractions were provided in the Supplement as a table.

9. page 3. L30. "From the grid, only locations that were on upland soils and on forest, according to Food and Agriculture Organization of the United Nations (FAO) forest definitions were chosen. This classification is based on Multisource National Forest inventory products (Tomppo et al. 2008).", this is an important point and I am struggling to fully understand how this was defined (i.e., for upland soil, what soil map or was a topopgraphic property used) and the impact this has on model evealuation.

Text was clarified and the content of the Multisource National Forest inventory product is described in the text on page 4, lines 25-26.

10. page 4. L5. NFI9 or NFI10

Here we used sample trees of NFI10. We had a good routine for that in hands. Results for BEFs would be the same with using sample trees from NFI9 (there could be differences in the decimals).

11. page 4. can you give a bit more information such as goodness-of-fit statistics for this model?

Sample size and adjusted R^2 were added into the text. See the end of section 2.1, page 5 line 23.

12. page. L15. "parts, if applicable. These models were estimated separately for southern and northern Finland.", Good linear mixed models can be developed on a sample size of only 9?

*This was not properly described in the earlier version of the paper. Text was modified on page 5 and page 6 and it was made clear that biomass models were based on sampling done in total of 504 of 0.3*0.3 m^2 sample squares from 18 forest stands, while co-kriging was done on 2501 permanent sample plots with understorey coverage measurements. Text was modified on page 6 line 1 and on page 6 line 18.*

13. page 7. L15. how do you get litter quality for each of the items listed in Table 2? I would think these properties would vary significantly for the same species depending on fertility status of the site.

Text under "2.4.2 Yasso07" was modified and the reference to Yasso07 manual was added, see page 8 line 18.

Litter quality (solubility ratios) varied by species, but not by site types. Unfortunately we don't have litter quality data available by site types.

14. page 7. L25 "Here, we used the Yasso07 model with Scandinavian parameters (Rantakari et al. 2012) and with global parameters, these being different from Tuomi et al., (2011) parameters.", this is awkwardly phrased. I thought you use the global parameters of Tuomi et al. but this sentence makes it sound like you did something different.

Text under "2.4.2 Yasso07" was modified and we explain that our parameter set is a preliminary version from those published by Tuomi et al. 2011. This set provides practically same results as those published and is used here due to fact that it has been earlier used by the Finnish GHG inventory. With MCMC parameter estimation methods one never gets exactly same results with models that have several parameters. See page 6 line 26.

15. page 8. L5. "We applied the ROMUL model using daily time-steps of the environmental variables impacting the decomposition.", how were litter inputs imputed at a daily timestep

Litter was distributed evenly for each day of the year. This procedure was chosen due to unknown timing of the belowground litter and due to fact that we are here interested about long term C accumulation, not short term fluctuations of C between forests and atmosphere. Text was added on page 9 lines 19-20.

16. page 8. L20. What depth are the models assumed to be working to? This will really impact how much root inputs there will be and the SWHC data including the 20/80 split of SWHC between O and M soil.

Sections 2.4.2 and 2.4.3 about Yasso07 & ROMULv models were modified in order to describe how soil depth was defined with models. For Biosoil data this information was given in the section 2.4.4. See page 8 line 28 and page 9 23-25.

17. page 9. L15. there is a lot of discussion material in the results section. I do not mind combined R&D sections but it has to be one or the other.

Results section was re-organized. We introduced subtitles there and we removed texts that were discussing the findings with understorey litter. See pages 10 - 12.

18. page 9. L15. given this MS is focused on soil carbon model development not biomass model development, perhaps consider moving Fig 2 and 3 and Table 3 to supplemental material.

We agree with this comment, those graphs and that table were moved into the Supplement of the manuscript.

19. page 9. L25. “Our estimate of mean litter input from trees was 1962 kg ha-1 and 903 kg ha-1 of carbon for southern and northern Finland, respectively”, are these values reasonable when compared to estimates of NPP?

Comparison to modeled NPP values and measured litter fall data were added into the discussion under section 4, page 12 from line 32.

20. page 10. L5. “the southernmost plots (Fig 3).”, wrong figure reference”

This was corrected, page 11 line 27.

21. page 10. L30. “We also found that litter input from understorey vegetation is equal of that from trees in northern Finland. This”, this seems like an important finding and shouldn't be buried within a model development paper.

We re-organized results section and currently we have there two subtitles, 3.1. Performance of the soil carbon models and 3.2. Improved understorey litter input. We hope that using subtitles brings up the finding of the high understorey litter input in northern Finland. See page 11 lines 10-17 and page 12 line 13.

22. page 11. L1. “To sum up, litter input from understorey vegetation has to be quantified properly when soil carbon models are parameterised.”, but this only mattered when the local parameterization of the model was used. Including understory litter actually decreased the performance of the global model.

The reason why the performance of the global model was reduced with understorey litter is the fact that parametrization of the model has lacked that larger input of understorey litter (found in this paper) into the soil system. And now providing correct litter input (which is more than earlier thought) results higher C stocks compared to those measured. This is our point here. And we added a sentence on page 13 line 4-5 to clarify this.

23. page 11. L20. “This result indicated that the quantity of precipitation alone was not a sufficient modifier for decomposition but when complemented with soil water holding capacity results improved. This finding supports the use of models including soil texture and

water holding capacity.", latitudinally averaged results improved but the site to site variability seems to have increased dramatically.

This is true and we added "average latitudinal results" into the text, see page 13 line 25. Site to site variability increases due to fact that variation in the soil properties cause very different decomposition conditions under varying precipitation schemes (see Fig. 4).

24. page 11. L20. "According to our results, the time step of the simulation plays a critical role; running", BUT there were so many other differences between models that this is a hard conclusion to reach. You would have to run the same model at the different time steps to assess this.

We agree, text was modified and now it says that our results support earlier findings, where …. This modification was done on page 13 from line 27.

25 page 12. L1. "The use of water holding capacity was critical for accurate soil carbon stock estimation by the ROMUL model…", you never defined what success looks like. An R2 of 0.368 is considered success but an R2 of 0.367 is not? Or are you using RMSE? I would argue slope is perhaps the most important.

We added text in the end of material and methods section, where we say: "We used root mean square error (RMSE) to rank these models applications due to its ability to take into account both accuracy and precision when comparing model estimates and data." See page 10 from line 21.

Thereafter all judgements about performance of the models have been based on that.

26. page 12. L5. "(Fig. 6). The fact that Yasso07 soil carbon stocks were more accurate when litter input of understory vegetation was omitted from simulations suggests that the model calibration did not account for the whole range of understory litter input.", OR there are other important drivers (such as soil properties) that are missing from the model.

We mean here that if Yasso07 would have been originally parametrized with our understorey litter input, thereafter it would have been able to model latitudinal trends of soil carbon in Finland. We added a sentence after, where we explain the meaning of this finding. See page 14 line 11.

27. page 12. L5 "However, three model simulations out of six produced relatively accurate", how defined? this is not a very quantitative term.

This is true. We modified the text on page 14 line 16. And we added a RMSE threshold there.

28. page 12. L10. "Our findings confirm the fact that GHG inventory methods and soil modules of Earth system models need to be improved by incorporating the impact of soil

texture and soil moisture to decomposition. This is a prerequisite for unbiased soil carbon stock and stock change estimates.”, weak concluding comments.

We modified our concluding remarks. See page 14 from line 20.

Forest s~~S~~oil carbon stock estimates in a nationwide inventory: evaluating performance of the ROMULv and Yasso07 models in Finland

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Abstract. ~~We test whether litter quality, litter quantity and weather data are enough to estimate soil carbon stocks by models~~. Dynamic soil models are needed for estimating impact of weather and climate change on soil carbon stocks and fluxes. Here, we evaluate performance of Yasso07 and ROMULv models against forest soil carbon stock measurements. More specifically we ask, if litter quantity, -quality and weather data are sufficient drivers for soil carbon stock estimation. We also test whether inclusion of soil water holding capacity improves reliability of modelled soil carbon stock ~~model~~ estimates. Litter input of trees was estimated from stem volume maps provided by the National Forest Inventory, while understorey vegetation was estimated using new biomass models. The litter production rates of trees were based on ~~previous~~ earlier research, while for understorey biomass those were estimated from measured data. We applied Yasso07 and ROMULv models across Finland and ran those models into steady state; thereafter, measured soil carbon stocks were compared with model estimates. We found that the role of understorey litter input ~~is~~ was underestimated when the Yasso07 model is parameterised, especially in northern Finland. We also found that the inclusion of soil water holding capacity in the ~~ROMUL~~ ROMULv model improved predictions, especially in southern Finland. ~~Our results imply that the ecosystem modelling community and greenhouse gas inventories should improve understorey litter estimation in the northern latitudes.~~ Our simulations and measurements show that models using only litter quality, litter quantity and weather data underestimate soil carbon stock in southern Finland and this underestimation is due to omission of the impact of droughts to the decomposition of organic layers. Our results also imply that the ecosystem modelling community and greenhouse gas inventories should improve understorey litter estimation in the northern latitudes.

1 Introduction

Soil carbon is a significant component of terrestrial carbon stocks and understanding its dynamics under changing climate is crucial. However, the significance and interactions of different mechanism for long term carbon accumulation ~~different drivers of soil carbon stocks is~~are still unknown and therefore often lack from models. If we want to understand the role of different abiotic and environmental factors to soil carbon stocks and their dynamics, we have to combine experimental research with process-based models. On~~ the other hand, we~~e way forward is to ~~ can ~~establish soil carbon inventories in order to quantify soil carbon stocks and their change. Conventional soil inventories measuring various nutrients, carbon contents, bulk densities and stoniness (e.g. Gamfeldt et al. 2013) allow us to study the distribution of soil carbon across landscapes and correlations between different soil properties. Generally, it is shown that soil carbon inventories are able to produce soil maps and covariates between soil carbon quantities and other variables, such as various nutrients; although, the sample size of these inventories is usually not adequate for national-level soil carbon stock change assessment, with few exceptions (e.g., Sweden and Germany) (Gamfeldt et al. 2013, Grüneberg et al. 2014).

According to the United Nations ~~various international ~~climate ~~agreements~~convention, countries are requested to report annual carbon stock changes of soils under different land-uses and under land-use change. The majority of countries apply soil carbon models, like Yasso07 (Tuomi et al. 2011) and CENTURY (Parton et al. 1987) to estimate soil carbon stock changes. These annual submission are reviewed annually and methods should be transparent and verifiable favouring simple soil models instead of complex ones.

The scientific community is also aiming to predict future soil–climate change feedbacks on a global ~~level ~~scale using Earth system models (ESMs). The ESMs are tested against soil carbon measurements in order to evaluate model performance but unfortunately results have been poor. Guenet et al. (2013) present a test whereby soil carbon stocks predicted by ORCHIDEE model were plotted at a plot level against measurements and failed to display any correlation. Similarly, Todd-Brown et al. (2013) concluded that most ESMs are not able to ~~re~~produce measured soil carbon stocks at a grid level. This finding is somewhat alarming due to fact that it is essential to have correct initial carbon stocks with soil models, because carbon stock change estimates depend on those. Initial soil carbon stock estimates are particularly important when carbon stock changes of deforestation events are modelled.

Individual soil carbon models are tested against repeated soil inventories and it ~~is ~~has been found that models are able to estimate soil carbon stock change of the same magnitude as was measured (Ortiz et al. 2009, Rantakari et al. 2012). The limitation of this conclusion was that uncertainties of both measurements and model estimates are often higher that actual estimates (Ortiz et al. 2013, Rantakari et al. 2012). While the uncertainties between model output and real measurements ~~can establish~~reveal whether models agree with data or not, they put less emphasis on whether all the most important soil carbon stock drivers were included in these models.

Simplistic soil carbon models like Yasso07 (Tuomi et al. 2011) are driven only by weather conditions and by litter input; while more complex models, like ~~ROMUL ~~ROMUL (Chertov et al. 2001) also include the nitrogen cycle and the impact of soil water holding capacity on decomposition (Linkosalo et al. 2013). It is clear evident that soil properties affect soil carbon stocks (Schimel et al. 1994, Six et al. 2002) and therefore they are explicitly included in complex models. For example, in the CENTURY model clay content limits decomposition (Parton et al. 1987) and due to the low specific surface area of clay minerals in the model, clay rich soils have larger passive soil carbon stocks and lower C:N ratios (Parfitt et al. 1997). In simplistic models soil properties are omitted. For example, in Yasso07 the role of soil properties on soil carbon stock accumulation is included only implicitly through the model calibration with large datasets (Tuomi et al. 2011). Although the simpler models lack some predominant drivers of soil carbon accumulation, the strength of these models lies in their easier calibration with data; however, the impact of soil properties, especially nutrient status, on the accuracy of estimated soil carbon stock estimates needs to be re-evaluated in both CENTURY and Yasso07 models (Tupek et al. 2016).

It is well known that decomposition and soil respiration is controlled by water content, whereby in dry soils lack of water slows down decomposition, while excess water reduces it by limiting oxygen diffusion (Skopp et al. 1990). For boreal forest conditions, Pumpanen et al. (2003) proposed a model whereby maximum soil respiration drops after the relative water content of soil reaches a level of 60%. The limiting effect of soil moisture on decomposition in dry or water-saturated soils is widely included in models, although the degree of this dependency varies widely between models (Sierra et al. 2015).

In addition to the model structure, precise and accurate estimates of litter input quantity and quality are also essential for successful model applications. Stand-alone soil models rely on forest inventory data or other external estimates for getting correct litter inputs, while ecosystem models utilise plant sub-models to describe vegetation productivity and litter inputs. A common feature of ecosystem models and stand-alone soil models is that often understorey vegetation is neglected during the calibration and application of models, resulting in biased litter inputs. This omission is more critical in boreal landscapes where the contribution of understorey vegetation increases with northerly latitude. For example, Yuan et al. (2014) report that the bryophyte biomass contributes 20%–60% of the total normalized difference vegetation index (NDVI) in high northern latitudes.

In order to assess the necessary drivers for soil carbon models in Finland we tested the performance of Yasso07 and ROMUL ROMULv models against measured nation-wide soil C data. The ROMULv refers to a modified ROMUL model version where decomposition rate functions are derived from the model presented by Pumpanen et al. (2003), and a simple volumetric soil water model (Linkosalo et al. 2013) is applied to drive those decomposition functions.

We were specifically interested if the additional complexity of processes introduced by ROMULv improves the soil C stock estimate over Yasso07 model that is presently used by greenhouse gas (GHG) inventories of several countries. The Yasso07 and ROMUL ROMULv models differed in their time steps (annually versus daily), determination of the litter quality (litter solubility versus nitrogen content and litter source) and complexity of drivers (ROMUL ROMULv including the impact of nitrogen and soil water holding capacity to decomposition). Specifically with these models we tested:

1. Whether the litter quantity, species specific litter quality and weather data are enough to estimate spatial trends of carbon stocks in the upland soils of Finland. We hypothesise that by accounting for soil propertieswater holding capacity, ROMUL ROMULv would outperform, (i) ROMULv with constant soil water holding capacity and (ii) Yasso07 model with

different parametrisations (Yasso07 excludes soil properties entirely). ~~and that improving the estimation of understory litter input would positively affect accuracy of predicted soil carbon stocks.~~ ~~We hypothesise that an increased fraction of coarser soil textures, like sand, increases soil carbon stocks through increased drainage and reduced decomposition.~~

~~2. Whether variation in soil water holding capacity affects carbon stocks through drought limitation on decomposition. We hypothesise that an increased fraction of coarser soil textures, like sand, increases soil carbon stocks through increased drainage and reduced decomposition.~~

2. Weather improving the estimation of understory litter input would positively affect accuracy of predicted soil carbon stocks.

We use Yasso07 and ~~ROMUL~~ ROMULv soil models to estimate steady-state carbon stocks for upland soils in Finland on a spatial 10×10 km^2 grid. We ra~~u~~n Yasso07 model with parameters based on Scandinavian data (Rantakari et al. 2012) and also with parameters based on global data (Tuomi et al. 2011). The parameterisation for the ~~ROMUL~~ ROMULv model was the same as in the original ~~publication~~ ROMUL model (Chertov et al. 2001), except for decomposition rate functions depending on soil water content derived from Linkosalo et al. (2013). Yasso07 and ~~ROMUL~~ ROMULv models run with identically estimated litter quantity, quality and climate data. In addition, the ~~ROMUL~~ ROMULv model was ~~driven~~ tested with both constant ~~and varying~~ soil water holding capacity as well as variable water holding capacity based on digital soil maps of Lilja and Nevalainen (2006)~~ as in Linkosalo et al. (2013)~~. Furthermore, we developed new models for the understorey litter input and apply them alongside soil carbon models for improved estimates of spatial variation of litter inputs. Simulated soil carbon stocks are evaluated against measured soil carbon stocks.

2 Material and methods

Soil carbon simulations were performed for 10 × 10km^2 grid across Finland. This grid is used for meteorological data prediction (Venäläinen et al. 2005). Litter input was estimated for the same grid. From the grid, only locations that were on upland soils and on forest, according to Food and Agriculture Organization of the United Nations (FAO) forest definitions were chosen. This classification is based on Multisource National Forest Inventory products, which combine digital maps (including e.g. land-use and peatlands), forest inventory data and Landsat images (Tomppo et al. 2008).

2.1 Tree biomass

Firstly, stem volume maps by tree species from the National Forest Inventory 9 (NFI9, 1996-2003) were used, according to Tomppo et al. (2011), to account for large-scale variation of stem volume across Finland. These variations are primarily driven by soil properties, climate, site productivity, forest management techniques and tree species distribution.

Secondly, biomass expansion factors (BEFs, Mg/m^3) were estimated for main tree species groups, namely: Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and for broadleaved species (mainly *Betula* sp.). These BEFs were estimated for each biomass component (foliage, branches, bark, stemwood, stump and woody roots). Biomasses were estimated for sample trees in NFI10 based biomass models by Repola (2008, 2009); thereafter, mean BEFs were estimated at a cluster level (a cluster is formed of 10 to 15 field plots) by dividing the sum of given biomass components by the estimated sum of stem volumes. Biomass estimates for trees were based on biomass models, where diameter at breast height, tree height, crown height, increment of five years and bark thickness are used as predictors. To upscale BEFs across Finland, we applied collocated co-kriging (Bivand et al. 2008) by species group, to account for large-scale spatial correlation and co-variation of tree allometry. We used the *gstat* (Pebesma 2004) package of R (R Core Team 2014) for estimation. For Scots pine and Norway spruce we removed linear trends of latitude and longitude (using uniform coordinate system of Finland, YKJ), while for deciduous trees only trends of latitude were removed. For all species groups and components we assumed spherical variogram functions. For the details of the used biomass models see Appendix 7c by Statistics Finland (2014). Biomass components for each grid point were obtained by multiplying stem volume maps by species with component species-specific BEF estimates that were estimated via co-kriging for the same grid.

Biomass of harvest residues and natural mortality were estimated based on forest statistics and NFI data (Ylitalo 2013). From statistics, we attained an estimate of the stem volume of annual loggings and natural mortality by region (forestry centres) and these were subsequently converted to biomass with BEFs. These BEFs were based on a subset of permanent sample plots of NFI9 (1996–2003) and NFI10 (2004–2008). BEFs for logging were estimated separately from the subset of logged plots and these logging specific BEFs were used in the estimation of biomass of harvest residues. Furthermore, energy use of stumps and harvest residues were deducted from regional soil inputs, based on regional wood energy use (Ylitalo 2013). For biomass of natural mortality, BEFs were estimated based on data from those trees that died on permanent sample plots between measurements. Thereafter the volume of natural mortality was multiplied with corresponding BEFs. This procedure followed principles of Finnish greenhouse gas (GHG) inventory (Statistics Finland 2014).

Fine root biomass was estimated based on the work of Lehtonen et al. (2016). We selected a simple model formulation, where a natural logarithm of fine root mass was estimated as a function of the natural logarithm of stem volume. See Model 1 in Lehtonen et al. (2016) for details (study has 95 sites with fine root data, and model 1 has an adj-R^2 of 0.217). This model was used to approximate general fine root mass levels as a function of stem volume for each 10 × 10 km^2 grid point.

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2.2 Understorey vegetation biomass

In order to estimate the litter input of understorey vegetation to soils, we developed models for vegetation biomass. The relationship between the visually estimated percentage cover of plant species including vascular plants, bryophytes and lichens (projected onto the forest floor using 30 × 30 cm^2 frames) and their living biomass was studied in 18 forest ~~plots~~ stands across Finland (Table 1). The plots are part of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP) intensive monitoring plot network (e.g. Merilä et al. 2014). Altogether 28 systematically selected biomass samples were taken once from each plot during the period 2002 to 2009. In total sample size was 504 of 0.3×0.3 m^2 vegetation plots having detailed biomass measurements by species. Vascular plants were divided into aboveground (shoots) and belowground (rhizomes and roots in organic layer) parts. The study was carried out at the time of maximum biomass and vegetation growth between the end of July and end of August. Half of the plots were located in the north (five in *Pinus sylvestris*, three in *Picea abies* and one in *Betula pubescens* dominated stands) and the other half were in the south (four in *Pinus sylvestris*, four in *Picea abies* and one in *Betula pendula* dominated stands). The site types of the plots ranged from poor to rich fertility level (Table 1).

In order to predict the vegetation biomass, we built linear mixed models based on the relative coverage of five functional plant groups (dwarf shrubs, grasses, herbs, bryophytes and lichens). The biomass of understorey vegetation was estimated using models that correlate vegetation coverage with measured biomass. These models were estimated for the five aforementioned main species groups and for their belowground parts, if applicable. These models were estimated separately for southern and northern Finland. We used a linear mixed model with plot-level random effects using the *lme* command in *nlme* package (Pinheiro et al. 2012) of the R environment for the estimation (R Core Team 2014).

