Testing validity of soil carbon model Yasso07 against empirical data

FINAL REPORT

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Introduction

Forest soils are a heterogenic ecosystem with large carbon stock but small expected changes in relation to carbon stock size over time, and large spatial variation making it difficult to determine the changes of stock reliably with a small number of samples (Yanai et al.2003, Peltoniemi et al. 2004). Forests cover large areas of the Global land area and make them potentially significant sinks or sources of carbon over time. Reliable estimates of soil carbon stock are needed because changes of soil carbon stock are a part of the national greenhouse gas (GHG) inventories conducted under UNFCCC (United Nations Framework Convention on Climate Change) and Kyoto Protocol. Many countries have comprehensive and representative national forest inventories (NFI) that can be exploited as input data in assessing the changes in soil carbon pool by models. In between, models of biomass and turnover that convert NFI data into input data for the soil model are exploited. Therefore, soil carbon models predicting carbon stock changes are valuable tools in assessing changes in soil carbon stock. However, empirical data is necessary for verification of modelled soil carbon dynamics to achieve reliable estimates.

Currently, GHG inventory of Finland uses Yasso soil carbon model to determine changes in forest soil carbon stocks and the updated version of this model Yasso07 to determine changes in soil carbon stocks after land use changes. Yasso model was selected to be used in greenhouse gas inventory inter alia due to fewer requirements in respect to input data compared to many other soil carbon models ensuring applicability to large areas (Peltoniemi et al. 2007). Yasso07 is based on a much wider range of measurements than the earlier version of Yasso and the parameter values for Yasso07 have been determined using more advanced mathematical methods (Markov chain Monte Carlo, MCMC samplings). Currently used soil carbon model does not take into consideration variation in soil moisture, although soil moisture is an important feature in many widely used soil carbon models (eg. CENTURY). Yasso07 uses annual or monthly precipitation as an approximation for soil moisture. Furthermore, in Yasso07 model the parameter uncertainties are known and can be taken into account when calculating predictions. The uncertainty estimation are required in GHG reporting and therefore updating to the Yasso07 model would facilitate that. Creation and operation of Yasso07 model is described and published in the scientific literature (Tuomi et al. 2009; Tuomi et al. 2011a; Tuomi et al. 2011b).

The aim of this study was to test the validity of the soil carbon model Yasso07 against empirical data and to evaluate differences between model versions and their applicability to national green house gas inventory. Validation was done following the rules given in the IPCC Good Practice Guidance (2003) in order to estimate the model's applicability.

Materials and methods

In this study, we compared soil carbon change over time estimated by two different methods:

1) Repeated measurements of soil carbon stock in the organic layer of Finnish forest soils
2) Soil carbon stock changes in the top-most 1m soil layer simulated by soil carbon model Yasso07 based on FMI data

The comparison was restricted to mineral soils, because Yasso07 and old Yasso model only operate on mineral soils. Therefore, paludified sites were excluded from measured data. Soil carbon stock changes were compared between measured organic layer changes and the changes in the topmost 100 cm simulated by Yasso07 model assuming that changes in the soil carbon stock mainly occur in the organic layer.

Soil carbon simulations

The soil carbon stock was simulated with a dynamic decomposition model for soil organic carbon and litter, *Yasso07*, which is generalization of an earlier *Yasso* soil carbon model (Liski et al. 2005; Tuomi et al. 2009).

Yasso07 model requires as an input data:

- Carbon input to soil
  - Quantity
  - Chemical quality
  - Diameter of woody litter
- Climate
  - Temperature
  - Precipitation
  - Annually or monthly

Therefore, in order to simulate soil carbon stock change the following information is required:

- Estimation of the litter input data from trees, ground vegetation and drain with division into three different decomposition compartments 1) non-woody litter, 2) fine woody litter, 3) coarse woody litter.
- Estimation of weather parameters.
- Estimation of the initial values of model state variables based on the NFI6 (1971–1976) (sc. spin-up runs to obtain steady state of the model).

Structure of soil carbon model Yasso07

Yasso07 consists of five decomposition compartments (Figure 1). Non-woody, fine woody and coarse woody litters are divided into the decomposition compartments of extractives, celluloses and lignin-like compounds. Non-woody litter entering the soil is divided directly into the decomposition compartments, but fine woody and coarse woody litter compartments have fractionation rates that determine the proportion of their contents released to the decomposition compartments over time. Soil carbon model Yasso07 is based on three assumptions of litter decomposition (Tuomi et al. 2009):

(1) Non-woody litter consists of four compound groups, i.e. compounds soluble in a non-polar solvent, ethanol or dichloromethane (denoted using E), or in water (W), and compounds hydrolysable in acid (A) and neither soluble nor hydrolysable at all (N). Each group has its own mass loss rate independent of the origin of the litter. These compound groups are called the labile groups.
(2) The mass loss rate of the compound groups depend on the climatic conditions that can be described by using temperature and precipitation.
(3) Decomposition of the compound groups results in mass loss from the system and in mass flows between the compound groups. In addition, the mass loss of the four compound groups results in formation of more recalcitrant humus.