Each model was weighted according to the land area of different site types in southern and northern Finland using the weights option in *lme*. This was done to ensure that the sample of understorey biomass plots did not underestimate the weight of the most common site types (those of medium fertility). The weighting was performed on land areas based on NFI11 data (Ylitalo 2013). Models were linearised by taking natural logarithms from biomass and coverage. For model parameters, bias correction and their uncertainties see Table 3.

To quantify the biomass of understorey vegetation we used species-specific coverage measurements of 2501 permanent sample plots from 1995 forest inventory data (Mäkipää and Heikkinen 2003). We applied collocated co-kriging methods to account for the correlation between species groups and thereafter we generalised measured understorey coverage on a 10 × 10 km^2 grid on upland soils across Finland (Bivand et al. 2008). The co-kriging method was similar to that of BEF estimation described above. First, we de-trended all species group coverage (shrubs, herbs and grasses, lichens and bryophytes) by linear trends of latitude and longitude (using uniform coordinate system of Finland, YKJ). After that we estimated variograms and cross-variograms and applied co-kriging methods to predict coverage for understorey coverage for Finland by *gstat* package of R (R Core Team 2014) (for R code, variograms and cross-variograms, see Supplement). For all species groups we assumed spherical variograms with common range of 100 km.

2.3 Litter input estimation

To estimate litter input from living biomass components to the soil, litter turnover rates were used (Table 2). For needles, we used the detailed 10 × 10 km^2 grid litter turnover rates reported by Tupek et al. (2015). For tree fine roots we assumed that the life span was 1.18 years for southern Finland and 2 years for northern Finland (Kleja et al. 2008, Leppälammi-Kujansuu et al. 2014). In order to interpolate fine root turnover rates for Finland we assumed a linear dependency for turnover rate and mean temperature sum (mean for 1981–2010). For areas with a temperature sum (5 C˚ threshold) higher than 1200 degrees a turnover rate of 85% was used and for areas where temperature sums less than 700 degrees a rate of 50% was used. Turnover rates were interpolated between 700 and 1200 degrees (see Supplement).

For branch and coarse roots litter, the constant turnover rates of the branches were used across Finland (Lehtonen et al. 2004, Muukkonen and Lehtonen 2004). For bark litter we assumed a constant ratio to stem biomass according to Viro (1955) and Mälkönen (1977). For fellings and natural mortality we assumed that all biomass was left to the site, excluding stems for wood used and harvesting residues for energy use. The quantity of wood use was based on regional forestry statistics (Ylitalo 2013).

The turnover rates of different functional plant groups were partly based on literature (Table 2) but we also estimated some rates from our own biomass samples of understorey vegetation described above. We calculated the proportion of the current-year growth out of the total living biomass of dwarf shrub shoots to estimate the turnover rates for aboveground plant parts. We used the average values of deciduous and evergreen dwarf shrubs. Most of the grasses growing in boreal forests (like *Deschampsia flexuosa*) are perennial and we used the ratio between the living and dead biomass to estimate the turnover rate of those species. The aboveground parts of the most herb species (like *Maiathemum bifolium*) are annual, so we used 100% for their turnover rate. Furthermore, we used the number of annual growth segments in the green upper parts of the bryophytes to estimate their rate. We assumed that over a long time period the estimate for annual biomass growth corresponds to the amount of litter input to the soil from understorey vegetation.

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Nitrogen content of all litter components was derived from Komarov et al. (2007), for details see Supplement.

2.4 Application of soil carbon models

Carbon stocks were estimated by running Yasso07 and ~~ROMUL~~ ROMULv models into a steady state (i.e., a state where carbon input for the model equals carbon flux due to decomposition). For a dynamic model a steady state is a state to which model aims with given inputs. Here model inputs were: average climatic conditions (1961–2012) and litter inputs for each grid point, depending on dominant tree species and understorey vegetation coverage plus regional estimates of litter from harvestings and natural mortality (sc. forestry centres). If we assume that this average level of inputs and climate has remained steady over centuries, then our soils should approach steady state conditions. Litter inputs were given to these models as 10×10 km^2 grid points and weather data of that given grid point was then used for model input.

When evaluating model results for Yasso07, fresh woody litter and recently dead wood litter were excluded from model state variables, while all non-woody material and humus boxes (including more heavily decomposed material from fine-woody- and coarse-woody litter) were accounted as soil carbon stock. This separation was done as Yasso07 slows down decomposition of logs of high diameter, which increases soil steady state carbon stock estimates. Data from Biosoil does not include dead wood masses in soil carbon stocks. For ROMUL ROMULv we included all model state variables to the comparison, noting that log size does not affect decomposition.

2.4.1 Climate data

Daily weather data for steady state simulations are available as kriging estimates since 1961 at a 10 × 10 km^2 resolution across Finland (Venäläinen et al. 2005). Weather data for the grid points on upland soils and on forested land, according to multisource NFI, were included (Tomppo et al. 2008).

Daily weather predictions for a 10×10 km^2 grid were aggregated for the Yasso07 model from 1961 to 2012. The average temperature, temperature amplitude and precipitation of each grid cell were provided to Yasso07 to estimate the impact of climate on soil carbon stock steady states. The ROMUL ROMULv model was driven by mean daily temperature and precipitation for each grid cell.

2.4.2 Yasso07

The Yasso07 soil carbon model (Tuomi et al. 2011) is driven by litter quantity, litter quality and weather (temperature and precipitation). This model is widely used in the greenhouse gas inventories of European countries (e.g., Finland, Norway and Switzerland). This model has been also successfully coupled with climate-carbon cycle model ECHAM5/JSBACH (Thum et al. 2011).

The Yasso07 is a simple dynamic model with fluxes and state variables. The model has five compartments: acid, water, ethanol, non-soluble and humus boxes. Division of the litter input according to the litter solubility was species specific and followed that of Finnish GHG inventory, based on the appendix of Yasso07 manual by Liski et al (2009). Organic matter flows between these boxes and to atmosphere variably according to weather conditions (Fig. 1). The model builds on the assumption that organic matter solubility defines litter quality, while decomposition rates while fluxes are estimated numerically, without *a priori* assumptions. The model was calibrated using a large database of litter and wood decomposition measurements, and measurements of age chronosequences of soil carbon stocks (Liski et al. 2005, Liski et al. 1998, Rantakari et al. 2012, Tuomi et al. 2011). The Yasso07 soil carbon model parameter values were estimated with Markov chain Monte Carlo (MCMC) methods for which the source code is publicly available through the model website (www.syke.fi) (Tuomi et al. 2011). Here, we used the Yasso07 model with Scandinavian parameters (Rantakari et al. 2012) and with global parameters, these being a preliminary version different from Tuomi et al., (2011) parameters (practically identical). Yasso07 was run with total litter input (from trees and understorey vegetation) and also with litter excluding that of understorey vegetation. The model was applied with annual time-steps. Model has been calibrated with litter input estimates and soil carbon measurements down to 1 meter soil depth. See the Supplement for more details of Yasso07.

2.4.3 ROMULv

ROMUL ROMUL is a soil organic matter decomposition model developed by Chertov et al., (2001). It describes the flux of organic matter through the decomposition process, separated in cohorts of different litter origins: leaves, shoots, trunks, coarse roots, fine roots and ground vegetation. Litter from above ground (leaves, shoots and stems) falls onto the forest floor, whereas the root litter decomposes in the mineral soil layer. In the final stages, all decomposing matter ends up in a common storage of semi-stable humus residing in the mineral soil layer (Fig. 1). Decomposition rates of each cohort depend on the nitrogen and ash content of the specific litter type and for all cohorts the soil temperature and water content modify the decomposition rate. Here we used species specific nitrogen ratios for different litter fractions; these ratios were same across the country in given fraction of given species.

In this paper we utilised a version of the ROMUL model, where we adopt decomposition rate functions depending on soil water content and the model for soil water dynamics as described in Linkosalo et al. (2013). We call this version of the model ROMULv (where the "v" refers to decomposition rates based on volumetric soil water measures). The soil water holding capacity data was obtained from digital soil maps of Finland (Lilja and Nevalainen 2006). Total soil water holding capacity data was extracted to a 10 × 10 km^2 grid, when available. To evaluate the impact of soil water holding capacity variability, we also repeated the ROMULv simulation assuming a constant soil water holding capacity for the whole simulation area. As the ROMULv model segregates the organic and mineral soil layers, we assumed that 20% of the total soil water holding capacity was in the organic layer and 80% in mineral soil layer. See the Supplement for more details of ROMULv, the source code and parameter estimates.

We applied the ROMUL ROMULv model using daily time-steps of the environmental variables impacting the decomposition. The estimated annual litter input was evenly distributed for each day of year. The ROMUL ROMULv model explicitly simulates the flux of nitrogen through the decomposition process and therefore produces estimates for mineralised N in addition to the soil organic matter and N storages and CO_2 release from the soil. All model parameters, except the decomposition rate, which is dependent on soil water content, were taken from the Chertov et al. (2001) paper. Although ROMULv model does not explicitly define depth of soil layers, but the soil water layer of 1 meter has been assumed implicitly when gravimetric water content is estimated. Therefore we assume that decomposition occurs in that same layer of 1 meter.

In this paper we adopt decomposition rate functions depending on soil water content and the model for soil water dynamics as described in Linkosalo et al. (2013). We applied the ROMUL model with soil water holding capacity data, obtained from digital soil maps of Finland (Lilja and Nevalainen 2006). Total soil water holding capacity data was extracted to a 10 × 10 km^2 grid, when available. To evaluate the impact of soil water holding capacity variability, we also repeated the ROMUL simulation assuming a constant soil water holding capacity for the whole simulation area. As the ROMUL model segregates the organic and mineral soil layers, we assumed that 20% of the total soil water holding capacity was in the organic layer and 80% in mineral soil layer. See the Supplement for more details of ROMUL, the source code and parameter estimates.

2.4.4 Biosoil – soil carbon measurements

The Biosoil dataset resulted from EU-funded Forest Focus monitoring program and includes measurements of soil carbon and various other ecosystem variables from 2006. Data consists of 521 sample plots located across Finland. These plots were established as a subset of 3009 permanent sample plots from 1985–86 (see Mäkipää and Heikkinen 2003).

Biosoil sample plots have radii of 11.28 m (400 m^2). Trees and understorey vegetation coverage were measured. Soil carbon samples were taken separately from the litter and humus layers and mineral soil layers at 0–10, 11–20, 21–40 and 41–80 cm depth. In total 10 or 20 subsamples were taken from the organic layers with a cylinder (diameter = 60 mm) and 10 tube (diameter = 23 mm). Alternatviely, 5 spade subsamples were taken from the 0–10 cm mineral soil layer, a further 5 spade subsamples were taken from the layers 11–20 and 21–40 cm and one subsample from the layer 41–80 cm. Viro (1952) rod penetration method was used to quantify the volume of stones and boulders in the surface soil layer. Several properties were analysed from soil samples in the laboratory: soil texture, cation exchange capacity (CEC), base saturation (BS), pH, organic carbon and total nitrogen concentrations. Aqua regia extractable P, Ca, K, Mg, Mn, Pb, Na, Ni, Fe and S were also measured (Derome et al. 2007). Soil carbon stocks were estimated down to 1 m depth by extrapolation of 40–80 cm measurements for the 80–100 cm layer.

Measured soil carbon stocks were grouped into different latitudinal bands forming a gradient in Finland to which we compared soil carbon estimates from Yasso07 and ~~ROMUL~~ ROMULv models against measured data. Comparisons were made with two different widths of latitude bands: firstly we used bands of 100 km and thereafter bands of 20 km. Bands were included in the analysis when there were four or more Biosoil observations in a band. We also identified those Biosoil plots that had been under the Litorina Sea 7000–8000 BP (Miettinen 2004, Sohlenius et al. 1996) using map products produced by the Geological Survey of Finland (Eronen 1974). We used root mean square error (RMSE) to rank these models applications due to its ability to take into account both accuracy and precision when comparing model estimates and data.

We also studied differences between mean stand and soil properties for two regions in southern Finland (Region 1 with a latitude below 60˚46’, and Region 2 with a latitude between 60˚46’ and 62˚34’).

3 Results

~~Aboveground biomass of dwarf shrub vegetation was twice as large in the North compared to the South (Fig. 2) and the difference was even more pronounced with belowground biomass (Fig. 3). For bryophytes we found large variability, especially when their ground coverage approached 100%; therefore, our model is valid up to 80% ground coverage and for ground coverage over 80% we estimate mean biomass of bryophytes to be 1124 kg ha^{-1} and 1055 kg ha^{-1}, respectively, for southern and northern Finland. All understorey biomass models displayed substantial unexplained variation, owing to the fact that we had only ground coverage [%] as an explanatory variable and because we pooled together different species into~~

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~~these functional groups (e.g., dwarf shrubs with different leaf weights, like *Vaccinium myrtillus* and *Empetrum nigrum*). See Table 3 for model parameter values and their uncertainties.~~

~~The amount of litterfall from trees and understorey vegetation showed opposite trends with latitude. Total litter input of trees and other vegetation in southern Finland was four times higher than that in northern Finland. Though, the understorey vegetation at northern sites displayed much higher litter inputs than those in southern Finland. According to our results, fall of understorey litter in eastern and northern Lapland was equal to that from trees (Fig. 4). We estimated mean litterfall from understorey vegetation to approximately equate to 473 kg ha^{-1} and 863 kg ha^{-1} of carbon for southern and northern Finland, respectively. In the Finnish GHG inventory these estimates, based on Muukkonen et al. (2006), were 506 kg ha^{-1} and 665 kg ha^{-1} for southern and northern Finland, respectively. Our estimate of mean litter input from trees was 1962 kg ha^{-1} and 903 kg ha^{-1} of carbon for southern and northern Finland, respectively.~~

3.1. Performance of the soil carbon models

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The soil carbon stock estimates by Yasso07 model using global parameterisation (Tuomi et al. 2011) were systematically larger than measured data across Finland, whereas those obtained with Scandinavian parameterisation (Rantakari et al. 2012) were in the same magnitude as the Biosoil data (Fig. 2~~4~~A and B). In addition to the realistic level of soil carbon stock, the model that was based on parameterisation with the Scandinavian data also reproduced decreasing soil carbon stock trend from south to north, as displayed in the Biosoil data. Excluding understorey litter from the model input improved the match between Yasso07 soil carbon stocks simulated using global parameters and Biosoil data, whereas for Yasso07 using Scandinavian parameters, the same exclusion resulted in underestimation of soil carbon stocks, especially in northern Finland (Fig. 2~~4~~C and D). The ~~ROMUL~~ ROMULv model predictions generally agreed with Biosoil data when soil water holding capacity was taken into account. The inclusion of soil water holding capacity in ~~ROMUL~~ ROMULv introduced high variation in soil carbon stocks between dry and moist grid points in southern Finland (Fig. 2~~4~~E). When the ~~ROMUL~~ ROMULv model was driven with constant soil water holding capacity, it was unable to reproduce decreasing soil carbon stocks across Finland and the model underestimated carbon stocks, especially in the south (Fig. 2~~4~~E and F). Large deviations between the data and the model estimates were also seen for the largest Biosoil soil carbon stocks of the southernmost plots (Fig 2~~3~~).

The ~~ROMUL~~ ROMULv model using the soil water holding capacity was the only model able to reproduce the increase in measured soil carbon stocks at the southernmost plots. All other models predicted a substantial decrease in the soil carbon stocks for southern region, which was not observed in measurements (Fig. 4). Soil properties of southernmost plots (Region 1 (R1) with a latitude below 60˚46') were different compared to soil properties of forests further north (Region 2 (R2) with a latitude between 60˚46' and 62˚34'). The southern coast had lower silt content and higher sand content, but simultaneously higher carbon stocks in the organic layer than the other region (Table 3~~4~~). Also understorey vegetation differed between these regions and the southern coast had lower *sphagnum* species and herbs species coverage, indicating that soils there were drier. We also tested site type distributions between R1 and R2 but the p-value from a chi-square test was > 0.4, indicating that site fertilities did not differ. This is also supported by the measured C:N ratios, which did not differ between these regions (Table 3~~4~~). These southern sites were also younger and 29% of plots were under the Littorina Sea ~7000–8000 years BP, while the share of younger soils was only 6% for the slightly more northern region.

We found that Yasso07 model applications excluding litter input from understorey vegetation had the best agreement with the observed latitudinal gradient when evaluating with one-to-one plots (~~Fig. 6~~Fig. 3). The modelled and measured soil carbon stock fits were poor for the Yasso07 application with global parameters, including the understorey vegetation litter input and for the ~~ROMUL~~ ROMULv application not using soil water holding capacity data. These model applications showed no correlation with measurements and also failed to map the south to north soil carbon stock decrease (~~Fig. 6~~Fig. 3). The lowest ~~root mean square error~~ RMSE was obtained with the ~~ROMUL~~ ROMULv model applied with soil water holding capacity data indicating the best performance among these model applications.

3.2 Improved understorey litter input

The amount of litterfall from trees and understorey vegetation showed opposite trends with latitude. Total litter input of trees and other vegetation in southern Finland was four times higher than that in northern Finland following the temperature gradient (Fig. 4). Though, the understorey vegetation at northern sites displayed much higher litter inputs than those in southern Finland. According to our results, fall of understorey litter in eastern and northern Lapland was equal to that from trees (Fig. 4). We estimated mean litterfall from understorey vegetation to approximately equate to 0.0473 kg m^{-2} and 0.0863 kg m^{-2} of carbon for southern and northern Finland, respectively. Our estimate of mean litter input from trees was 0.1962 kg m^{-2} and 0.0903 kg m^{-2} of carbon for southern and northern Finland, respectively.

4 Discussion

We tested whether litter quality, litter quantity and mean climate are sufficient for estimating spatial trends in soil carbon stocks and if soil texture with low water holding capacity introduces water limitation to decomposition. While testing our hypothesis we found that Yasso07 and ~~ROMUL~~ ROMULv models were able to predict carbon stocks of the same magnitude as that of measurements for Finland; however, these models experienced more challenges when their performance was evaluated for smaller regions, like the southern coast of Finland.

We also found that litter input from understorey vegetation is equal of that from trees in northern Finland. This emphasises the large role of understorey vegetation in compensating trees in an ecosystem carbon cycle, especially under light and nutrient limited growth conditions. Total litter input varied from 0.4 to 0.01 kg m^{-2} of carbon from southern to northern Finland. These values agree with both, net primary production (NPP) estimates for trees that vary between 0.2 and 0.5 kg m^{-2}

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of carbon for southern Finland by Härkönen et al. (2010) and with measured litterfall values that range from 0.23 to 0.3 kg m^{-2} for Hyytiälä eddy covariance site (Ilvesniemi et al. 2009).

To sum up, litter input from understorey vegetation has to be quantified properly when soil carbon models are parameterised. This means that model developers should have unbiased estimates of total carbon inputs into the soil system when they use litter estimates and soil carbon stocks to calibrate parameters that affect long term carbon accumulation. The results of our biomass models for the understorey agreed with previous estimates for southern Finland but for northern Finland our estimates were substantially larger. Yasso07 was parameterised using understorey litter inputs ranging from 40–60 g carbon m^{-2} a^{-1} and therefore Yasso07, with updated understorey litter estimates, overestimated the level of soil carbon stocks. Our data for understorey vegetation biomass was mostly from stands that were over 60 years old and therefore more data for younger sites are needed. Furthermore, the litter input of belowground understorey vegetation was uncertain due to limited data on the life span of roots. More research is therefore needed to confirm the high contribution of dwarf shrub vegetation to total belowground litter input.

When evaluating modelled and measured soil carbon stocks against northern latitude we could see that two out of six simulations failed to map measured soil carbon stock decreases towards the north (Fig 4). Five model simulations showed that southern coast had less carbon than the next region further north, while the Biosoil data showed the opposite. Only the ~~ROMUL~~ ROMULv model, using soil water holding capacity data from Lilja and Nevalainen (2006) ~~and applied as in Linkosalo et al. (2013),~~ was able to estimate the largest soil carbon stocks for southern Finland, similar to Biosoil measurements (~~Fig. 5~~Fig. 2). This indicated that litter quality, litter quantity and climate data are not sufficient when estimating spatial trends of soil carbon stocks. When we evaluated Biosoil data for these regions, the southern sites were better drained and drier that those in North. Better drainage was indicated by higher sand content, significantly lower silt content and significantly lower *Sphagnum* and herb vegetation coverage (Table 3~~4~~). We also found out that the southern coast experiences a 1.3 C° higher mean annual temperature than the next region to the north. Therefore, the organic layer was larger for southern coast likely due to limited decomposition during dry spells (Table 3~~4~~). This result indicated that the quantity of precipitation alone was not a sufficient modifier for decomposition but when complemented with soil water holding capacity average latitudinal results improved. This finding supports the use of models including soil texture and water holding capacity.

~~According to our results~~Our results support also earlier findings, where the time step of the simulation plays a critical role; running models with monthly and annual time steps excludes extreme conditions and may produce biased estimates of carbon stocks simply due to fact that non-linear models are run with mean conditions (Dalsgaard et al. 2016, Rantakari et al. 2012)~~(Dalsgaard et al. 2016)~~. This is especially critical with soil moisture, which has a bell shaped relation to decomposition (Sierra et al. 2015, Skopp et al. 1990). Compared to daily time steps of ROMUL, model simulations with longer time steps (e.g., a year as in Yasso07) exclude both extreme dry and extreme moist conditions, leading to underestimation of steady states soil carbon stocks. On the other hand, reduction of the decomposition rate during limited and excess water conditions are not well known. Sierra et al. (2015) compared the effect of moisture on decomposition in different models with the

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largest variability for dry and saturated conditions. They showed that a moisture index of 0.2 can have a decomposition modifier between 0.2 and 1 and similarly with a moisture index of 1 this modifier can be anywhere between 0 and 1, depending on the model. These large discrepancies indicate differences between soil properties of sites used for model calibration and between conceptualisations of soil moisture.

The Yasso07 and ROMUL ROMULv model simulations with litter input and climate data alone were not enough to reproduce the observed soil carbon stocks. Model application without soil moisture impacts on decomposition failed under conditions where soil drainage played a significant role in limiting decomposition. The use of water holding capacity was critical for accurate soil carbon stock estimation by the ROMUL ROMULv model, while Yasso07 performed best when the variation in litter input correlated with that of the observed soil carbon stocks (Fig. 6Fig. 3). The fact that Yasso07 soil carbon stocks (Tuomi et al. 2011) were more accurate when litter input of understory vegetation was omitted from simulations suggests that the model calibration did not account for the whole range of understory litter input. This implies that in future, improved estimates for understorey litter input are needed when Yasso07 or similar models will be parametrised for boreal conditions. In order to improve model performance, shorter time steps complemented with more detailed topography and soil properties are needed to map the impact of extreme events to soil carbon decomposition (e.g., droughts and water logging conditions). However, three model simulations out of six produced relatively accurate estimates of soil carbon stocks compared to the measurement means of smaller regions, having RMSE less than 1.1 for soil carbon stock -(Fig. 6Fig. 3). This suggests that improved calibration with updated understorey litter and accounting for the soil properties as with ROMUL ROMULv (using data on water holding capacity) produces model estimates that agree regionally with data.

Our simulations and measurements show that models using only litter quality, litter quantity and weather data underestimate soil carbon stock in regions like southern Finland and this underestimation is due to omission of the impact of droughts to the decomposition of organic layers. Thus, we conclude that GHG inventory methods and soil modules of Earth system models need to be improved by incorporating the impact of soil texture and soil moisture to decomposition. This is a prerequisite for unbiased soil carbon stock and stock change estimates.

Our findings confirm the fact that GHG inventory methods and soil modules of Earth system models need to be improved by incorporating the impact of soil texture and soil moisture to decomposition. This is a prerequisite for unbiased soil carbon stock and stock change estimates.

Code availability

The fortran code of the ROMUL ROMULv is given in the supplement, while fortran code for Yasso07 is available through website [http://code.google.com/p/yasso07ui/], for details see Supplement.

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Table 1. Site description of ICP Forests Level II plots studied for understorey vegetation biomass.

Plot no	Area	Region	North coord.	East coord.	Tree species	Site type	Forest type	Stand age	Basal area m^2	DF	GR	HE	BR	LI	Year of sampling	n above/below
1	Sevettijärvi	1	7723	3573	1	5	UVET	210	13.52	x	-	-	x	x	2009	28/12
2	Pallasjärvi	1	7543	3377	1	4	EMT	100	17.85	x	-	-	x	x	2003	28/28
3	Pallasjärvi	1	7549	3384	2	3	HMT	150	15.42	x	x	x	x	-	2003	28/28
4	Sodankylä	1	7472	3485	1	4	EMT	80	19.66	x	-	-	x	x	2003	28/28
5	Kivalo	1	7360	3484	2	3	HMT	80	17.95	x	x	-	x	-	2002	28/28
6	Kivalo	1	7364	3488	1	4	EMT	65	18.94	x	-	-	x	x	2002	28/28
32	Kivalo	1	7371	3486	3	3	HMT	58	14.39	a	a	a	x	-	2009	28/0
21	Oulanka	1	7359	3612	2	3	HMT	180	21.03	a	a	a	x	-	2009	28/0
20	Lieksa	2	7012	3687	1	4	EVT	140	22.27	a	-	a	x	-	2009	28/0
10	Juupajoki	2	6866	3353	1	4	VT	90	23.55	x	x	x	x	-	2002	28/28
11	Juupajoki	2	6863	3359	2	2	OMT	90	30.4	x	x	x	x	-	2002	28/28
12	Tammela	2	6730	3325	2	3	MT	70	33.08	x	x	x	x	-	2002	28/28
13	Tammela	2	6727	3330	1	4	VT	70	29.27	x	x	x	x	-	2002	28/28
16	Punkaharju	2	6854	3627	1	4	VT	90	31.95	x	-	x	x	-	2002	28/28
17	Punkaharju	2	6858	3622	2	2	OMT	80	30.76	-	-	x	x	-	2002	28/28
33	Punkaharju	2	6862	3622	3	1	OMaT	27	16.13	-	a	a	-	-	2009	28/0
34	Luumäki	2	6763	3515	1	5	CT	60	13.55	x	-	-	x	x	2009	28/12
35	Luumäki	2	6756	3513	2	3	MT	60	28.21	x	x	x	x	-	2009	28/12

Region (1 = northern Finland, 2 = southern Finland); tree species (1 = Scots pine, 2 = Norway spruce and 3 = deciduous trees); site type (1–5, from rich to poor fertility level); forest site types (abbreviations explained in Salemaa et al. (2008), Table 1); plant species groups in biomass samples: DF = dwarf shrubs, GR = grasses, HE = herbs, BR = bryophytes and LI = lichens. x = biomass sample includes both aboveground and belowground (in organic soil layer) part of vegetation, a = sample includes only aboveground vegetation, - = plant group does not grow in the plot. n = number of samples (each sized 30 x 30 cm^2) for aboveground and belowground biomass.

Table 2. Litter turnover rates for tree and understorey biomass by component, species and region.

Biomass	Species	Region	Value [%]	Reference
Leaves	Scots pine		27% [18-34%]	Tupek et al., (2015)
Leaves	Norway spruce		13% [9-15%]	Tupek et al., (2015)
Leaves	Broadleaved		79%	Tupek et al., (2015)
Branches	Scots pine		2%	Lehtonen et al. (2004)
Branches	Norway spruce		1.25%	Muukkonen and Lehtonen (2004)
Branches	Broadleaved		1.35%	Lehtonen et al. (2004)
Bark	Scots pine		0.3%	(Mälkönen 1977, Viro 1955)
Bark	Norway spruce	-	-	(Mälkönen 1977, Viro 1955)
Bark	Broadleaved		0.01%	(Mälkönen 1977, Viro 1955)
Coarse roots	Scots pine		2%	Lehtonen et al. (2004)
Coarse roots	Norway spruce		1.25%	Muukkonen and Lehtonen (2004)
Coarse roots	Broadleaved		1.35%	Lehtonen et al. (2004)
Fine roots	Scots pine	South	85%	Kleja et al., (2008)
Fine roots	Norway spruce	South	85%	Kleja et al., (2008)
Fine roots	Broadleaved	South	85%	Kleja et al., (2008)
Fine roots	Scots pine	North	50%	Leppälammi-Kujansuu et al., (2014)
Fine roots	Norway spruce	North	50%	Leppälammi-Kujansuu et al., (2014)
Fine roots	Broadleaved	North	50%	Leppälammi-Kujansuu et al., (2014)
Aboveground	Dwarf shrubs	-	37%	This study
Belowground	Dwarf shrubs	-	8%	This study& Helmisaari et al. (2015)
Aboveground	Grasses	-	33%	This study
Belowground	Grasses	-	59%	Leppälammi-Kujansuu et al., (2014)
Aboveground	Herbs	-	100%	
Belowground	Herbs	-	59%	This study & Leppälammi-Kujansuu et al., (2014)
Aboveground	Bryophytes	-	42%	This study
Aboveground	Lichen	-	10%	Kumpula et al., (2000)

Table 34. Mean soil and forest stand properties for R1 and R2 and 1.96 times their standard error of mean (SEM). R1 is south from 60˚46', while R2 lies between 60˚46' and 62˚34'northern latitude. P-values based on two sided t-test, where group variances are assumed to be different variables where p-value < 0.05 are in bold. Sample sizes were 31 and 127 plots, for southern (R1) and northern (R2) areas, respectively. For mean temperature and precipitation sample sizes were more than 150 based on Finnish Meteorological Institute (FMI) weather grid (Venäläinen et al. 2005).

	Sand [%]	**Silt [%]**	Clay [%]	BS O [%]	BS M [%]	CEC O [cmol(+)/kg]	CEC M [cmol(+)/kg]	pH (H_2O)	C:N O	C:N M	**Sphagnum [%]**	Lichen [%]	**Herb [%]**	G [m^2]	Decid [%]	Spruce [%]	**Lito [%]**
R1 mean	64.92	**30.08**	4.98	67.2	23.26	32.23	5.27	4.23	26.41	23.11	**0.3**	0.86	**4.43**	23.45	15.55	39.81	**29**
R1 sem	7.31	**5.39**	2.64	6.08	5.5	3.22	0.54	0.12	1.25	1.57	**0.53**	1.05	**1.83**	3.29	6.87	12.01	**16**
R2 mean	57.76	**37.09**	5.15	68.8	27.72	29.06	4.91	4.17	25.13	21.6	**1.51**	0.45	**8.56**	23.9	19.28	37.1	**6**
R2 sem	3.34	**2.55**	1.2	2.29	3.28	0.87	0.43	0.05	1.56	0.79	**0.98**	0.26	**2.18**	1.43	4.58	6.09	**4**
p-value (t.test)	0.09	**0.03**	0.91	0.63	0.18	0.07	0.31	0.4	0.21	0.1	**0.04**	0.48	**0.01**	0.81	0.38	0.69	**0.01**

	T mean [C]	**Prec [mm]**	**extrCd [mg/kg]**	**extrPb [mg/kg]**	extrK [mg/kg]	extrP [mg/kg]	extrNa [mg/kg]	extrNi [mg/kg]	extrCa [mg/kg]	extrMg [mg/kg]	extrFe [mg/kg]	extrS [mg/kg]	extrMn [mg/kg]	TWI	**Altitude [dm]**	**SOC O [Mg ha^{-1}]**	SOC M [Mg ha^{-1}]
R1 mean	**4.91**	**580.71**	**0.48**	**47.88**	1149.16	943.61	139.71	10.8	4638.39	992.52	5157.74	1435.39	459.47	6.97	**588**	**25.82**	31.65
R1 sem	**0.09**	**6.25**	**0.05**	**3.62**	138.59	80.16	14.87	1.03	1044.39	329.89	984.63	85.95	167.12	1.83	**124**	**5**	7.15
R2 mean	**3.62**	**545.66**	**0.38**	**36.02**	1225.03	940.32	131.19	11.07	4058.02	1063.51	4675.6	1380.96	537.84	8.79	**1119**	**17.46**	35.23
R2 sem	**0.05**	**2.28**	**0.03**	**5.77**	85.23	38.99	11.11	1.05	256.21	159.48	643.98	55.04	148.54	1.14	**55**	**1.57**	3.31
p-value (t.test)	**0**	**0**	**0**	**0**	0.37	0.94	0.38	0.73	0.3	0.71	0.43	0.31	0.5	0.1	**0**	**0**	0.38

Here sand, silt and clay content are given as a percentage. Base saturation (BS). cation exchange capacity (CEC) and C:N ratios are given separately for organic layer (O) and for mineral soil layer (M). pH is measured in water. Abundance of ground vegetation given as percentage coverage. Basal area of trees (G) and relative shares of deciduous species and Norway spruce from basal area. Lito indicates the proportions of sites that were under the Littorina Sea 8000–7000 BP. Aqua regia extractable K, P, Na, Ni, Ca, Mg, Fe, S and Mn unit mg/kg. Topographical wetness index (TWI). Altitude of plots based on 10 m resolution map layer. Amount of carbon in organic and mineral soil horizon.

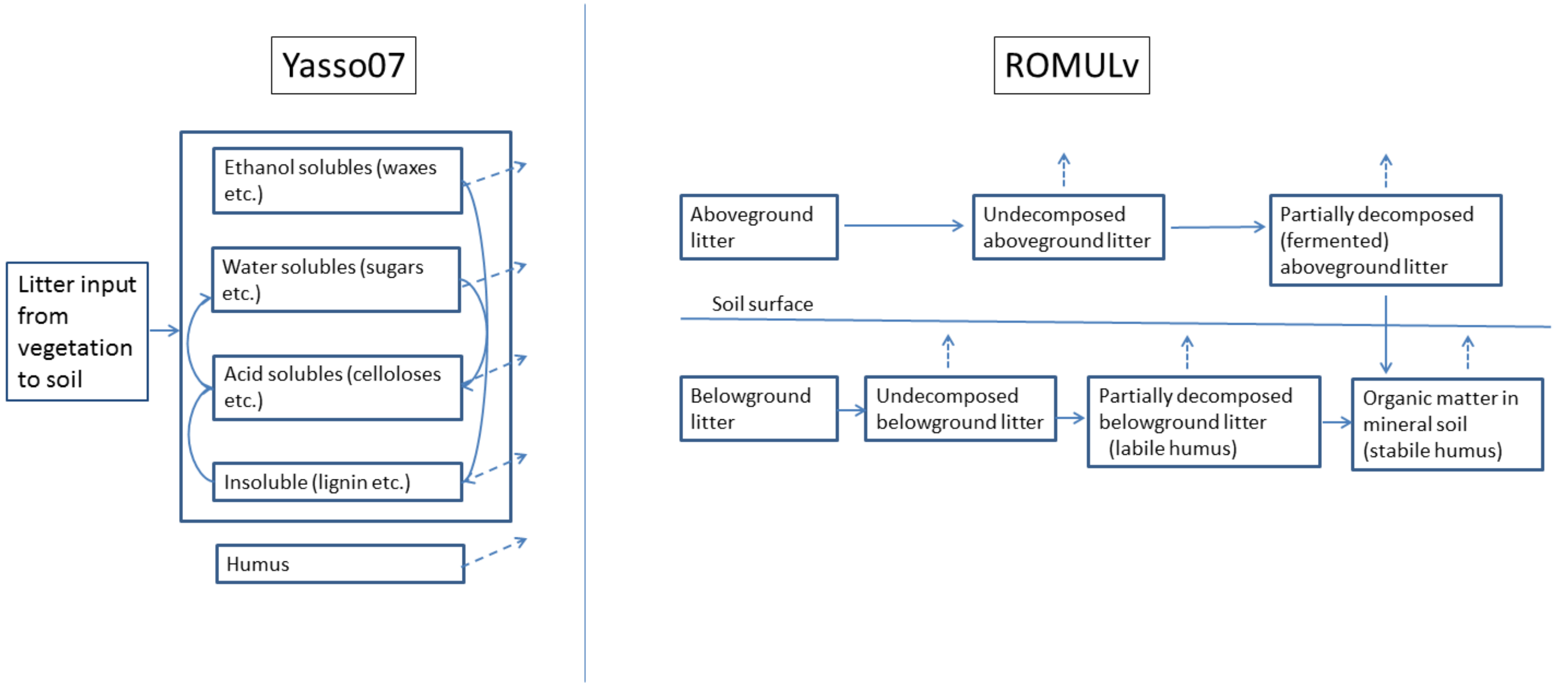

Figure 1: Schematic illustration of Yasso07 (left) and ROMULv (right) soil carbon models. Solid arrows indicate fluxes of organic matter, while dashed arrows indicate CO_2 fluxes to atmosphere.

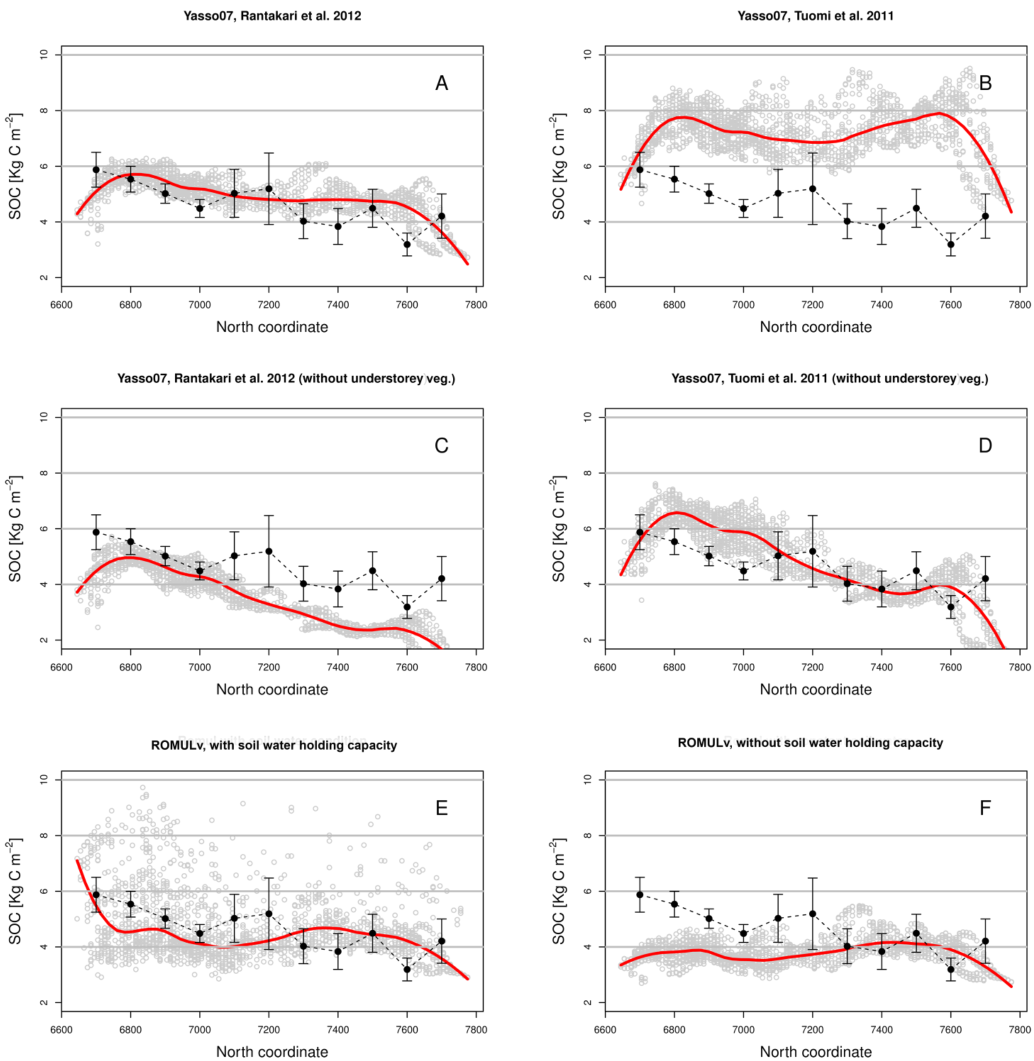

Figure 25. Latitudinal trends of measured and modelled soil carbon stocks across Finland. X-axis is the North coordinate according to Finnish YKJ system and Y-axis is the soil carbon stock Mg ha^{-1}. Grey dots are individual model estimates and red line is a 2nd order *loess* fit. Panel A is Yasso07 with Rantakari et al. (2012) parameters, while B is with Tuomi et al. (2011)

parameters. C and D are same as A and B, but without understorey litter input. E and F are with ~~ROMUL~~ ROMULv model where E includes soil water holding capacity data and F is with constant soil water holding capacity. Black dots are means from Bio soil data for each latitude band and whiskers are 1.96 times standard error of the mean.

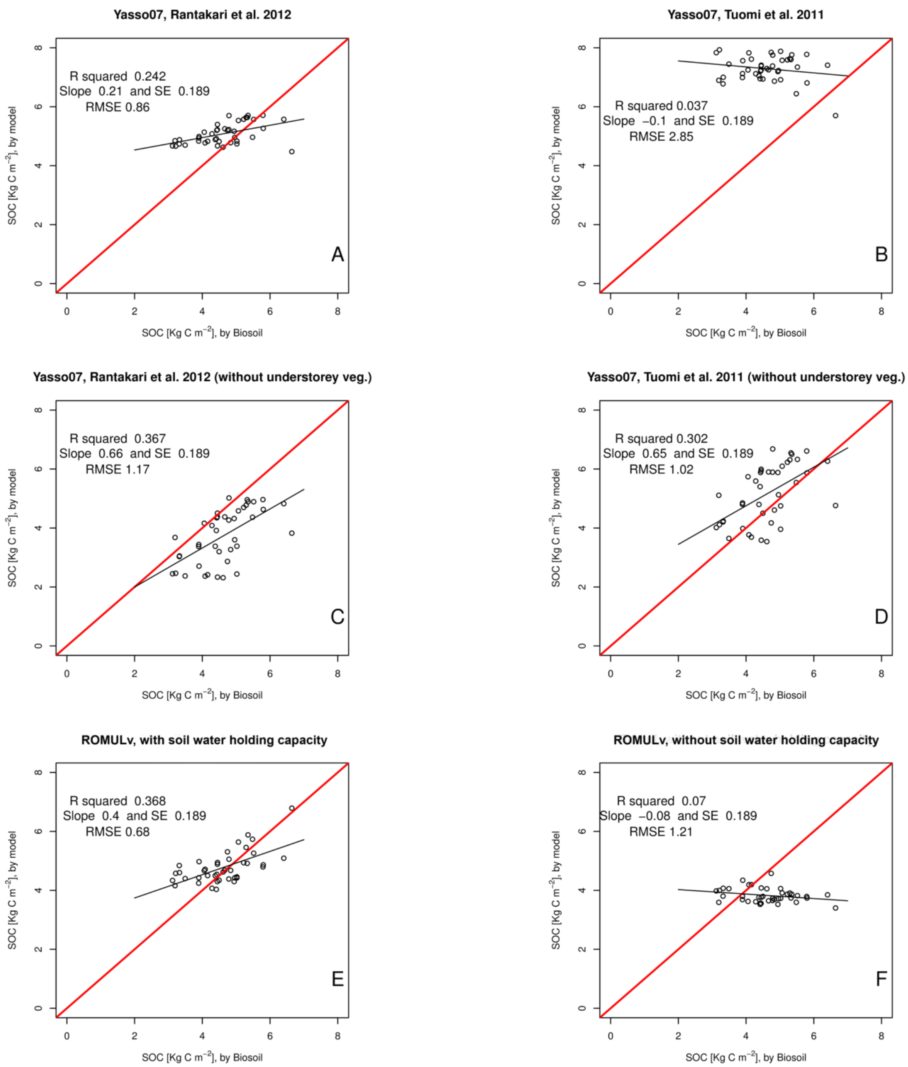

Figure 3~~6~~. One-by-one plots for mean model estimates and mean Biosoil measurements of soil carbon stocks for 41 latitudinal bands across Finland. Panel A is Yasso07 with Rantakari et al. (2012) parameters, while B is with Tuomi et al. (2011) parameters. C and D are same as A and B but without understorey litter input. E and F are with ~~ROMUL~~ ROMULv model where E is with soil water holding capacity data and F is with constant soil water holding capacity. R^2, slope of the regression and the slope standard error are reported. RMSE is based on the difference between model estimate and measurements.