Estimation of forest litter input to the soil

The major flows of litter to soil were assumed to be litter from living trees, litter from ground vegetation, harvest residues and litter due to natural mortality (Figure 2).

The litter production estimates are based on the annual stocks of living biomass in tree compartments. Litter production from living trees was estimated using biomass and litter production rate coefficients (Table 1). The biomass of living trees was estimated using tree-level measurements on field sample plots of the National Forest Inventory (NFI) and Finnish biomass models (Repola et al. 2007, Repola 2008, Repola 2009). The data from the national forest inventories 6 to 10 (NFI6, NFI7, NFI8, NFI9 and NFI 10) was used to obtain time series 1972-2008 for the whole data and the subsets (Figure 3 and Figure 4). The stock estimates contain only the trees with a height of at least 1.3 m, since smaller trees were not measured in the NFIs. The stocks by tree species and compartments on mineral soil were estimated for Southern Finland. Each estimate was allocated to the appropriately weighted mean of the measurement dates. Fine root biomass was estimated using coefficients that describe the relation between root and leaf biomass in different site types (Helmisaari et al. 2007). Furthermore, biomass for the ground vegetation of the mineral soils was estimated using 3,000 permanent sample plots described by Mäkipää and Heikkinen (2003). The models by Muukkonen and Mäkipää (2006) and Muukkonen et al. (2006) were applied to estimate the biomass of shrubs, herbs and grasses and mosses on mineral soils. The estimated litter production of ground vegetation was 50.6 g C m^{-2} a^{-1}.

Litter production rates from biomass compartments of trees were estimated using turnover rates presented in the literature (Lehtonen et al. 2004, Muukkonen and Lehtonen 2004, Starr et al. 2005, Liski et al. 2006) Table 1). The litter input of the ground vegetation was estimated with litter turnover rates presented by Liski et al. (2006). Litter from harvest residues was weighted in the proportions of the implemented harvesting for spruce and pine sites according to Finnish Statistical Yearbook of Forestry.

Model initiation and soil carbon simulations

The Finnish Meteorological Institute (FMI) provided the daily weather data (1961-2008) that was applied in the model runs (Figure 5). The weather data covered whole Finland in 10*10 km grids. The daily weather data was fetched from the nearest point from the grid for each NFI plot. Weighted average annual temperature, precipitation and temperature amplitude were calculated for Southern Finland (Figure 5). The model initialisation was done with the NFI6 data from (1971-1974) in Southern Finland. The average annual litter input of trees, ground vegetation, harvesting and natural mortality of the time period were given to the Yasso07 model. The model was driven with the given litter and mean weather data of 1972-2008 to the steady state using 10 000 years as an initiation period. According to earlier research approximately 10 years of simulation since spin-up is enough to cancel out the effect of spin-up level (Peltoniemi et al. 2006). Therefore, modelled soil carbon time series reach 1972-2008 although the comparison between measured and modelled data falls between years 1986-2006.

One of the aims of the project was to produce new parameters for Yasso07 model based on areal measurements. Therefore, three different parameter values were tested: Parameter values based on Scandinavian measurements, parameters based on European measurements and parameters based on Global measurements.

Uncertainty estimations

Uncertainty of the results was estimated by calculating the standard error of the mean for the measured (BioSoil) and modelled (Yasso07) soil carbon stocks and stock changes. Uncertainty of the results modelled by Yasso07 consists of error from the parameter values and error from the litter input data. Uncertainty from the error of the parameter values was evaluated varying parameter combinations 500 times from the MCMC parameter estimates listings and uncertainty from the error of the litter input data was evaluated taking observations randomly from normal distribution taking into account the known error of the litter type using 500 iterations. The uncertainty of litter input was based on the Peltoniemi et al. (2006).

Collection of the soil carbon samples, BioSoil data

The soil carbon samples were collected from sampling plots representing soil survey network covering the whole country. This systematic network was established selecting 486 plots from the network of 3000 permanent monitoring plots of eighth national forest inventory (NFI) Mäkipää and Heikkinen (2003). These plots represent the average Finnish mineral soil forests in respect of both soil type and tree species distributions. The soil samples (referred in this text as BioSoil) were collected for the first time in 1986-1988 or in 1995 and the sampling was repeated in 2006 giving either 11 or 16-20 years between the measurements.