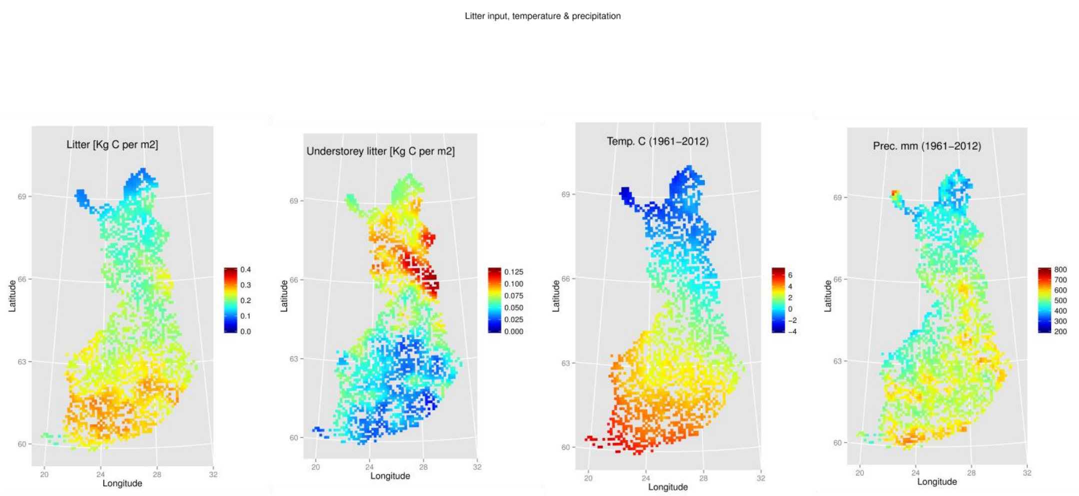

Figure 4. Maps for total litter input [Mg ha^{-1}], understorey litter input [Mg ha^{-1}], mean annual temperature [C°] and mean annual precipitation [mm].

Forest soil carbon stock estimates in a nationwide inventory: evaluating performance of the ROMULv and Yasso07 models in Finland

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Abstract. Dynamic soil models are needed for estimating impact of weather and climate change on soil carbon stocks and fluxes. Here, we evaluate performance of Yasso07 and ROMULv models against forest soil carbon stock measurements. More specifically we ask, if litter quantity, -quality and weather data are sufficient drivers for soil carbon stock estimation. We also test whether inclusion of soil water holding capacity improves reliability of modelled soil carbon stock estimates. Litter input of trees was estimated from stem volume maps provided by the National Forest Inventory, while understorey vegetation was estimated using new biomass models. The litter production rates of trees were based on earlier research, while for understorey biomass those were estimated from measured data. We applied Yasso07 and ROMULv models across Finland and ran those models into steady state; thereafter, measured soil carbon stocks were compared with model estimates. We found that the role of understorey litter input was underestimated when the Yasso07 model is parameterised, especially in northern Finland. We also found that the inclusion of soil water holding capacity in the ROMULv model improved predictions, especially in southern Finland. Our simulations and measurements show that models using only litter quality, litter quantity and weather data underestimate soil carbon stock in southern Finland and this underestimation is due to omission of the impact of droughts to the decomposition of organic layers. Our results also imply that the ecosystem modelling community and greenhouse gas inventories should improve understorey litter estimation in the northern latitudes.

1 Introduction

Soil carbon is a significant component of terrestrial carbon stocks and understanding its dynamics under changing climate is crucial. However, the significance and interactions of different mechanism for long term carbon accumulation are still unknown and therefore often lack from models. If we want to understand the role of different abiotic and environmental factors to soil carbon stocks and their dynamics, we have to combine experimental research with process-based models. One way forward is to establish soil carbon inventories in order to quantify soil carbon stocks and their change. Conventional soil inventories measuring various nutrients, carbon contents, bulk densities and stoniness (e.g. Gamfeldt et al. 2013) allow us to study the distribution of soil carbon across landscapes and correlations between different soil properties. Generally, it is shown that soil carbon inventories are able to produce soil maps and covariates between soil carbon quantities and other variables, such as various nutrients; although, the sample size of these inventories is usually not adequate for national-level soil carbon stock change assessment, with few exceptions (e.g., Sweden and Germany) (Gamfeldt et al. 2013, Grüneberg et al. 2014).

According to the United Nations climate convention, countries are requested to report annual carbon stock changes of soils under different land-uses and under land-use change. The majority of countries apply soil carbon models, like Yasso07 (Tuomi et al. 2011) and CENTURY (Parton et al. 1987) to estimate soil carbon stock changes. These annual submission are reviewed annually and methods should be transparent and verifiable favouring simple soil models instead of complex ones.

The scientific community is also aiming to predict future soil–climate change feedbacks on a global scale using Earth system models (ESMs). The ESMs are tested against soil carbon measurements in order to evaluate model performance but unfortunately results have been poor. Guenet et al. (2013) present a test whereby soil carbon stocks predicted by ORCHIDEE model were plotted at a plot level against measurements and failed to display any correlation. Similarly, Todd-Brown et al. (2013) concluded that most ESMs are not able to produce measured soil carbon stocks at a grid level. This finding is somewhat alarming due to fact that it is essential to have correct initial carbon stocks with soil models, because carbon stock change estimates depend on those. Initial soil carbon stock estimates are particularly important when carbon stock changes of deforestation events are modelled.

Individual soil carbon models are tested against repeated soil inventories and it has been found that models are able to estimate soil carbon stock change of the same magnitude as was measured (Ortiz et al. 2009, Rantakari et al. 2012). The limitation of this conclusion was that uncertainties of both measurements and model estimates are often higher that actual estimates (Ortiz et al. 2013, Rantakari et al. 2012). While the uncertainties between model output and real measurements reveal whether models agree with data or not, they put less emphasis on whether all the most important soil carbon stock drivers were included in these models.

Simplistic soil carbon models like Yasso07 (Tuomi et al. 2011) are driven only by weather conditions and by litter input; while more complex models, like ROMUL (Chertov et al. 2001) also include the nitrogen cycle and the impact of soil water holding capacity on decomposition. It is evident that soil properties affect soil carbon stocks (Schimel et al. 1994, Six et al. 2002) and therefore they are explicitly included in complex models. For example, in the CENTURY model clay content limits decomposition (Parton et al. 1987) and due to the low specific surface area of clay minerals in the model, clay rich soils have larger passive soil carbon stocks and lower C:N ratios (Parfitt et al. 1997). In simplistic models soil properties are omitted. For example, in Yasso07 the role of soil properties on soil carbon stock accumulation is included only implicitly through the model calibration with large datasets (Tuomi et al. 2011). Although the simpler models lack some predominant drivers of soil carbon accumulation, the strength of these models lies in their easier calibration with data; however, the impact of soil properties, especially nutrient status, on the accuracy of estimated soil carbon stock estimates needs to be re-evaluated in both CENTURY and Yasso07 models (Tupek et al. 2016).

It is well known that decomposition and soil respiration is controlled by water content, whereby in dry soils lack of water slows down decomposition, while excess water reduces it by limiting oxygen diffusion (Skopp et al. 1990). For boreal forest conditions, Pumpanen et al. (2003) proposed a model whereby maximum soil respiration drops after the relative water content of soil reaches a level of 60%. The limiting effect of soil moisture on decomposition in dry or water-saturated soils is widely included in models, although the degree of this dependency varies widely between models (Sierra et al. 2015).

In addition to the model structure, precise and accurate estimates of litter input quantity and quality are also essential for successful model applications. Stand-alone soil models rely on forest inventory data or other external estimates for getting correct litter inputs, while ecosystem models utilise plant sub-models to describe vegetation productivity and litter inputs. A common feature of ecosystem models and stand-alone soil models is that often understorey vegetation is neglected during the calibration and application of models, resulting in biased litter inputs. This omission is more critical in boreal landscapes where the contribution of understorey vegetation increases with northerly latitude. For example, Yuan et al. (2014) report that the bryophyte biomass contributes 20%–60% of the total normalized difference vegetation index (NDVI) in high northern latitudes.

In order to assess the necessary drivers for soil carbon models in Finland we tested the performance of Yasso07 and ROMULv models against measured nation-wide soil C data. The ROMULv refers to a modified ROMUL model version where decomposition rate functions are derived from the model presented by Pumpanen et al. (2003), and a simple volumetric soil water model (Linkosalo et al. 2013) is applied to drive those decomposition functions.

We were specifically interested if the additional complexity of processes introduced by ROMULv improves the soil C stock estimate over Yasso07 model that is presently used by greenhouse gas (GHG) inventories of several countries. The Yasso07 and ROMULv models differed in their time steps (annually versus daily), determination of the litter quality (litter solubility versus nitrogen content and litter source) and complexity of drivers (ROMULv including the impact of nitrogen and soil water holding capacity to decomposition). Specifically with these models we tested:

1. Whether the litter quantity, species specific litter quality and weather data are enough to estimate spatial trends of carbon stocks in the upland soils of Finland. We hypothesise that by accounting for soil water holding capacity, ROMULv would outperform, (i) ROMULv with constant soil water holding capacity and (ii) Yasso07 model with different parametrisations (Yasso07 excludes soil properties entirely).
2. Weather improving the estimation of understory litter input would positively affect accuracy of predicted soil carbon stocks.

We use Yasso07 and ROMULv soil models to estimate steady-state carbon stocks for upland soils in Finland on a spatial 10×10 km^2 grid. We ran Yasso07 model with parameters based on Scandinavian data (Rantakari et al. 2012) and also with parameters based on global data (Tuomi et al. 2011). The parameterisation for the ROMULv model was the same as in the original ROMUL model (Chertov et al. 2001), except for decomposition rate functions depending on soil water content derived from Linkosalo et al. (2013). Yasso07 and ROMULv models run with identically estimated litter quantity, quality and climate data. In addition, the ROMULv model was tested with both constant soil water holding capacity as well as variable water holding capacity based on digital soil maps of Lilja and Nevalainen (2006). Furthermore, we developed new models for the understorey litter input and apply them alongside soil carbon models for improved estimates of spatial variation of litter inputs. Simulated soil carbon stocks are evaluated against measured soil carbon stocks.

2 Material and methods

Soil carbon simulations were performed for 10 × 10km^2 grid across Finland. This grid is used for meteorological data prediction (Venäläinen et al. 2005). Litter input was estimated for the same grid. From the grid, only locations that were on upland soils and on forest, according to Food and Agriculture Organization of the United Nations (FAO) forest definitions were chosen. This classification is based on Multisource National Forest Inventory products, which combine digital maps (including e.g. land-use and peatlands), forest inventory data and Landsat images (Tomppo et al. 2008).

2.1 Tree biomass

Firstly, stem volume maps by tree species from the National Forest Inventory 9 (NFI9, 1996-2003) were used, according to Tomppo et al. (2011), to account for large-scale variation of stem volume across Finland. These variations are primarily driven by soil properties, climate, site productivity, forest management techniques and tree species distribution.

Secondly, biomass expansion factors (BEFs, Mg/m^3) were estimated for main tree species groups, namely: Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and for broadleaved species (mainly *Betula* sp.). These BEFs were estimated for each biomass component (foliage, branches, bark, stemwood, stump and woody roots). Biomasses were estimated for sample trees in NFI10 based biomass models by Repola (2008, 2009); thereafter, mean BEFs were estimated at a cluster level (a cluster is formed of 10 to 15 field plots) by dividing the sum of given biomass components by the estimated sum of stem volumes. Biomass estimates for trees were based on biomass models, where diameter at breast height, tree height, crown height, increment of five years and bark thickness are used as predictors. To upscale BEFs across Finland, we applied collocated co-kriging (Bivand et al. 2008) by species group, to account for large-scale spatial correlation and co-variation of tree allometry. We used the *gstat* (Pebesma 2004) package of R (R Core Team 2014) for estimation. For Scots pine and Norway spruce we removed linear trends of latitude and longitude (using uniform coordinate system of Finland, YKJ), while for deciduous trees only trends of latitude were removed. For all species groups and components we assumed spherical variogram functions. For the details of the used biomass models see Appendix 7c by Statistics Finland (2014). Biomass components for each grid point were obtained by multiplying stem volume maps by species with component species-specific BEF estimates that were estimated via co-kriging for the same grid.

Biomass of harvest residues and natural mortality were estimated based on forest statistics and NFI data (Ylitalo 2013). From statistics, we attained an estimate of the stem volume of annual loggings and natural mortality by region (forestry centres) and these were subsequently converted to biomass with BEFs. These BEFs were based on a subset of permanent sample plots of NFI9 (1996–2003) and NFI10 (2004–2008). BEFs for logging were estimated separately from the subset of logged plots and these logging specific BEFs were used in the estimation of biomass of harvest residues. Furthermore, energy use of stumps and harvest residues were deducted from regional soil inputs, based on regional wood energy use (Ylitalo 2013). For biomass of natural mortality, BEFs were estimated based on data from those trees that died on permanent sample plots between measurements. Thereafter the volume of natural mortality was multiplied with corresponding BEFs. This procedure followed principles of Finnish greenhouse gas (GHG) inventory (Statistics Finland 2014).

Fine root biomass was estimated based on the work of Lehtonen et al. (2016). We selected a simple model formulation, where a natural logarithm of fine root mass was estimated as a function of the natural logarithm of stem volume. See Model 1 in Lehtonen et al. (2016) for details (study has 95 sites with fine root data, and model 1 has an adj-R^2 of 0.217). This model was used to approximate general fine root mass levels as a function of stem volume for each 10×10 km^2 grid point.

2.2 Understorey vegetation biomass

In order to estimate the litter input of understorey vegetation to soils, we developed models for vegetation biomass. The relationship between the visually estimated percentage cover of plant species including vascular plants, bryophytes and lichens (projected onto the forest floor using 30×30 cm^2 frames) and their living biomass was studied in 18 forest stands across Finland (Table 1). The plots are part of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP) intensive monitoring plot network (e.g. Merilä et al. 2014). Altogether 28 systematically selected biomass samples were taken once from each plot during the period 2002 to 2009. In total sample size was 504 of 0.3×0.3 m^2 vegetation plots having detailed biomass measurements by species. Vascular plants were divided into aboveground (shoots) and belowground (rhizomes and roots in organic layer) parts. The study was carried out at the time of maximum biomass and vegetation growth between the end of July and end of August. Half of the plots were located in the north (five in *Pinus sylvestris*, three in *Picea abies* and one in *Betula pubescens* dominated stands) and the other half were in the south (four in *Pinus sylvestris*, four in *Picea abies* and one in *Betula pendula* dominated stands). The site types of the plots ranged from poor to rich fertility level (Table 1).

In order to predict the vegetation biomass, we built linear mixed models based on the relative coverage of five functional plant groups (dwarf shrubs, grasses, herbs, bryophytes and lichens). The biomass of understorey vegetation was estimated using models that correlate vegetation coverage with measured biomass. These models were estimated for the five aforementioned main species groups and for their belowground parts, if applicable. These models were estimated separately for southern and northern Finland. We used a linear mixed model with plot-level random effects using the *lme* command in *nlme* package (Pinheiro et al. 2012) of the R environment for the estimation (R Core Team 2014).

Each model was weighted according to the land area of different site types in southern and northern Finland using the weights option in *lme*. This was done to ensure that the sample of understorey biomass plots did not underestimate the weight of the most common site types (those of medium fertility). The weighting was performed on land areas based on NFI11 data (Ylitalo 2013). Models were linearised by taking natural logarithms from biomass and coverage. For model parameters, bias correction and their uncertainties see Supplement (Table S1, Fig. S1 and Fig. S2).

To quantify the biomass of understorey vegetation we used species-specific coverage measurements of 2501 permanent sample plots from 1995 forest inventory data (Mäkipää and Heikkinen 2003). We applied collocated co-kriging methods to account for the correlation between species groups and thereafter we generalised measured understorey coverage on a 10 × 10 km^2 grid on upland soils across Finland (Bivand et al. 2008). The co-kriging method was similar to that of BEF estimation described above. First, we de-trended all species group coverage (shrubs, herbs and grasses, lichens and bryophytes) by linear trends of latitude and longitude (using uniform coordinate system of Finland, YKJ). After that we estimated variograms and cross-variograms and applied co-kriging methods to predict coverage for understorey coverage for Finland by *gstat* package of R (R Core Team 2014) (for R code, variograms and cross-variograms, see Supplement). For all species groups we assumed spherical variograms with common range of 100 km.

2.3 Litter input estimation

To estimate litter input from living biomass components to the soil, litter turnover rates were used (Table 2). For needles, we used the detailed 10 × 10 km^2 grid litter turnover rates reported by Tupek et al. (2015). For tree fine roots we assumed that the life span was 1.18 years for southern Finland and 2 years for northern Finland (Kleja et al. 2008, Leppälammi-Kujansuu et al. 2014). In order to interpolate fine root turnover rates for Finland we assumed a linear dependency for turnover rate and mean temperature sum (mean for 1981–2010). For areas with a temperature sum (5 C˚ threshold) higher than 1200 degrees a turnover rate of 85% was used and for areas where temperature sums less than 700 degrees a rate of 50% was used. Turnover rates were interpolated between 700 and 1200 degrees (see Supplement).

For branch and coarse roots litter, the constant turnover rates of the branches were used across Finland (Lehtonen et al. 2004, Muukkonen and Lehtonen 2004). For bark litter we assumed a constant ratio to stem biomass according to Viro (1955) and Mälkönen (1977). For fellings and natural mortality we assumed that all biomass was left to the site, excluding stems for wood used and harvesting residues for energy use. The quantity of wood use was based on regional forestry statistics (Ylitalo 2013).

The turnover rates of different functional plant groups were partly based on literature (Table 2) but we also estimated some rates from our own biomass samples of understorey vegetation described above. We calculated the proportion of the current-year growth out of the total living biomass of dwarf shrub shoots to estimate the turnover rates for aboveground plant parts. We used the average values of deciduous and evergreen dwarf shrubs. Most of the grasses growing in boreal forests (like

Deschampsia flexuosa) are perennial and we used the ratio between the living and dead biomass to estimate the turnover rate of those species. The aboveground parts of the most herb species (like *Maiathemum bifolium*) are annual, so we used 100% for their turnover rate. Furthermore, we used the number of annual growth segments in the green upper parts of the bryophytes to estimate their rate. We assumed that over a long time period the estimate for annual biomass growth corresponds to the amount of litter input to the soil from understorey vegetation.

Nitrogen content of all litter components was derived from Komarov et al. (2007), for details see Supplement.

2.4 Application of soil carbon models

Carbon stocks were estimated by running Yasso07 and ROMULv models into a steady state (i.e., a state where carbon input for the model equals carbon flux due to decomposition). For a dynamic model a steady state is a state to which model aims with given inputs. Here model inputs were: average climatic conditions (1961–2012) and litter inputs for each grid point, depending on dominant tree species and understorey vegetation coverage plus regional estimates of litter from harvestings and natural mortality (sc. forestry centres). If we assume that this average level of inputs and climate has remained steady over centuries, then our soils should approach steady state conditions. Litter inputs were given to these models as 10×10 km^2 grid points and weather data of that given grid point was then used for model input.

When evaluating model results for Yasso07, fresh woody litter and recently dead wood litter were excluded from model state variables, while all non-woody material and humus boxes (including more heavily decomposed material from fine-woody- and coarse-woody litter) were accounted as soil carbon stock. This separation was done as Yasso07 slows down decomposition of logs of high diameter, which increases soil steady state carbon stock estimates. Data from Biosoil does not include dead wood masses in soil carbon stocks. For ROMULv we included all model state variables to the comparison, noting that log size does not affect decomposition.

2.4.1 Climate data

Daily weather data for steady state simulations are available as kriging estimates since 1961 at a 10 × 10 km^2 resolution across Finland (Venäläinen et al. 2005). Weather data for the grid points on upland soils and on forested land, according to multisource NFI, were included (Tomppo et al. 2008).

Daily weather predictions for a 10×10 km^2 grid were aggregated for the Yasso07 model from 1961 to 2012. The average temperature, temperature amplitude and precipitation of each grid cell were provided to Yasso07 to estimate the impact of climate on soil carbon stock steady states. The ROMULv model was driven by mean daily temperature and precipitation for each grid cell.

2.4.2 Yasso07

The Yasso07 soil carbon model (Tuomi et al. 2011) is driven by litter quantity, litter quality and weather (temperature and precipitation). This model is widely used in the greenhouse gas inventories of European countries (e.g., Finland, Norway and Switzerland). This model has been also successfully coupled with climate-carbon cycle model ECHAM5/JSBACH (Thum et al. 2011).

The Yasso07 is a simple dynamic model with fluxes and state variables. The model has five compartments: acid, water, ethanol, non-soluble and humus boxes. Division of the litter input according to the litter solubility was species specific and followed that of Finnish GHG inventory, based on the appendix of Yasso07 manual by Liski et al (2009). Organic matter flows between these boxes and to atmosphere variably according to weather conditions (Fig. 1). The model builds on the assumption that organic matter solubility defines litter quality, while decomposition rates while fluxes are estimated numerically, without *a priori* assumptions. The model was calibrated using a large database of litter and wood decomposition measurements, and measurements of age chronosequences of soil carbon stocks (Liski et al. 2005, Liski et al. 1998, Rantakari et al. 2012, Tuomi et al. 2011). The Yasso07 soil carbon model parameter values were estimated with Markov chain Monte Carlo (MCMC) methods for which the source code is publicly available through the model website (www.syke.fi) (Tuomi et al. 2011). Here, we used the Yasso07 model with Scandinavian parameters (Rantakari et al. 2012) and with global parameters, these being a preliminary version from Tuomi et al., (2011) parameters (practically identical). Yasso07 was run with total litter input (from trees and understorey vegetation) and also with litter excluding that of understorey vegetation. The model was applied with annual time-steps. Model has been calibrated with litter input estimates and soil carbon measurements down to 1 meter soil depth. See the Supplement for more details of Yasso07.

2.4.3 ROMULv

ROMUL is a soil organic matter decomposition model developed by Chertov et al., (2001). It describes the flux of organic matter through the decomposition process, separated in cohorts of different litter origins: leaves, shoots, trunks, coarse roots, fine roots and ground vegetation. Litter from above ground (leaves, shoots and stems) falls onto the forest floor, whereas the root litter decomposes in the mineral soil layer. In the final stages, all decomposing matter ends up in a common storage of semi-stable humus residing in the mineral soil layer (Fig. 1). Decomposition rates of each cohort depend on the nitrogen and ash content of the specific litter type and for all cohorts the soil temperature and water content modify the decomposition rate. Here we used species specific nitrogen ratios for different litter fractions; these ratios were same across the country in given fraction of given species.

In this paper we utilised a version of the ROMUL model, where we adopt decomposition rate functions depending on soil water content and the model for soil water dynamics as described in Linkosalo et al. (2013). We call this version of the model ROMULv (where the “v” refers to decomposition rates based on volumetric soil water measures). The soil water holding capacity data was obtained from digital soil maps of Finland (Lilja and Nevalainen 2006). Total soil water holding capacity data was extracted to a 10 × 10 km^2 grid, when available. To evaluate the impact of soil water holding capacity variability, we also repeated the ROMULv simulation assuming a constant soil water holding capacity for the whole simulation area. As the ROMULv model segregates the organic and mineral soil layers, we assumed that 20% of the total soil water holding capacity was in the organic layer and 80% in mineral soil layer. See the Supplement for more details of ROMULv, the source code and parameter estimates.

We applied the ROMULv model using daily time-steps of the environmental variables impacting the decomposition. The estimated annual litter input was evenly distributed for each day of year. The ROMULv model explicitly simulates the flux of nitrogen through the decomposition process and therefore produces estimates for mineralised N in addition to the soil organic matter and N storages and CO_2 release from the soil. All model parameters, except the decomposition rate, which is dependent on soil water content, were taken from the Chertov et al. (2001) paper. Although ROMULv model does not explicitly define depth of soil layers, but the soil water layer of 1 meter has been assumed implicitly when gravimetric water content is estimated. Therefore we assume that decomposition occurs in that same layer of 1 meter.

2.4.4Biosoil – soil carbon measurements

The Biosoil dataset resulted from EU-funded Forest Focus monitoring program and includes measurements of soil carbon and various other ecosystem variables from 2006. Data consists of 521 sample plots located across Finland. These plots were established as a subset of 3009 permanent sample plots from 1985–86 (see Mäkipää and Heikkinen 2003).

Biosoil sample plots have radii of 11.28 m (400 m^2). Trees and understorey vegetation coverage were measured. Soil carbon samples were taken separately from the litter and humus layers and mineral soil layers at 0–10, 11–20, 21–40 and 41–80 cm depth. In total 10 or 20 subsamples were taken from the organic layers with a cylinder (diameter = 60 mm) and 10 tube (diameter = 23 mm). Alternatviely, 5 spade subsamples were taken from the 0–10 cm mineral soil layer, a further 5 spade subsamples were taken from the layers 11–20 and 21–40 cm and one subsample from the layer 41–80 cm. Viro (1952) rod penetration method was used to quantify the volume of stones and boulders in the surface soil layer. Several properties were analysed from soil samples in the laboratory: soil texture, cation exchange capacity (CEC), base saturation (BS), pH, organic carbon and total nitrogen concentrations. Aqua regia extractable P, Ca, K, Mg, Mn, Pb, Na, Ni, Fe and S were also measured (Derome et al. 2007). Soil carbon stocks were estimated down to 1 m depth by extrapolation of 40–80 cm measurements for the 80–100 cm layer.

Measured soil carbon stocks were grouped into different latitudinal bands forming a gradient in Finland to which we compared soil carbon estimates from Yasso07 and ROMULv models against measured data. Comparisons were made with two different widths of latitude bands: firstly we used bands of 100 km and thereafter bands of 20 km. Bands were included in the analysis when there were four or more Biosoil observations in a band. We also identified those Biosoil plots that had been under the Litorina Sea 7000–8000 BP (Miettinen 2004, Sohlenius et al. 1996) using map products produced by the

Geological Survey of Finland (Eronen 1974). We used root mean square error (RMSE) to rank these models applications due to its ability to take into account both accuracy and precision when comparing model estimates and data.

We also studied differences between mean stand and soil properties for two regions in southern Finland (Region 1 with a latitude below 60˚46’, and Region 2 with a latitude between 60˚46’ and 62˚34’).

3 Results

3.1. Performance of the soil carbon models

The soil carbon stock estimates by Yasso07 model using global parameterisation (Tuomi et al. 2011) were systematically larger than measured data across Finland, whereas those obtained with Scandinavian parameterisation (Rantakari et al. 2012) were in the same magnitude as the Biosoil data (Fig. 2A and B). In addition to the realistic level of soil carbon stock, the model that was based on parameterisation with the Scandinavian data also reproduced decreasing soil carbon stock trend from south to north, as displayed in the Biosoil data. Excluding understorey litter from the model input improved the match between Yasso07 soil carbon stocks simulated using global parameters and Biosoil data, whereas for Yasso07 using Scandinavian parameters, the same exclusion resulted in underestimation of soil carbon stocks, especially in northern Finland (Fig. 2C and D). The ROMULv model predictions generally agreed with Biosoil data when soil water holding capacity was taken into account. The inclusion of soil water holding capacity in ROMULv introduced high variation in soil carbon stocks between dry and moist grid points in southern Finland (Fig. 2E). When the ROMULv model was driven with constant soil water holding capacity, it was unable to reproduce decreasing soil carbon stocks across Finland and the model underestimated carbon stocks, especially in the south (Fig. 2E and F). Large deviations between the data and the model estimates were also seen for the largest Biosoil soil carbon stocks of the southernmost plots (Fig 2).

The ROMULv model using the soil water holding capacity was the only model able to reproduce the increase in measured soil carbon stocks at the southernmost plots. All other models predicted a substantial decrease in the soil carbon stocks for southern region, which was not observed in measurements (Fig. 4). Soil properties of southernmost plots (Region 1 (R1) with a latitude below 60˚46’) were different compared to soil properties of forests further north (Region 2 (R2) with a latitude between 60˚46’ and 62˚34’). The southern coast had lower silt content and higher sand content, but simultaneously higher carbon stocks in the organic layer than the other region (Table 3). Also understorey vegetation differed between these regions and the southern coast had lower *sphagnum* species and herbs species coverage, indicating that soils there were drier. We also tested site type distributions between R1 and R2 but the p-value from a chi-square test was > 0.4, indicating that site fertilities did not differ. This is also supported by the measured C:N ratios, which did not differ between these regions (Table 3). These southern sites were also younger and 29% of plots were under the Littorina Sea ~7000–8000 years BP, while the share of younger soils was only 6% for the slightly more northern region.

We found that Yasso07 model applications excluding litter input from understorey vegetation had the best agreement with the observed latitudinal gradient when evaluating with one-to-one plots (Fig. 3). The modelled and measured soil carbon stock fits were poor for the Yasso07 application with global parameters, including the understorey vegetation litter input and for the ROMULv application not using soil water holding capacity data. These model applications showed no correlation with measurements and also failed to map the south to north soil carbon stock decrease (Fig. 3).The lowest RMSE was obtained with the ROMULv model applied with soil water holding capacity data indicating the best performance among these model applications.

3.2 Improved understorey litter input

The amount of litterfall from trees and understorey vegetation showed opposite trends with latitude. Total litter input of trees and other vegetation in southern Finland was four times higher than that in northern Finland following the temperature gradient (Fig. 4). Though, the understorey vegetation at northern sites displayed much higher litter inputs than those in southern Finland. According to our results, fall of understorey litter in eastern and northern Lapland was equal to that from trees (Fig. 4). We estimated mean litterfall from understorey vegetation to approximately equate to 0.0473 kg m^{-2} and 0.0863 kg m^{-2} of carbon for southern and northern Finland, respectively. Our estimate of mean litter input from trees was 0.1962 kg m^{-2} and 0.0903 kg m^{-2} of carbon for southern and northern Finland, respectively.

4 Discussion

We tested whether litter quality, litter quantity and mean climate are sufficient for estimating spatial trends in soil carbon stocks and if soil texture with low water holding capacity introduces water limitation to decomposition. While testing our hypothesis we found that Yasso07 and ROMULv models were able to predict carbon stocks of the same magnitude as that of measurements for Finland; however, these models experienced more challenges when their performance was evaluated for smaller regions, like the southern coast of Finland.

We also found that litter input from understorey vegetation is equal of that from trees in northern Finland. This emphasises the large role of understorey vegetation in compensating trees in an ecosystem carbon cycle, especially under light and nutrient limited growth conditions. Total litter input varied from 0.4 to 0.01 kg m^{-2} of carbon from southern to northern Finland. These values agree with both, net primary production (NPP) estimates for trees that vary between 0.2 and 0.5 kg m^{-2} of carbon for southern Finland by Härkönen et al. (2010) and with measured litterfall values that range from 0.23 to 0.3 kg m^{-2} for Hyytiälä eddy covariance site (Ilvesniemi et al. 2009).

To sum up, litter input from understorey vegetation has to be quantified properly when soil carbon models are parameterised. This means that model developers should have unbiased estimates of total carbon inputs into the soil system when they use litter estimates and soil carbon stocks to calibrate parameters that affect long term carbon accumulation. The results of our biomass models for the understorey agreed with previous estimates for southern Finland but for northern Finland our estimates were substantially larger. Yasso07 was parameterised using understorey litter inputs ranging from 40–60 g carbon m^{-2} a^{-1} and therefore Yasso07, with updated understorey litter estimates, overestimated the level of soil carbon stocks. Our data for understorey vegetation biomass was mostly from stands that were over 60 years old and therefore more data for younger sites are needed. Furthermore, the litter input of belowground understorey vegetation was uncertain due to limited data on the life span of roots. More research is therefore needed to confirm the high contribution of dwarf shrub vegetation to total belowground litter input.

When evaluating modelled and measured soil carbon stocks against northern latitude we could see that two out of six simulations failed to map measured soil carbon stock decreases towards the north (Fig 4). Five model simulations showed that southern coast had less carbon than the next region further north, while the Biosoil data showed the opposite. Only the ROMULv model, using soil water holding capacity data from Lilja and Nevalainen (2006) was able to estimate the largest soil carbon stocks for southern Finland, similar to Biosoil measurements (Fig. 2). This indicated that litter quality, litter quantity and climate data are not sufficient when estimating spatial trends of soil carbon stocks. When we evaluated Biosoil data for these regions, the southern sites were better drained and drier that those in North. Better drainage was indicated by higher sand content, significantly lower silt content and significantly lower *Sphagnum* and herb vegetation coverage (Table 3). We also found out that the southern coast experiences a 1.3 C° higher mean annual temperature than the next region to the north. Therefore, the organic layer was larger for southern coast likely due to limited decomposition during dry spells (Table 3). This result indicated that the quantity of precipitation alone was not a sufficient modifier for decomposition but when complemented with soil water holding capacity average latitudinal results improved. This finding supports the use of models including soil texture and water holding capacity.

Our results support also earlier findings, where the time step of the simulation plays a critical role; running models with monthly and annual time steps excludes extreme conditions and may produce biased estimates of carbon stocks simply due to fact that non-linear models are run with mean conditions (Dalsgaard et al. 2016, Rantakari et al. 2012). This is especially critical with soil moisture, which has a bell shaped relation to decomposition (Sierra et al. 2015, Skopp et al. 1990). Compared to daily time steps of ROMUL, model simulations with longer time steps (e.g., a year as in Yasso07) exclude both extreme dry and extreme moist conditions, leading to underestimation of steady states soil carbon stocks. On the other hand, reduction of the decomposition rate during limited and excess water conditions are not well known. Sierra et al. (2015) compared the effect of moisture on decomposition in different models with the largest variability for dry and saturated conditions. They showed that a moisture index of 0.2 can have a decomposition modifier between 0.2 and 1 and similarly with a moisture index of 1 this modifier can be anywhere between 0 and 1, depending on the model. These large discrepancies indicate differences between soil properties of sites used for model calibration and between conceptualisations of soil moisture.

The Yasso07 and ROMULv model simulations with litter input and climate data alone were not enough to reproduce the observed soil carbon stocks. Model application without soil moisture impacts on decomposition failed under conditions where soil drainage played a significant role in limiting decomposition. The use of water holding capacity was critical for accurate soil carbon stock estimation by the ROMULv model, while Yasso07 performed best when the variation in litter input correlated with that of the observed soil carbon stocks (Fig. 3). The fact that Yasso07 soil carbon stocks (Tuomi et al. 2011) were more accurate when litter input of understory vegetation was omitted from simulations suggests that the model calibration did not account for the whole range of understory litter input. This implies that in future, improved estimates for understorey litter input are needed when Yasso07 or similar models will be parametrised for boreal conditions. In order to improve model performance, shorter time steps complemented with more detailed topography and soil properties are needed to map the impact of extreme events to soil carbon decomposition (e.g., droughts and water logging conditions). However, three model simulations out of six produced relatively accurate estimates of soil carbon stocks compared to the measurement means of smaller regions, having RMSE less than 1.1 for soil carbon stocks (Fig. 3). This suggests that improved calibration with updated understorey litter and accounting for the soil properties as with ROMULv (using data on water holding capacity) produces model estimates that agree regionally with data.

Our simulations and measurements show that models using only litter quality, litter quantity and weather data underestimate soil carbon stock in regions like southern Finland and this underestimation is due to omission of the impact of droughts to the decomposition of organic layers. Thus, we conclude that GHG inventory methods and soil modules of Earth system models need to be improved by incorporating the impact of soil texture and soil moisture to decomposition. This is a prerequisite for unbiased soil carbon stock and stock change estimates.

Code availability

The fortran code of the ROMULv is given in the supplement, while fortran code for Yasso07 is available through website [http://code.google.com/p/yasso07ui/], for details see Supplement.

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Table 1. Site description of ICP Forests Level II plots studied for understorey vegetation biomass.

Plot no	Area	Region	North coord.	East coord.	Tree species	Site type	Forest type	Stand age	Basal area m^2	DF	GR	HE	BR	LI	Year of sampling	n above/below
1	Sevettijärvi	1	7723	3573	1	5	UVET	210	13.52	x	-	-	x	x	2009	28/12
2	Pallasjärvi	1	7543	3377	1	4	EMT	100	17.85	x	-	-	x	x	2003	28/28
3	Pallasjärvi	1	7549	3384	2	3	HMT	150	15.42	x	x	x	x	-	2003	28/28
4	Sodankylä	1	7472	3485	1	4	EMT	80	19.66	x	-	-	x	x	2003	28/28
5	Kivalo	1	7360	3484	2	3	HMT	80	17.95	x	x	-	x	-	2002	28/28
6	Kivalo	1	7364	3488	1	4	EMT	65	18.94	x	-	-	x	x	2002	28/28
32	Kivalo	1	7371	3486	3	3	HMT	58	14.39	a	a	a	x	-	2009	28/0
21	Oulanka	1	7359	3612	2	3	HMT	180	21.03	a	a	a	x	-	2009	28/0
20	Lieksa	2	7012	3687	1	4	EVT	140	22.27	a	-	a	x	-	2009	28/0
10	Juupajoki	2	6866	3353	1	4	VT	90	23.55	x	x	x	x	-	2002	28/28
11	Juupajoki	2	6863	3359	2	2	OMT	90	30.4	x	x	x	x	-	2002	28/28
12	Tammela	2	6730	3325	2	3	MT	70	33.08	x	x	x	x	-	2002	28/28
13	Tammela	2	6727	3330	1	4	VT	70	29.27	x	x	x	x	-	2002	28/28
16	Punkaharju	2	6854	3627	1	4	VT	90	31.95	x	-	x	x	-	2002	28/28
17	Punkaharju	2	6858	3622	2	2	OMT	80	30.76	-	-	x	x	-	2002	28/28
33	Punkaharju	2	6862	3622	3	1	OMaT	27	16.13	-	a	a	-	-	2009	28/0
34	Luumäki	2	6763	3515	1	5	CT	60	13.55	x	-	-	x	x	2009	28/12
35	Luumäki	2	6756	3513	2	3	MT	60	28.21	x	x	x	x	-	2009	28/12

Region (1 = northern Finland, 2 = southern Finland); tree species (1 = Scots pine, 2 = Norway spruce and 3 = deciduous trees); site type (1–5, from rich to poor fertility level); forest site types (abbreviations explained in Salemaa et al. (2008), Table 1); plant species groups in biomass samples: DF = dwarf shrubs, GR = grasses, HE = herbs, BR = bryophytes and LI = lichens. x = biomass sample includes both aboveground and belowground (in organic soil layer) part of vegetation, a = sample includes only aboveground vegetation, - = plant group does not grow in the plot. n = number of samples (each sized 30 x 30 cm^2) for aboveground and belowground biomass.

Table 2. Litter turnover rates for tree and understorey biomass by component, species and region.

Biomass	Species	Region	Value [%]	Reference
Leaves	Scots pine		27% [18-34%]	Tupek et al., (2015)
Leaves	Norway spruce		13% [9-15%]	Tupek et al., (2015)
Leaves	Broadleaved		79%	Tupek et al., (2015)
Branches	Scots pine		2%	Lehtonen et al. (2004)
Branches	Norway spruce		1.25%	Muukkonen and Lehtonen (2004)
Branches	Broadleaved		1.35%	Lehtonen et al. (2004)
Bark	Scots pine		0.3%	(Mälkönen 1977, Viro 1955)
Bark	Norway spruce	-	-	(Mälkönen 1977, Viro 1955)
Bark	Broadleaved		0.01%	(Mälkönen 1977, Viro 1955)
Coarse roots	Scots pine		2%	Lehtonen et al. (2004)
Coarse roots	Norway spruce		1.25%	Muukkonen and Lehtonen (2004)
Coarse roots	Broadleaved		1.35%	Lehtonen et al. (2004)
Fine roots	Scots pine	South	85%	Kleja et al., (2008)
Fine roots	Norway spruce	South	85%	Kleja et al., (2008)
Fine roots	Broadleaved	South	85%	Kleja et al., (2008)
Fine roots	Scots pine	North	50%	Leppälammi-Kujansuu et al., (2014)
Fine roots	Norway spruce	North	50%	Leppälammi-Kujansuu et al., (2014)
Fine roots	Broadleaved	North	50%	Leppälammi-Kujansuu et al., (2014)
Aboveground	Dwarf shrubs	-	37%	This study
Belowground	Dwarf shrubs	-	8%	This study& Helmisaari et al. (2015)
Aboveground	Grasses	-	33%	This study
Belowground	Grasses	-	59%	Leppälammi-Kujansuu et al., (2014)
Aboveground	Herbs	-	100%	
Belowground	Herbs	-	59%	This study & Leppälammi-Kujansuu et al., (2014)
Aboveground	Bryophytes	-	42%	This study
Aboveground	Lichen	-	10%	Kumpula et al., (2000)

Table 3. Mean soil and forest stand properties for R1 and R2 and 1.96 times their standard error of mean (SEM). R1 is south from 60˚46’, while R2 lies between 60˚46’ and 62˚34’northern latitude. P-values based on two sided t-test, where group variances are assumed to be different variables where p-value < 0.05 are in bold. Sample sizes were 31 and 127 plots, for southern (R1) and northern (R2) areas, respectively. For mean temperature and precipitation sample sizes were more than 150 based on Finnish Meteorological Institute (FMI) weather grid (Venäläinen et al. 2005).