Permanent NFI plots are circles of 300 m^2 in size with the radius of 9.77m. The soil samples were taken during the first round of sampling (1986-1988, 1995) outside this circle 11m from centre of the NFI sampling plot (Figure 6). Additionally, there were 20 intensive sampling plots, in which samples were taken 14m from the centre of the plot. In the first sampling, the amount of sampling points depended on the average thickness of the organic layer so that with average organic layer thickness of 0-2 cm the amount of sampling points was 30, with 2-9 cm thickness 20 points and with over 9 cm thickness 10 sampling points, respectively. No mineral soil samples were included in this analysis. Above-ground parts of the living plants as well as the litter layer were excluded from the samples.

During the second sampling round in 2006, subsamples from the organic layer were taken 9 m from the plot centre (Figure 6). A composite sample consisted of 10 subsamples if the thickness of the organic layer was at least 7 cm, and 20 subsamples if the thickness was 1-6 cm.

In some cases, sampling was not possible in the determined spots and in these cases the sample was taken at the maximum 3 meters along the tangent or radius from the original spot to avoid sampling in disturbed soils, e.g. paths, ant nests, ditches etc.

Organic layer samples were dried at a temperature of 35-44 ºC, weighted and ground with a mill with a 2 mm bottom sieve. The moisture content of the air-dry samples was determined with a TGA analyzer. Total C was analyzed on soil samples with a Leco CHN devise (Leco, St Joseph, MI, USA).

Comparison between measured and simulated soil carbon stocks and stock changes

In order to have meaningful comparison data was narrowed down to include samples only from southern Finland. Furthermore, the data was restricted to most frequent fertility classes on upland soils and to site types *Oxalis-Myrtillus*-type (the most productive sites), *Myrtillus*-type (richer intermediate sites) and *Vaccinium*-type (poorer intermediate sites) according to Cajander's (1949) classification (Hotanen et al. 2008). The selected monitoring plots were dominated either by Scots pine (Pinus sylvestris) or Norway spruce (Picea abies). Respectively, in soil carbon simulations with Yasso07 model the input data was restricted to Southern Finland and to the corresponding forest and site types.

Soil carbon stocks were compared between the measured soil carbon stocks published by Peltoniemi et al. 2004 and simulated stocks by Yasso07. In Peltoniemi et al. (2004) the soil carbon stock was measured between 0-70cm and the results were extrapolated to attain soil carbon stock 0-100cm.

Although there are tree stock measurements available for BioSoil sampling plots, these measurements were not used as an input data for the model, because plot-scale comparison was expected to be highly uncertain according to previous study (Häkkinen et al. 2011). However, the site type distributions, tree species distributions, stand age distributions as well as the basal area of the tree stands were similar on the permanent plot used in soil sampling and in the NFI data that was used as an input data for the Yasso07 model.

Sensitivity analysis of Yasso07 model

In order to test weather Yasso07 model is more sensitive to variation in temperature or precipitation the simulations were carried out standardising either temperature or precipitation. The Alternate input weather datasets were 1) annually varying precipitation, but average long term (1972-2008) temperature and temperature amplitude and 2) annually varying temperature and temperature amplitude but average long term (1972-2008) precipitation. Furthermore, climate sensitivity was demonstrated by running the model with annually varying weather, using sliding average of climate variables over 5 years and using average long term climate (1972-2008). In order to test weather Yasso07 model is more sensitive to variation in input climate data or input litter data simulations were carried out using either annual litter data together with average climate data or annual climate data together with standardised litter input data.

Results

Comparison between measured (BioSoil) and modelled (Yasso07) soil carbon stocks and carbon stock changes

Average measured and simulated soil carbon changes are of the same magnitude in Southern Finland (dataset ”All”) (Figure 7, Table 2). However, in the empirical measurements, variation is large (Figure 8) contributing to high standard error especially in the subgroups (Table 3). Yasso07 estimations for the subgroups differed more from the measured than the estimation for the combined data (dataset “All”). In OMT forests, Yasso07 overestimates the soil C changes, and in MT forests underestimates the soil C changes (Figure 9). Measured carbon stocks based on Peltoniemi et al. (2004) are higher than the carbon stocks estimated by Yasso07 (Figure 10, Table 4), but the simulated carbon stocks are within the error limits of the measured (Table 5).