	Sand [%]	**Silt [%]**	Clay [%]	BS O [%]	BS M [%]	CEC O [cmol(+)/ kg]	CEC M [cmol(+)/ kg]	pH (H_2O)	C:N O	C:N M	**Sphagnum [%]**	Lichen [%]	**Herb [%]**	G [m^2]	Decid [%]	Spruce [%]	**Lito [%]**
R1 mean	64.92	**30.08**	4.98	67.2	23.26	32.23	5.27	4.23	26.41	23.11	**0.3**	0.86	**4.43**	23.45	15.55	39.81	**29**
R1 sem	7.31	**5.39**	2.64	6.08	5.5	3.22	0.54	0.12	1.25	1.57	**0.53**	1.05	**1.83**	3.29	6.87	12.01	**16**
R2 mean	57.76	**37.09**	5.15	68.8	27.72	29.06	4.91	4.17	25.13	21.6	**1.51**	0.45	**8.56**	23.9	19.28	37.1	**6**
R2 sem	3.34	**2.55**	1.2	2.29	3.28	0.87	0.43	0.05	1.56	0.79	**0.98**	0.26	**2.18**	1.43	4.58	6.09	**4**
p-value (t.test)	0.09	**0.03**	0.91	0.63	0.18	0.07	0.31	0.4	0.21	0.1	**0.04**	0.48	**0.01**	0.81	0.38	0.69	**0.01**

	T mean [C]	**Prec [mm]**	**extrCd [mg/kg]**	**extrPb [mg/kg]**	extrK [mg/kg]	extrP [mg/kg]	extrNa [mg/kg]	extrNi [mg/kg]	extrCa [mg/kg]	extrMg [mg/kg]	extrFe [mg/kg]	extrS [mg/kg]	extrMn [mg/kg]	TWI	**Altitude [dm]**	**SOC O [Mg ha^{-1}]**	SOC M [Mg ha^{-1}]
R1 mean	**4.91**	**580.71**	**0.48**	**47.88**	1149.16	943.61	139.71	10.8	4638.39	992.52	5157.74	1435.39	459.47	6.97	**588**	**25.82**	31.65
R1 sem	**0.09**	**6.25**	**0.05**	**3.62**	138.59	80.16	14.87	1.03	1044.39	329.89	984.63	85.95	167.12	1.83	**124**	**5**	7.15
R2 mean	**3.62**	**545.66**	**0.38**	**36.02**	1225.03	940.32	131.19	11.07	4058.02	1063.51	4675.6	1380.96	537.84	8.79	**1119**	**17.46**	35.23
R2 sem	**0.05**	**2.28**	**0.03**	**5.77**	85.23	38.99	11.11	1.05	256.21	159.48	643.98	55.04	148.54	1.14	**55**	**1.57**	3.31
p-value (t.test)	**0**	**0**	**0**	**0**	0.37	0.94	0.38	0.73	0.3	0.71	0.43	0.31	0.5	0.1	**0**	**0**	0.38

Here sand, silt and clay content are given as a percentage. Base saturation (BS). cation exchange capacity (CEC) and C:N ratios are given separately for organic layer (O) and for mineral soil layer (M). pH is measured in water. Abundance of ground vegetation given as percentage coverage. Basal area of trees (G) and relative shares of deciduous species and Norway spruce from basal area. Lito indicates the proportions of sites that were under the Littorina Sea 8000–7000 BP. Aqua regia extractable K, P, Na, Ni, Ca, Mg, Fe, S and Mn unit mg/kg. Topographical wetness index (TWI). Altitude of plots based on 10 m resolution map layer. Amount of carbon in organic and mineral soil horizon.

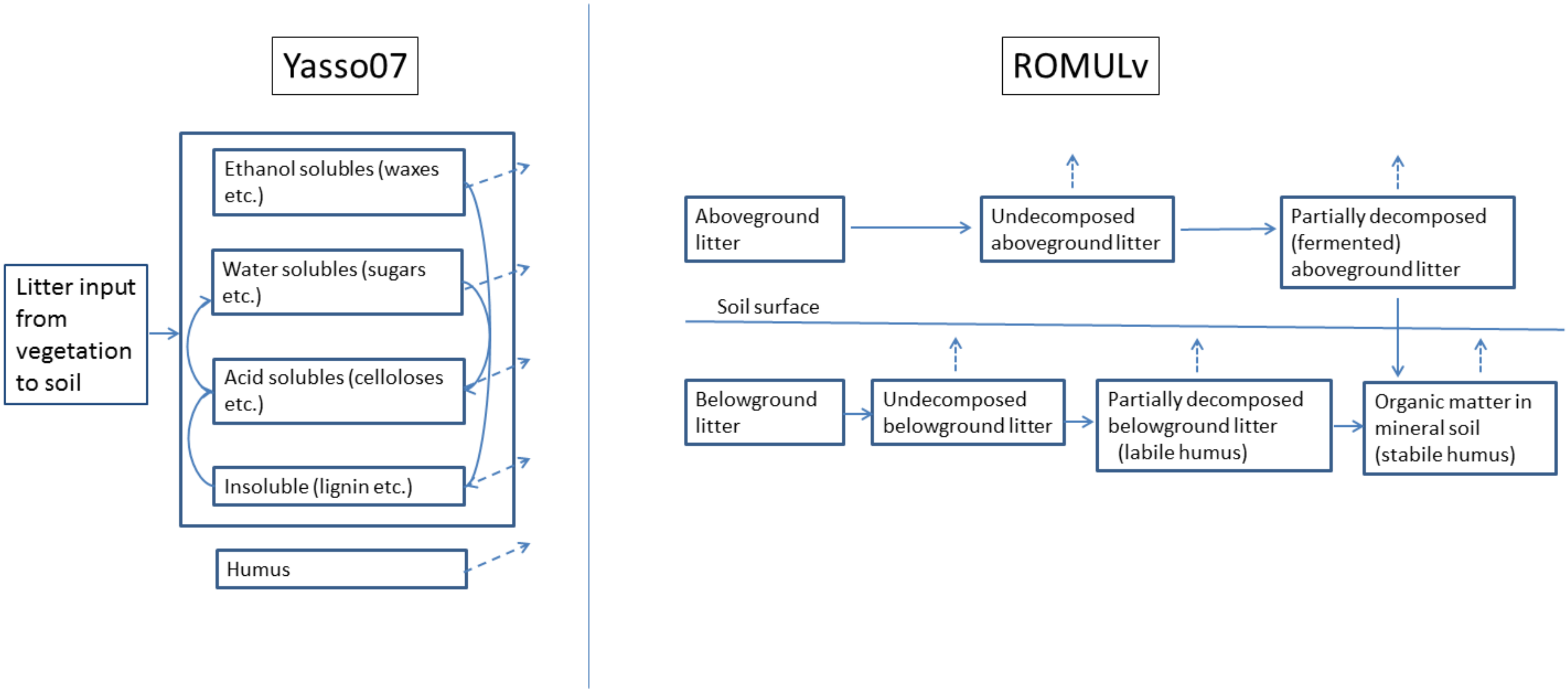

Figure 1: Schematic illustration of Yasso07 (left) and ROMULv (right) soil carbon models. Solid arrows indicate fluxes of organic matter, while dashed arrows indicate CO_2 fluxes to atmosphere.

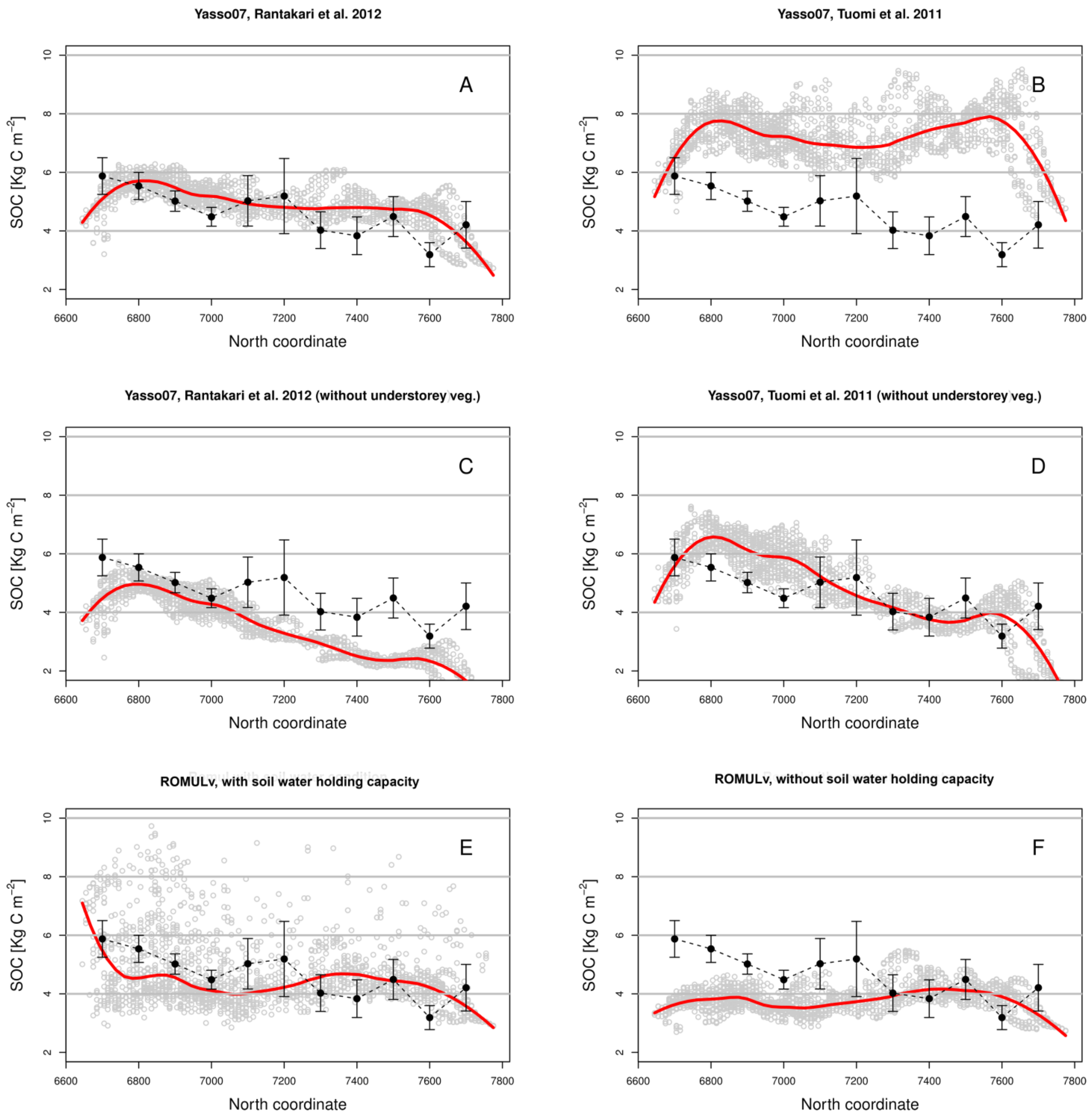

Figure 2. Latitudinal trends of measured and modelled soil carbon stocks across Finland. X-axis is the North coordinate according to Finnish YKJ system and Y-axis is the soil carbon stock Mg ha^{-1}. Grey dots are individual model estimates and red line is a 2nd order *loess* fit. Panel A is Yasso07 with Rantakari et al. (2012) parameters, while B is with Tuomi et al. (2011) parameters. C and D

are same as A and B, but without understorey litter input. E and F are with ROMULv model where E includes soil water holding capacity data and F is with constant soil water holding capacity. Black dots are means from Biosoil data for each latitude band and whiskers are 1.96 times standard error of the mean.

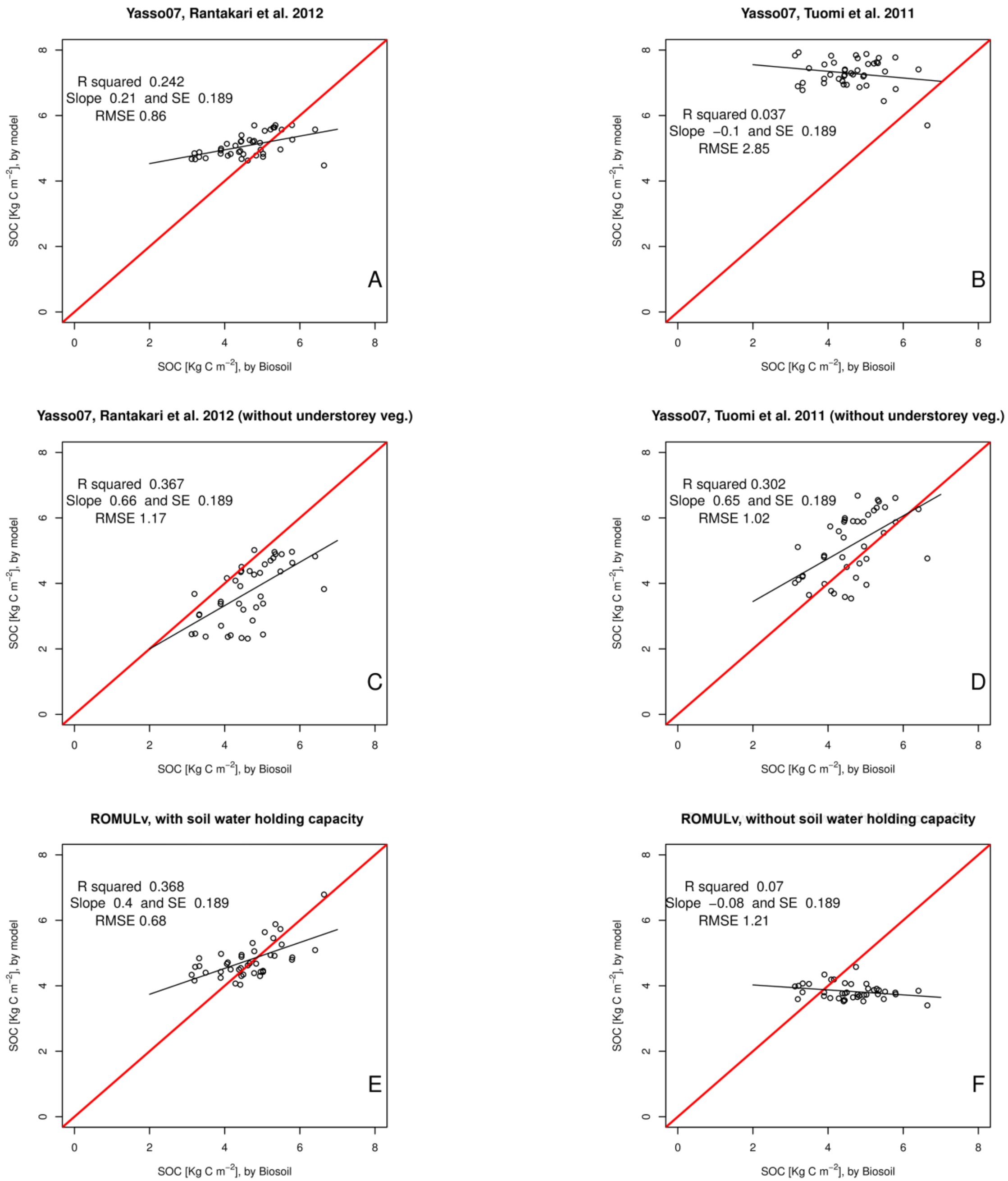

Figure 3. One-by-one plots for mean model estimates and mean Biosoil measurements of soil carbon stocks for 41 latitudinal bands across Finland. Panel A is Yasso07 with Rantakari et al. (2012) parameters, while B is with Tuomi et al. (2011) parameters. C and D are same as A and B but without understorey litter input. E and F are with ROMULv model where E is with soil water holding capacity data and F is with constant soil water holding capacity. R^2, slope of the regression and the slope standard error are reported. RMSE is based on the difference between model estimate and measurements.

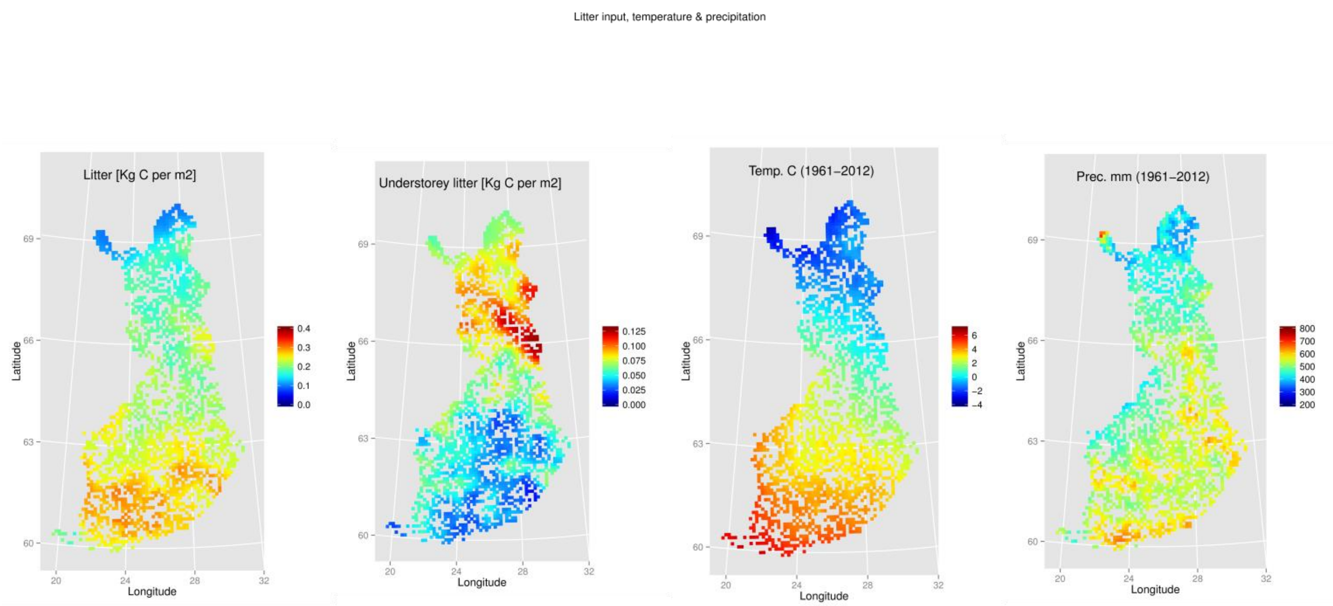

Figure 4. Maps for total litter input [Mg ha^{-1}], understorey litter input [Mg ha^{-1}], mean annual temperature [C°] and mean annual precipitation [mm].

Supplement to

Forest soil carbon stock estimates in a nationwide inventory: evaluating performance of the ROMULv and Yasso07 models in Finland

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1. Fineroot turnoverate modeling

Fineroot turnoverrates were based on Kleja et al. (2008) and to Leppälammi-Kujansuu et al. (2014). It was assumed that the turnoverrate of fineroots is 85% in Southern Finland in areas where temperature sum during the growing season (with 5 Cº treshold) is more than 1200. For Northern Finland we used turnoverate of 50% when temperature sum was less than 700. For sites where temperature sums were between 700 and 1200 we interpolated the turnoverrate with a simple linear regression,

$y = b_0 + b_1 \times x$, where

y is the turnoverrate and b_0 equals 0.0007, b_1 equals 0.001 and x is degree days that varies between 700 and 1200 degrees.

2. Estimation of understorey biomass

Here we provide parameter estimates for understorey models (Table S1) and figures for model fits (Figs. S1 & S2).

Table S1. Parameter estimates for understorey models by species groups and regions. Where β_0 is the intercept and β_1 is a slope of the fixed part of the model and bc is the bias correction. Var b_0, Cov $b_o b_1$ and Var b_1 originate from variance-covariance matrix of the fixed part of the model. Var pop lists unexplained variance and Var plt lists unexplained variance after plot as a random effect.

Group	Com.	Reg.	β_0	β_1	bc	Varβ_0	Covβ_o β_1	Varβ_1	Var Pop	Var Plt
Dwarf shrub	Ab	NF	3.62	0.948	0.135	0.115	-0.028	0.008	0.285	0.136
Dwarf shrub	Ab	SF	2.653	1.107	0.186	0.081	-0.015	0.005	0.45	0.16
Grass	Ab	-	2.75	0.918	0.292	0.129	-0.03	0.01	0.688	0.273
Herb	Ab	-	1.116	1.08	0.445	0.074	-0.018	0.008	0.832	0.572
Bryophytes	Ab	-	3.13	0.795	0.281	0.301	-0.072	0.018	0.633	0.306
Lichen	Ab	-	3.69	0.894	0.109	0.047	-0.012	0.005	0.27	0.175
Shrub	Bl	NF	6.278	0.45	0.161	0.086	-0.02	0.006	0.315	0.241
Shrub	Bl	SF	3.73	0.831	0.458	0.15	-0.035	0.011	1.06	0.867
Grass	Bl	NF	3.368	0.589	0.639	0.169	-0.039	0.017	1.423	0.859
Herb	Bl	SF	1.877	0.906	0.709	0.27	-0.067	0.03	1.195	0.898

Com. = compartment: Ab = aboveground, Bl = belowground
Reg. = region: NF = northern Finland, SF = southern Finland

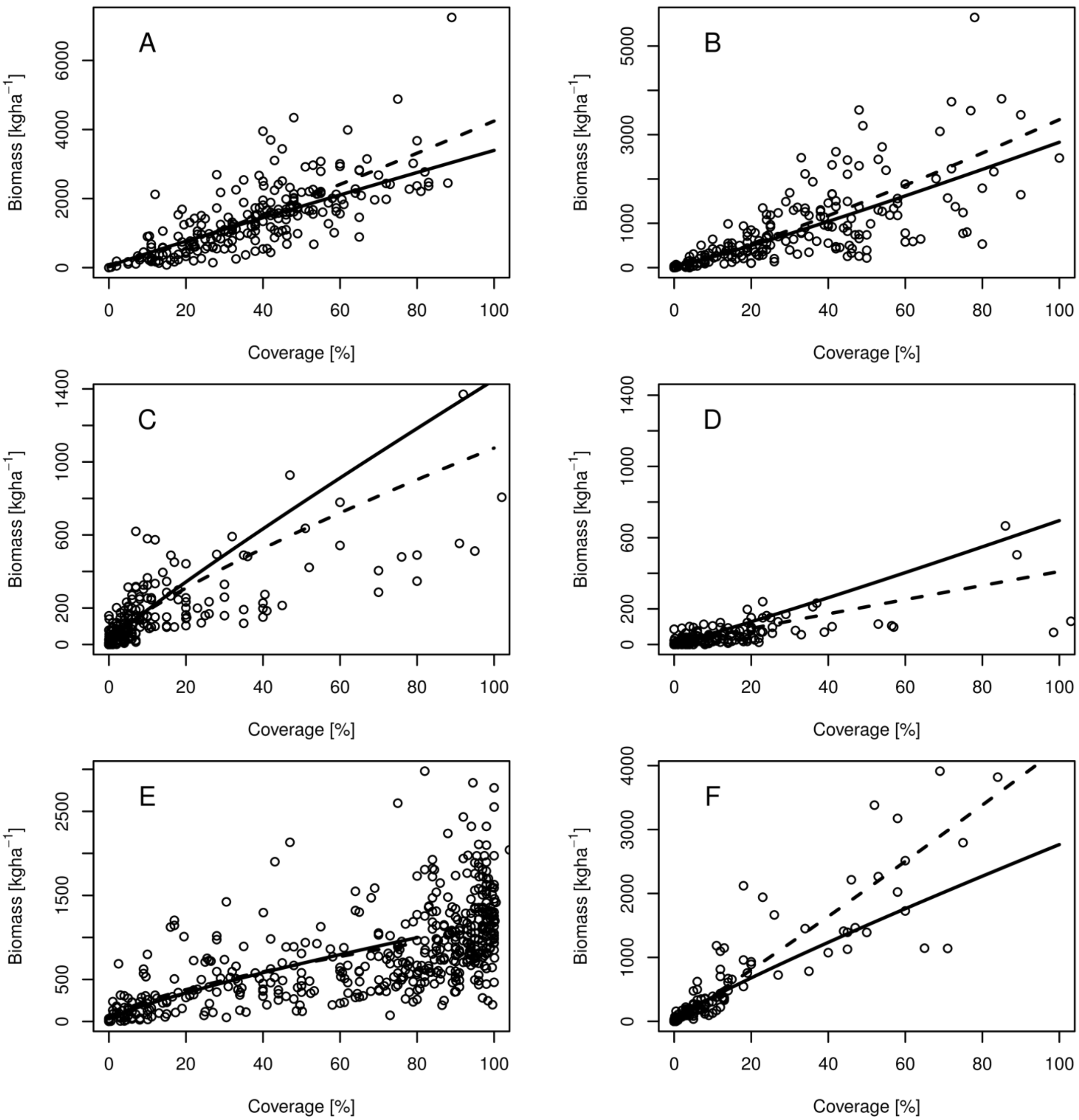

Figure S1: Models and data points for aboveground understorey biomass (A = Dwarf shrubs in northern Finland, B = Dwarf shrubs in southern Finland, C = Grasses, D = Herbs, E = Mosses and F = Lichen). Solid line based on modelling that takes into account site fertility distribution for Finland by weighting, while dashed line is the estimate without weights.

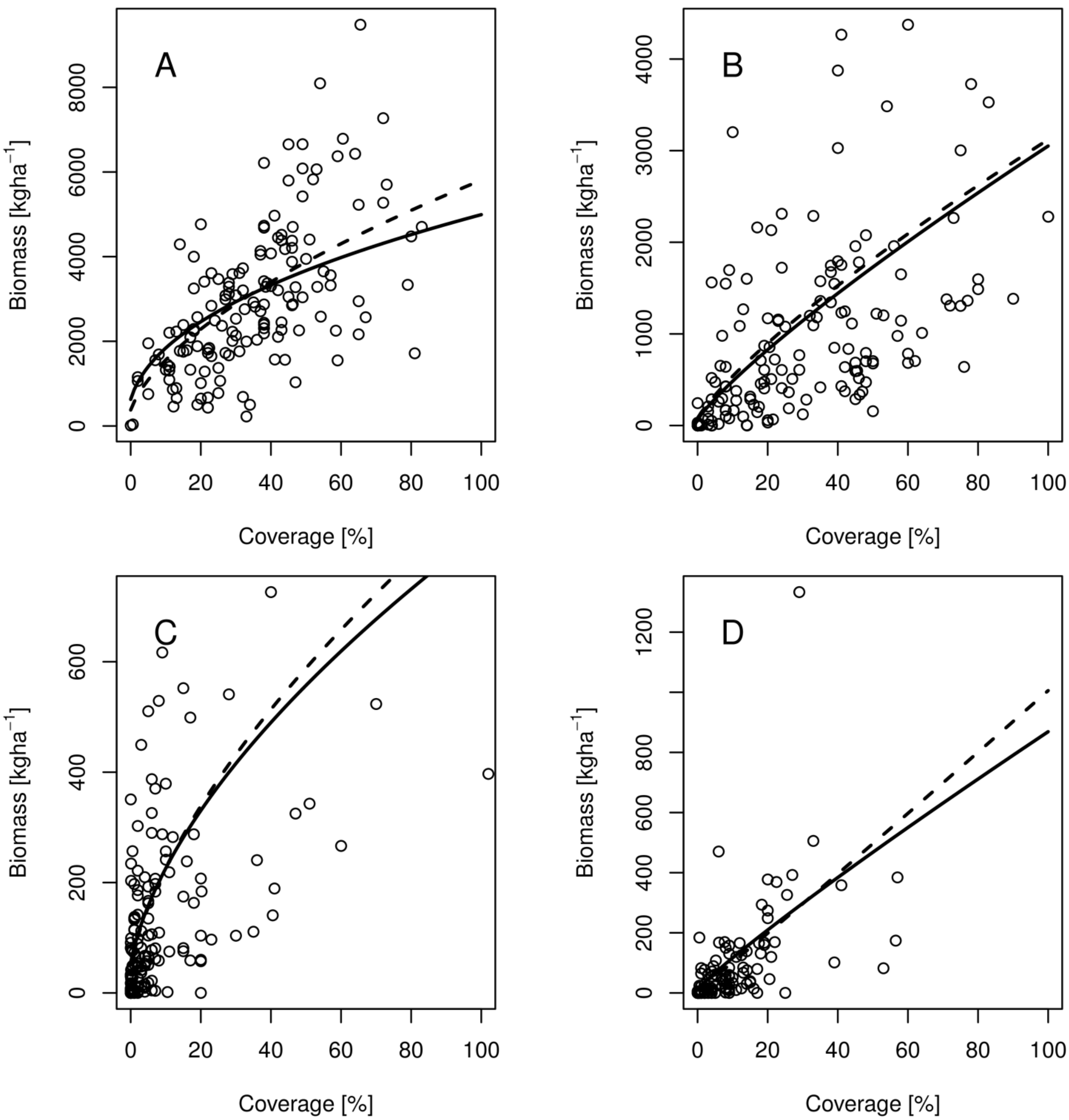

Figure S2. Models and data points for belowground understorey biomass (A = Dwarf shrubs in northern Finland, B = Dwarf shrubs in southern Finland, C = Grasses and D = Herbs). Solid line based on modelling that takes into account site fertility distribution for Finland by weighting, while dashed line is the estimate without weights.

R code for variograms and cross-variograms of vegetation group coverages and resulting figure with semivariance as a function of distance (Fig. S3).

```
library(gstat)

library(sp)

### peite34 object includes data for vegetation coverages and plot locations across Finland

coordinates(peite34) = c('x','y')

##################

g.r <- gstat(NULL, "dwarf shrubs", r1~x+y,data = peite34,  model = v.fitr1, nmax=200)

g.r <- gstat(g.r, "grass&herb", r2~x+y,data = peite34,  model = v.fitr2, nmax=200)

g.r <- gstat(g.r, "bryophyte", r3~x+y,data = peite34,  model = v.fitr3, nmax=200)

g.r <- gstat(g.r, "lichen", r4~x,data = peite34,  model = v.fitr4, nmax=200)

vm <- variogram(g.r)

vm.fit <- fit.lmc(vm,g.r,vgm(1200,"Sph",100,300))

plot(vm, vm.fit)

## thereafter predictions of the understorey coverage for each location by vegetation groups

cok.maps <- predict(vm.fit, nfi10loc)
```

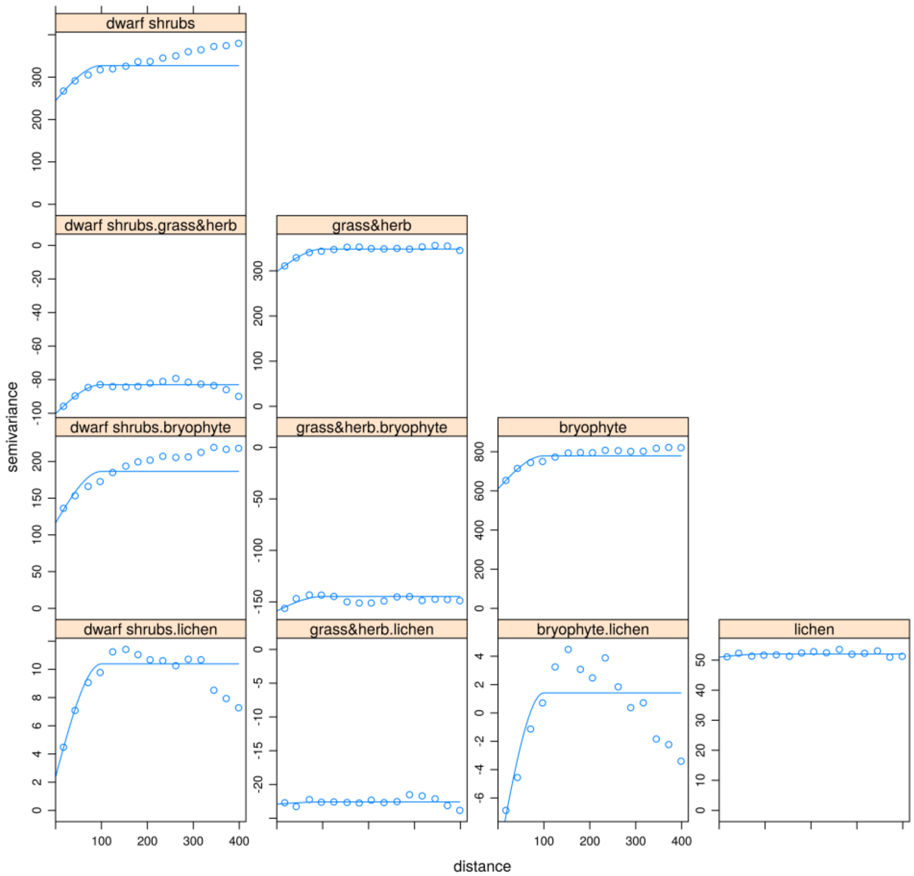

Figure S3. Variograms and cross-variograms for different functional types of understorey vegetation.

3. Nitrogen content of the litterfall

Table S2. Nitrogen content of litterfall as ratios from mass, based on Komarov et al. (2007).

	Foliage	Branches	Stem wood	Fine roots	Coarse roots	Total
Scots pine	0.003	0.004	0.0014	0.0047	0.0024	-
Norway spruce	0.0045	0.0035	0.002	0.0035	0.003	-
Deciduous	0.007	0.004	0.0015	0.005	0.0045	-
Understorey[1]	-	-	-	-	-	0.006

4. Soil carbon model Yasso07

Parameters for the Yasso07 have been estimated with Markov Chain Monte Carlo (MCMC) methods where litter bag, wood decomposition and soil carbon stock data were used to calibrate model parameters. Maximum posterior parameters estimates used in this study were based on works by Rantakari et al. (2012) and for earlier version of the global Yasso07 parameterisation that is a close

[1] The nitrogen content of the understorey litterfall was estimated to be 0.6% from dry mass.

variant of the Tuomi et al. (2011) publication (Table S2). Model have been described more in detail in papers where individual components have been reported (Tuomi et al. 2009, Tuomi et al. 2011, Tuomi et al. 2008)

Fortran code of the Yasso07 model is available here:

http://code.google.com/p/yasso07ui/

Table S2. Yasso07 maximum *a posterior* (MAP) point estimates Scandinavian (Rantakari et al. 2012) and global parameterization (Tuomi et al. 2011).

Parameter	Scandinavia	Global	Unit	Meaning
aA	0.52	0.72	a^{-1}	decomposition rate of A
aW	3.55	5.9	a^{-1}	decomposition rate of W
aE	0.35	0.28	a^{-1}	decomposition rate of E
aN	0.27	0.031	a^{-1}	decomposition rate of N
p1	0.04	0.48	.	mass flow from W to A
p2	0.03	0.01	.	mass flow from E to A
p3	0.98	0.83	.	mass flow from N to A
p4	0.64	0.99	.	mass flow from A to W
p5	0.31	0.00	.	mass flow from E to W
p6	0.019	0.01	.	mass flow from N to W
p7	0.023	0.00	.	mass flow from A to E
p8	0.01	0.00	.	mass flow from W to E
p9	0.001	0.02	.	mass flow from N to E
p10	0.34	0.00	.	mass flow from A to N
p11	0.042	0.015	.	mass flow from W to N
p12	0.09	0.95	.	mass flow from E to N
b1	0.09	0.95	C^{-1}	temperature dependence parameter
b2	-0.0023	-1.4	10^{-}	temperature dependence parameter
y	-2.94	-1.21	m^{-1}	precipitation dependence parameter
pH	0.15	4.5	10^{-3}	mass flow from A,W,E,N to humus
aH	-0.24	-1.6	10^{-3}	humus decomposition coefficient
roo1	-0.539	-1.71	cm^{-1}	size dependence parameter
roo2	1.186	0.86	cm^{-2}	size dependence parameter
r	-0.264	-0.306	.	size dependence parameter

5. Soil carbon model ROMULv

ROMUL decomposition model describes the flux of soil organic matter (SOM) through the soil decomposition process, divided into separate parallel paths of matter based on the different origins of the litter (Chertov and Komarov 1997, Chertov et al. 2001). All fluxes have essentially the same pattern of flux. The litter entering the decomposition process is stored in a store of undecomposed litter (H). This then decomposes into a mixture of partly decomposed (humified) SOM (F). The SOM in the F fraction is decomposed by different types of organisms (fungi, bacteria and earthworms) and end up in storage of semi-stable humus (H). These fluxes (for litter of different origins) are for SOM, but the model also describes a parallel decomposition process for nitrogen in soil, following the same pattern of storages and fluxes.

Litter → L → F → H

In each transition from one storage to another, the rate of decomposition depends on the nitrogen content of the storage (calculated from the ratio of the SOM storage and the corresponding N storage) and the ash content of the litter (fixed percentage for each litter source). These transfer rates are adjusted with coefficient functions depending on soil temperature and soil water content. During each transition, a fraction of the pool is mineralized – SOM released as CO_2 and N released into a pool of mineralized N available to plants, while most of the matter moves to the next pool in the decomposition process. The litter from different sources follow different routes, until they all end up in a common pool of semi-stable humus (H). Finally, also the matter in the H pool slowly decomposes. In each transition from one pool to another, the rate of SOM and N decomposition is the same, except for the transition from F pool to H; here the C:N ratio of the transition is characteristic for all decomposer classes (fungi, bacteria and earthworms), and in this phase the N content of the soil is enriched.

The litter from aboveground (leaves, shoots and trunks) fall onto the forest floor, whereas the root litter (fine roots and coarse roots) decomposes in the mineral soil layer. For the two layers, the decomposition rates based on SOM properties are mostly similar, but the environmental conditions (temperature and soil moisture) may differ for the two layers, resulting in different decomposition rates. The semi-stable storage H is common for all fluxes and resides in the mineral soil layer.

The original ROMUL model uses decomposition rate functions that use gravimetric measures of soil water as input. As these figures are somewhat tedious to calculate and would require detailed information of the soil characteristics, such as soil density and precise thickness of the soil layers, we used instead a modification presented by Linkosalo et al. (2013) named here as ROMULv. In their paper they produced decomposition rate functions that are based on volumetric soil water measures, and a volumetric soil water model to predict the variation in the soil water content, driven by environmental measures. The volumetric soil water model was easier to apply for multiple simulation points, as it only needs the total potential soil water storage (i.e. difference between field capacity and wilting point) to characterize the soil for the simulations of relative soil water content.

The description of the original ROMUL model is available from here:

http://ecomodelling.ru/

For the source code used in this study, see the end of this document.

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Source code of the ROMULv model used here

```
Main program loop (meta-code):

Initialize ROMUL (read initial values from file)

Loop_over_data {

  read meteorological data
  calculate soil temperature

  calculate evapotranspiration
  calculate soil water status

  calculate decomposition and update soil storages
}

write ROMUL results
```

```
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c       This implementation of the ROMUL model is based on
c       Chertov et al. 2001, with "new functions" from
c       Komarov et at. 2008.
c
c       Tapio Linkosalo (METLA) & Annikki Mäkelä (UH)
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
```

```
       subroutine ROMUL(litter,litter_N,T,SW,Navail,
     +                site, year, init)

       implicit none

c litterfall by cohort, soil temperature and water content for organic (==1)  and mineral soil layer
(==2)
c init-parameter for initializing the model (1), normal simulation (0) or output the results (2).

      double precision litter(11), litter_N(11)
      real T(2), SW(2)

c mass storages are save-variables, values persist from one call to another
c First dimension of pools is for the SOM cohort, the second for spatial locations
c (except only one pool per geographic location for humus)
      double precision Lpool(11,4000), Fpool(11,4000)
      double precision LNpool(11,4000), FNpool(11,4000)
      double precision Hpool(4000), HNpool(4000)
      save Lpool, Fpool, Hpool, LNpool, FNpool, HNpool

      double precision Navail(4000)
       real time, Nup, fnf, gnf, fnwb, Ndemand, qctot
       integer site, year, init

      integer local_year
      static local_year

c declare decomposition coefficient functions
      real f_1, f_2, f_3, f_4, f_5, f_6
      real g_1, g_2, g_3, g_4, g_5, g_6
c
c * N pools etc
c
c  litter in 11 separate pools
c  all have L and F fractions, one H fraction
c  all fractions have SOM and N
c  cohorts are order thus:
c     1   foliage
c     2   branches
c     3   stems
c     4   fine roots
c     5   coarse roots
c     11  ground vegetation
c  Note! Cohorts 6 to 10 are for felling residues, but in this version
c  they are calculated in corresponding litter cohorts (6->1 etc.)

c parameters - following ROMUL
c
c      kL             specific rate of leaching (yr-1)     1.0
```

```
c      kDL(i)  specific rate of litter decomposition (yr-1)       0.3
c      kDF(i)  specific rate of SOM decomposition (yr-1)   0.3
c      kTL(i)  specific rate of transfer from litter to SOM  (yr-1)
c      kTF(i)  specific rate of transfer from SOM to humus, comp. 1  (yr-1)      0.3
c      kTF2(i) specific rate of transfer from SOM to humus, comp. 2  (yr-1)      0.3
c      kDH            specific rate of humus decomposition (yr-1) 1/6000
c      kUG            maximum specific N uptake rate of ground vegetation (yr-1) 100
c      DeposN  N deposition (free input) (kg yr-1) 1
c
c     ash_cont(i) ash content of cohorts
c     fnf     foliar N concentration in live foliage
c      gnf            retention of foliar N when shedding foliage 0.45
c
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

c Declare internal variables

      double precision DeposN, LeachN
       double precision d_Lpool(11),d_Fpool(11),d_HumusPool
      double precision d_LNpool(11),d_FNpool(11),d_HumusNPool
       double precision d_Navail
      double precision fn(11)
       real kL, kM, DM
      double precision kDL(11), kDH
      double precision kDF(11)
      double precision kTL(11)
      double precision kTF(11),kTF2(11)
      real LKP_decomp
      double precision K_1S_rma, K_2S_rma,K_3S_rma, k_1L_rma,K_2L_rma
      double precision k_3L_rma, k_4_rma,k_5_rma,k_6_rma
      double precision ML, MF(11), MFres(11), MH, gamma, GVN1, GVN2
       double precision N_release, FH_FluxB, FH_fluxL, FHN_FluxB, FHN_fluxL
      double precision MF_flux, MF_min
      double precision H_miner, H_C, C_C, DeltaB, DeltaL, dL
      double precision x1, x2, ash_cont(11)
      integer inttime, i, j, k, inttimetot
      double precision Lpoolsum(5),Fpoolsum(5),LNpoolsum(5),FNpoolsum(5)
      double precision littersum(5), Fpooltot(2), FNpooltot(2), H_CN
      double precision Lpooltot(2), LNpooltot(2)
      double precision NFconc(2), NLconc(2)
       double precision step


c assign parameter values
       data kL
     1 /0.12/

      data (ash_cont(i) , i=1,11)
     1 /0.02,  0.02,  0.01,  0.02,  0.02, 0.02, 0.02, 0.01,
```

```
     1 0.02, 0.01, 0.04/

      data fnf, gnf  /0.02, 0.45/

      data DeposN, kM, DM /2., 2., 0.3/
      data ML, gamma, C_C / 0.1, 0.8, 0.5/
      data deltaB, deltaL /24., 12.8/


      dL = 1




c read inputs when coming to this subroutine for the first time (init = 1)
      if (init.eq.1) then
          open(unit=25,file='soil.dat',status = 'old', err = 999)
         do 100 i = 1, site
          read(25,*) j, (Lpool(j,i),j=1,5),Lpool(11,i),
     +                    (Fpool(j,i),j=1,5),Fpool(11,i),
     +                       Hpool(i),
     +            (LNpool(j,i),j=1,5),LNpool(11,i),
     +            (FNpool(j,i),j=1,5),FNpool(11,i),
     +            HNpool(i)

100      continue
          close(25)
         goto 998
999      write(*,*) "failed to open soil.dat"


         local_year = 0

998         return
      endif


c write storages to file when coming to this subroutine for the last time (init = 2)
      if (init.eq.2) then
          open(unit=25,file='soil.dat',status = 'old')

         write(*,*) "writing soil.dat..."
         do 101 i = 1, site
              write(25,997) i,(Lpool(j,i),j=1,5),Lpool(11,i),
     +                       (Fpool(j,i),j=1,5),Fpool(11,i),
     +         Hpool(i),
     +        (LNpool(j,i),j=1,5),LNpool(11,i),
     +        (FNpool(j,i),j=1,5),FNpool(11,i),
     +            HNpool(i)
997   format(i5,12f12.2,f14.2,12f12.5,f14.3)
```

```
101      continue
          close(25)
         return
      endif


c Daily calculation starts here!

         do 65 i = 1, 11
             fn(i) = litter_N(i)/litter(i)
65       continue

c "step" is for substeN of differential calculation, with daily weather data
c no substeN needed.
            step = 1

c compute specific rate parameters as functions of ash content and N content
c compute total N in litter

c first the N concentration for the F-pools:
c index 1 = organic layer, and 2 = mineral soil

      Lpooltot(1) = Lpool(1,site) + Lpool(2,site) + Lpool(3,site) +
     +                Lpool(11,site)
      LNpooltot(1) = LNpool(1,site) + LNpool(2,site) + LNpool(3,site) +
     +                LNpool(11,site)
      Fpooltot(1) = Fpool(1,site) + Fpool(2,site) + Fpool(3,site) +
     +                Fpool(11,site)
      FNpooltot(1) = FNpool(1,site) + FNpool(2,site) + FNpool(3,site) +
     +                FNpool(11,site)
      Fpooltot(2) = Fpool(4,site) + Fpool(5,site)
      FNpooltot(2) = FNpool(4,site) + FNpool(5,site)


      NFconc(1) = FNpooltot(1) / Fpooltot(1)
      NFconc(2) = FNpooltot(2) / Fpooltot(2)
      NLconc(1) = LNpooltot(1) / Lpooltot(1)
      NLconc(2) = LNpooltot(2) / Lpooltot(2)


      do 25 i = 1,5

          if(i.ge.4) then
              kDL(i) = k_1S_rma(ash_cont(i), fn(i)) *
     *            f_1(T(2)) * LKP_decomp(SW(2), 0.55)
             kDF(i) = k_2S_rma(ash_cont(i), NFconc(2)) *
     *            f_2(T(2)) * LKP_decomp(SW(2), 0.55)
              kTL(i) = k_3S_rma(ash_cont(i), fn(i)) *
     *            f_3(T(2)) *LKP_decomp(SW(2), 0.55)
          else
```

```
            kDL(i) = k_1L_rma(ash_cont(i), fn(i)) *
     *           f_1(T(1)) * LKP_decomp(SW(1), 0.7)
            kDF(i) = k_2L_rma(ash_cont(i), NFconc(1)) *
     *           f_2(T(1)) * LKP_decomp(SW(1), 0.7)
            kTL(i) = k_3L_rma(ash_cont(i), fn(i)) *
     *           f_3(T(1)) * LKP_decomp(SW(1), 0.7)
        endif

        kTF(i) = k_4_rma(ash_cont(i), NFconc(2)) *
     *           f_4(T(2)) * LKP_decomp(SW(2), 0.55)
        kTF2(i) = k_5_rma(ash_cont(i), NFconc(2)) *
     *           f_5(T(2)) * LKP_decomp(SW(2), 0.55)

25    continue

        kDL(11) = k_1L_rma(ash_cont(11), fn(11)) *
     *           f_1(T(1)) * LKP_decomp(SW(1), 0.7)
        kDF(11) = k_2L_rma(ash_cont(11), NFconc(1)) *
     *           f_2(T(1)) * LKP_decomp(SW(1), 0.7)
        kTL(11) = k_3L_rma(ash_cont(11), fn(11)) *
     *           f_3(T(1)) * LKP_decomp(SW(1), 0.7)

        kTF(11) = k_4_rma(ash_cont(11), NFconc(2)) *
     *           f_4(T(1)) * LKP_decomp(SW(1), 0.55)
        kTF2(11) = k_5_rma(ash_cont(11), NFconc(1)) *
     *           f_5(T(1)) * LKP_decomp(SW(1), 0.55)


      kDH = k_6_rma() * f_6(T(2)) * LKP_decomp(SW(2), 0.55)




c       update N pools

        Nup = 0.

c      do 100 inttime = 1, inttimetot




      LeachN = kL * Navail(site)
      LeachN = max(LeachN, 0.)


c C pools: derivatives

      FH_fluxB = 0.
      FH_fluxL = 0.
      FHN_fluxB = 0.
```

```
      FHN_fluxL = 0.

      do 10 i = 1,5

          d_Lpool(i) = litter(i) + litter(i+5) -
     -        (kDL(i) + kTL(i)) * Lpool(i,site)

          d_Fpool(i) = kTL(i) * Lpool(i,site)
     1                 -(kDF(i) + kTF(i) + kTF2(i)) * Fpool(i,site)

          FHN_fluxB = FHN_fluxB + kTF(i) * FNpool(i,site)
          FHN_fluxL = FHN_fluxL + kTF2(i) * FNpool(i,site)
          FH_fluxB = FH_fluxB + kTF(i) * Fpool(i,site)
          FH_fluxL = FH_fluxL + kTF2(i) * Fpool(i,site)

10    continue



          d_Lpool(11) = litter(11)  -
     -        (kDL(11) + kTL(11)) * Lpool(11,site)

          d_Fpool(11) = kTL(11) * Lpool(11,site)
     1                 -(kDF(11) + kTF(11) + kTF2(11)) * Fpool(11,site)

          FHN_fluxB = FHN_fluxB + kTF(11) * FNpool(11,site)
          FHN_fluxL = FHN_fluxL + kTF2(11) * FNpool(11,site)
          FH_fluxB = FH_fluxB + kTF(11) * Fpool(11,site)
          FH_fluxL = FH_fluxL + kTF2(11) * Fpool(11,site)



           d_HumusPool = DeltaB * FHN_fluxB + DeltaL * FHN_fluxL
     +                 - kDH * Hpool(site)

c calculate MF(i)

      do 11 i = 1,5

          if((100.*NFconc(2) - 1.16 * 100.*NFconc(1)) . le. 0.44) then
              MF(i) = 0.1
          else
              if((100.*NFconc(2) - 1.16*100.*NFconc(1)) . le. 1.50) then
                  MF(i) = 0.5
              else
                  MF(i) = 1.0
              endif
          endif
```

```
11    continue

          if((100.*NFconc(2) - 1.16 * 100.*NFconc(1)) . le. 0.44) then
              MF(11) = 0.1
          else
              if((100.*NFconc(2) - 1.16*100.*NFconc(1)) . le. 1.50) then
                  MF(11) = 0.5
              else
                  MF(11) = 1.0
              endif
          endif



c MF_flux is transferred from F to H, MF_min is released

      MF_flux = 0.
      MF_min = 0.

      do 20 i = 1,5


          d_LNpool(i) = litter_N(i) + litter_N(i+5)
     1                 - (ML*kDL(i) + kTL(i)) * LNpool(i,site)


          d_FNpool(i) = (kTL(i)) * LNpool(i,site)
     1                  - MF(i) * kDF(i) * FNpool(i,site)
     1                  -(kTF(i) + kTF2(i)) * FNpool(i,site)

          MF_flux = MF_flux + (1-MF(i)) * kDF(i) * FNpool(i,site)
          MF_min = MF_min + MF(i) * kDF(i) * FNpool(i,site)

          Lflux(i,site) = Lflux(i,site) + ML*kDL(i) * LNpool(i,site)
          Fflux(i,site) = Fflux(i,site) + MF(i)*kDF(i) * FNpool(i,site)



20    continue



          d_LNpool(11) = fn(11) * litter(11)
     1                 - (ML*kDL(11) + kTL(11)) * LNpool(11,site)


          d_FNpool(11) = (kTL(11)) * LNpool(11,site)
     1                  - MF(11) * kDF(11) * FNpool(11,site)
     1                  -(kTF(11) + kTF2(11)) * FNpool(11,site)
```

```
          MF_flux = MF_flux + (1-MF(11)) * kDF(11) * FNpool(11,site)
          MF_min = MF_min + MF(11) * kDF(11) * FNpool(11,site)



       if(HNpool(site) .gt. 0.) then
          H_CN = Hpool(site) / HNPool(site) / 2.
      else
          H_CN = 100.
      endif

      if(H_CN .gt. 8.) then
          MH = 0.8
      else
          MH = 1.
      endif


          d_HumusNPool =
     +                   - kDH * MH * HNpool(site)
     1                   + gamma * (FHN_fluxB + FHN_fluxL)



C  Calculate mineralised carbon

      H_miner = kDH * Hpool(site) + FH_fluxB + FH_fluxL
     1                 - DeltaB * FHN_fluxB - DeltaL * FHN_fluxL
     1                 - DeltaB * kM * Navail(site)

      do 15 i = 1,5
          H_miner = H_miner + kDL(i) * Lpool(i,site)
     +              + kDF(i) * Fpool(i,site)
15    continue

          H_miner = H_miner + kDL(11) * Lpool(11,site)
     +              + kDF(11) * Fpool(11,site)


      H_C = C_C * H_miner
      C_sum(site) = C_sum(site) + H_C

c calculate N release

      N_release =    kDH * MH * HNpool(site)
     1              + (1. - gamma) *(FHN_fluxB + FHN_fluxL)
     1                 + DeposN
c     1                 - kM * Navail(site) + DeposN
```

```
      Hflux(site) = Hflux(site) + kDH* MH * HNpool(site)


      do 16 i = 1,5
          N_release = N_release + ML * kDL(i) * LNpool(i,site)
     1                + MF(i) * kDF(i) * FNpool(i,site)


16    continue

          N_release = N_release + ML * kDL(11) * LNpool(11,site)
     1                + MF(11) * kDF(11) * FNpool(11,site)


       d_Navail = N_release  - LeachN
c     1             - N_coeff_TR * Ndemand
c     1             - N_coeff_GV1 * Gr_GVegN1 - N_coeff_GV2 *  Gr_GVegN2


c Update pools - use simple Euler

      do 17 i = 1, 5
c daily version -> step equals one!
          Lpool(i,site) = Lpool(i,site) + d_Lpool(i) * step
          Fpool(i,site) = Fpool(i,site) + d_Fpool(i) * step
          LNpool(i,site) = LNpool(i,site) + d_LNpool(i) * step
          FNpool(i,site) = FNpool(i,site) + d_FNpool(i) * step
17    continue

          Lpool(11,site) = Lpool(11,site) + d_Lpool(11) * step
          Fpool(11,site) = Fpool(11,site) + d_Fpool(11) * step
          LNpool(11,site) = LNpool(11,site) + d_LNpool(11) * step
          FNpool(11,site) = FNpool(11,site) + d_FNpool(11) * step


      HPool(site) = HPool(site) + d_HumusPool * step
       HNPool(site) = HNPool(site) + d_HumusNPool * step
       Navail(site) = Navail(site) + d_Navail * step

      N_sum(site) = N_sum(site) + d_Navail * step

c      Navail(site) = max(Navail(site), 0.)




      return
      end subroutine ROMUL
```

```
c       ----------------------------------------------------------------------------
c       The functions for rate of decomposition modifiers depending on temperature
c       of the corresponding cohort. These new functions are from Komarov et al. 2008.
c
c       Tapio Linkosalo October 2008
c       ----------------------------------------------------------------------------
        real function f_1(T)

               real T

               if (T .LE. -5.0 .OR. T .GT. 60.0) then
                      f_1 = 0
               endif
               if (T .GT. -5.0 .AND. T .LE. 1.0) then
                      f_1 = 0.1595 + 0.0319 * T
               endif
               if (T . GT. 1.0 .AND. T .LE. 35.0) then
                      f_1 = 0.1754 * exp(0.0871 * T)
               endif
               if (T . GT. 35.0 .AND. T .LE. 60.0) then
                      f_1 = 8.791 - 0.1465 * T
               endif

               return
        end
c       ----------------------------------------------------------------------------
        real function f_2(T)

               real T

               if (T .LE. -5.0 .OR. T .GT. 60.0) then
                      f_2 = 0
               endif
               if (T .GT. -5.0 .AND. T .LE. 1.0) then
                      f_2 = 0.1595 + 0.0319 * T
               endif
               if (T . GT. 1.0 .AND. T .LE. 35.0) then
                      f_2 = 0.1754 * exp(0.0871 * T)
               endif
               if (T . GT. 35.0 .AND. T .LE. 60.0) then
                      f_2 = 3.690 - 0.0615 * T
               endif

               return
        end
c       ----------------------------------------------------------------------------
        real function f_3(T)
```

```
        real T

        if (T .LE. -3.0) then
               f_3 = 0
        endif
        if (T .GT. -3.0 .AND. T .LE. 7.0) then
               f_3 = 1.3
        endif
        if (T .GT. 7.0 .AND. T .LE. 60.0) then
               f_3 = 1.472 - T * 0.0245
        endif
        if (T. GT. 60.0) then
               f_3 = 0
        endif

        return
      end
c     --------------------------------------------------------------------------
      real function f_4(T)

        real T

        if (T .LE. -5.0) then
               f_4 = 0
        endif
        if (T .GT. -5.0 .AND. T .LE. 1.0) then
               f_4 = 0.1595 + 0.0319 * T
        endif
        if (T .GT. 1.0 .AND. T .LE. 20.0) then
               f_4 = 0.1754 * exp(0.0871 * T)
        endif
        if (T .GT. 20.0 .AND. T .LE. 40.0) then
               f_4 = 1
        endif
        if (T .GT. 40.0 .AND. T .LE. 80.0) then
               f_4 = 2.0 - 0.025 * T
        endif
        if (T. GT. 80.0) then
               f_4 = 0
        endif

        return
      end
c     --------------------------------------------------------------------------
      real function f_5(T)

        real T

        if (T .LE. -5.0) then
```

```
                f_5 = 0
            endif
            if (T .GT. -5.0 .AND. T .LE. 1.0) then
                f_5 = 0.078 + 0.0156 * T
            endif
            if (T .GT. 1.0 .AND. T .LE. 13.0) then
                f_5 = 0.0675 * exp(0.2088 * T)
            endif
            if (T .GT. 13.0 .AND. T .LE. 25.0) then
                f_5 = 1
            endif
            if (T .GT. 25.0 .AND. T .LE. 50.0) then
                f_5 = 2.0 - 0.04 * T
            endif
            if (T. GT. 50.0) then
                f_5 = 0
            endif

            return
        end
c       ------------------------------------------------------------------------------
        real function f_6(T)

            real T

            if (T .LE. -5.0) then
                f_6 = 0
            endif
            if (T .GT. -5.0 .AND. T .LE. 1.0) then
                f_6 = 0.1595 + 0.0319 * T
            endif
            if (T .GT. 1.0 .AND. T .LE. 27.5) then
                f_6 = 0.1754 * exp(0.0871 * T)
            endif
            if (T .GT. 27.5 .AND. T .LE. 35.0) then
                f_6 = 1.95
            endif
            if (T .GT. 35.0 .AND. T .LE. 60.0) then
                f_6 = 4.68 - 0.078 * T
            endif
            if (T. GT. 60.0) then
                f_6 = 0
            endif

            return
        end
c       ------------------------------------------------------------------------------
c
c      Decomposition rate function for volumetric soil water content (theta) (where
c      theta = 0 == wilting point and theta = 1 == saturation), based on paper
```

```
c     Linkosalo, Kolari & Pumpanen 2013.
c
c      -----------------------------------------------------------------------------
      real function LKP_decomp(theta, porosity)

          real  theta, porosity, P1, P2

          P1 = 3.83 * theta ** 1.25
          P2 = 4.43 * (1-theta)**0.8854
          LKP_decomp = min(P1,P2,1.)

          return
          end


c      -----------------------------------------------------------------------------
c      The following are the k coefficients for the decomposition rate, depending on
c      litter ash and N content. The two values are given as parameters (absolute
c      values g/g, NOT percentage as in Romul equations!) so that the same functions
c      can be used whether the parameter values are for a specific cohort or litter
c      in general. These are the "new" functions as in Komarov et al. 2008.
c
c      TL October 2008.
c      -----------------------------------------------------------------------------
       double precision function k_1L_rma(ash, N)

              double precision ash, N

              k_1L_rma = 0.0005 + 0.54 * N

              return
       end
c      -----------------------------------------------------------------------------
       double precision function k_1S_rma(ash, N)

              double precision ash, N

              k_1S_rma = 0.0136 + 0.06 * ash

              return
       end
c      -----------------------------------------------------------------------------
       double precision function k_2L_rma(ash, N)

              double precision ash, N

              k_2L_rma = 0.00060

              return
       end
```

```
c       ----------------------------------------------------------------------------
        double precision function k_2S_rma(ash, N)

                double precision ash, N

                k_2S_rma = 0.00126

                return
        end
c       ----------------------------------------------------------------------------
        double precision function k_3L_rma(ash, N)

                double precision ash, N


                k_3L_rma = 0.0089 + 0.78 * N

                return
        end
c       ----------------------------------------------------------------------------
        double precision function k_3S_rma(ash, N)

                double precision ash, N


                if (ash .LT. 0.18) then
               k_3s_rma = 0.0394 - 0.21 * ash
                else
               k_3S_rma = 0.0394 - 0.21 * 0.18
                endif

                return
        end
c       ----------------------------------------------------------------------------
        double precision function k_4_rma(ash, N)

                double precision ash, N

                if (N .LE. 0.02) then
                        k_4_rma = 0.05 * N
                else
                        k_4_rma = 0.001
                endif

        return
        end
c       ----------------------------------------------------------------------------
        double precision function k_5_rma(ash, N)

                double precision ash, N
```

```
            if (N .LE. 0.005) then
                  k_5_rma = 0
            else
                  if (N .GE. 0.02) then
                        k_5_rma = 0.007
                  else
                        k_5_rma = 0.007 * (100*(2*N - 0.01)/3)
                  endif
            endif
      return
      end
c     ------------------------------------------------------------------------------
      double precision function k_6_rma()

            k_6_rma = 0.00006

      return
      end
c     ------------------------------------------------------------------------------


c ****************************************************************
c
c Subroutine simulates the soil water content in two layers,
c organic layer on top and mineral soil layer in bottom.
c
c Model presented in Linkosalo, Kolari and Pumpanen 2013.
c
c Input/output parameters: SW (SoilWater, absolute, in mm)
c                          theta (output for calc, 0 = WP and 1 = sat)
c                          prec (precipitation, in mm)
c                          ET_tot (total evapotranspiration in mm)
c
c Local parameters per layer: saturation (mm), FC (mm), WP (mm), tau (days)
c                             ET_ratio (split of ET between layers)
c
c ****************************************************************

      Subroutine two_layer_soil_water(SoilW, SWmax, theta, prec, ET_tot)

c local variables
      integer i
      real theta(2), SoilW(2), ET_tot, prec
        real FC(2), WP(2), saturation(2), ET(2)
      real tau_soil(2), ET_ratio, overflow
      real P1, P2, P_H, P_M
        real SWmax(2)

c     Soil water submodel parameters
```

```
        ET_ratio = 0.256107371
        tau_soil(1) = 0.894587365
        tau_soil(2) = 9.418136372
        saturation(1) = SWmax(1)/0.65
        saturation(2) = SWmax(2)/0.65
       wp(1) = 0
       wp(2) = 0
       FC(1) = WP(1) + SWmax(1)
       FC(2) = WP(2) + SWmax(2)

c Split evapotranspiration for the two layers
        ET(1) = ET_ratio * ET_tot
        if(ET(1) .gt. SoilW(1)) then
               ET(1) = SoilW(1)
        endif
        ET(2) = ET_tot - ET(1)


c Soilwater of organic layer from previous day over field capacity? -> overflow
        if (SoilW(1) .gt. FC(1)) then
               overflow = (SoilW(1) - FC(1)) / tau_soil(1)
               SoilW(1) = FC(1)
        else
               overflow = 0
        endif

        SoilW(1) = SoilW(1) + prec - ET(1)

c New soil water of organic layer over saturation -> immediately drainage
        if (SoilW(1) .gt. saturation(1)) then
               overflow = overflow + (SoilW(1) - saturation(1))
               SoilW(1) = saturation(1)
        endif

c          SoilW(2) = max(SoilW(2), SoilWP(2))

c Mineral soil over FC -> overflow
        if (soilW(2) .gt. FC(2)) then
               soilW(2) = soilW(2) - (soilW(2) - FC(2)) / tau_soil(2)
        endif

c Now add new water and subtract ET
        SoilW(2) = SoilW(2) + overflow - ET(2)

        if (soilW(2) .gt. saturation(2)) then
               soilW(2) = saturation(2)
c              overflow = saturation(2) - SoilW(2)
        endif

        if (SoilW(2) .lt. WP(2)) then
```

```
              ET(2) = ET(2) - (WP(2) - SoilW(2))
              soilW(2) = WP(2)
       endif

       ET_tot = ET(1) + ET(2)

       theta(1) = (soilW(1) - WP(1)) / (Saturation(1) - WP(1))
       theta(2) = (soilW(2) - WP(2)) / (Saturation(2) - WP(2))


       return
      end


c---------------------------------------------------------------------------
c
c      Evapotranspiration function based loosely on paper
c      Duursma et al. Tree Physiology 2008, but the dependency of ET on irradiation
c      modified by T. Linkosalo and fitted to Hyytiälä data in spring 2009
c
c---------------------------------------------------------------------------
       real function EvapoTranspiration (Temp, PAR, VPD, x, CO2effect,
     +          CO2ppm, REW, fDET)

c
       real ET
       real Temp, PAR, VPD, x, REW, fDET
       real beta, tau, x0, kappa, a_1, a_2, CO2ppm
       integer CO2effect

c      parameters hard-coded...

       beta = 0.016752
       tau = 14.39305
       x0 = -6.94684
       kappa = -0.000263
       a_1 = 0.0007
       a_2 = 0.0837



c      calculate S and D functions
              x = x + (Temp - x)/tau
              fS = max(0.0, x - x0)
              fD = exp(kappa * VPD)

c      calculate ET
              ET = beta * PAR * fS * fD + a_1*PAR + a_2

c Convert ET from mol/m2/d to g/m2/d
              ET = ET * 18
```

```
c Convert ET from g/m2/d to mm/d  (ET/rho and m -> mm)
              ET = ET / 1000

              fDET = 1

              if (REW .LT. 0.4) then
                     fDET = REW/0.4
                     ET = ET * fDET
              endif

              EvapoTranspiration = ET
              return
      end


c--------------------------------------------------------------------------
      subroutine SoilTemperature(ST, T)

      implicit none

      real ST(2), T, adj_T(2)

c parameters for soil temperature model
      real minimum_temp(2), tau(2)
      minimum_temp(1) = -0.13
      minimum_temp(2) = 0.24
       tau(1) = 14.9
       tau(2) = 10.5

      adj_T(1) = max(T, minimum_temp(1))
      adj_T(2) = max(T, minimum_temp(2))

      ST(1) = ST(1) + (adj_T(1) - ST(1)) / tau(1)
      ST(2) = ST(2) + (adj_T(2) - ST(2)) / tau(2)

      return
      end
```