Comparison between Yasso07 and old Yasso

Yasso07 gave higher estimations of carbon stock changes than old version of Yasso (Figure 8, Table 2), although old Yasso predicted higher carbon stocks (Figure 10, Table 3). In the time series simulated by Yasso07 and old Yasso the soil carbon stock changes are of the same magnitude (Figure 11). However, models differ in sensitivity to temperature and precipitation variations. Old Yasso is sensitive to variation in temperature, whereas Yasso07 is more sensitive to variation in precipitation: The highest soil carbon accumulation predicted by old Yasso occurs in years with the lowest annual temperature, whereas Yasso07 predicts highest accumulation for years with lowest annual precipitation and vice versa (cf. Figure 5 and Figure 11). Using average climate data for estimations, models give similar results (Figure 12, Table 6).

Comparison between soil carbon stock change estimations based on different parameter values (Scandinavian, European and Global)

Yasso07 model was re-parameterised in this project using areal litter-bag measurements. New parameter sets based on Scandinavian, European and Global measurements had similar parameter values (Table 7), but had differences in climate dependence due to large variation in climate variables in Global data compared to European or Scandinavian data (Figure 13). Parameters for Yasso07 model based on areal measurements gave similar estimations for both soil carbon stock and soil carbon change (Figures 8-12). Parameters based on global measurements gave little higher estimates than European or Scandinavian parameters, but the differences were small. Global parameters contributed to slightly higher year-to-year variation in soil carbon changes than the two other parameter sets indicating higher sensitivity to weather conditions (Figure 11).

Although the response to climatic variables (temperature and precipitation) was different between parameter sets (Scandinavian, European, Global) (Figure 13), different parameterisations gave similar estimations for annual soil carbon change (Figure7, Figure 11).

Sensitivity of Yasso07 model to variation in climate data and litter input data

Year-to-year variation in weather had a more pronounced effect on soil carbon change estimations by Yasso07 than the variation in the litter input data (Figure 14a). Large variation between years was levelled out when using either five year floating mean or long term (1972-2008) average of the climate data (Figure 14b). In order to test whether Yasso07 model is more sensitive to variation in temperature or to variation in precipitation the simulation were run with either standard temperature or with standard precipitation. The results suggest that variation in precipitation changes the estimations for soil carbon more than variation in temperature (Figure 15). The variation in the decomposition rate factor (k) support this finding: In the prevailing Finnish climate (mean annual temperature ~1–5° C, mean annual precipitation 400 – 900 mm) variation in precipitation has greater effect on decomposition rate factor (k) than variation in temperature (Figure 13). Different parameterisations (Scandinavian, European and Global) were equally sensitive to variation in temperature and to variation in precipitation (Figure 15).

Comparison between Yasso07 and soil carbon model Romul

Soil carbon time series simulated by Yasso07 model were compared with soil carbon series simulated by soil carbon model ROMUL, which is a Russian soil carbon model. In the ROMUL model the temperature and soil moisture modifiers of the fluxes take a variety of forms, given as step-vice defined functions (Chertov et al. 2007). Typically, all these show an optimal range of values, where the decomposition takes place at a full rate and tapers off outside the optimal conditions.

The soil carbon model ROMUL operates at the daily time step, while Yasso07 has been applied here at with the annual time step. Although the time steps of the models differ, the comparison have been carried out by using the situation in soil at the end of the year. The soil carbon changes simulated by these two models using the same input litter data were similar (Figure 16). The highest and lowest values predicted by Yasso07 and ROMUL did not always occur in exact same time, but the overall trends of carbon stock changes over the years were congruent.

Updating from Yasso to Yasso07 –Effects on time series of the greenhouse gas inventory

Similar soil carbon stock changes were simulated with the old version of Yasso and Yasso07 for class "All" (Figure 7 and 9) suggesting that updating from Yasso to Yasso07 will have only minor effects on the soil carbon time series used in the greenhouse gas inventory. The application annual weather data instead of long term averages had greater effect on estimated soil carbon changes than used model version (Figure 17). Long term soil carbon change simulated by Yasso07 with Scandinavian parameterisation and annually changing weather was lower than measured values, while Scandinavian parameterisation and constant weather gave higher estimates than measured (Figure 17). In addition, old Yasso version with constant weather data gave values that were close to BioSoil data from 1986 – 2006. Due to large uncertainty in the soil carbon stock change measurements, model simulations for the class “All” did not differ statistically from the measurements – regardless model version and weather applied.

Discussion

Comparison between measured (BioSoil) and modelled (Yasso07) soil carbon changes

Although the variation is large in the empirical measurements, measured and simulated soil carbon changes are of the same magnitude in Southern Finland (dataset ”All”). In the study conducted in different geographical regions of Sweden, Yasso07 predicted similar soil carbon changes than the empirical measurements (Ortiz et al. 2009). In our study, Yasso07 estimations for the subgroups defined by forest types differ more from the measured than the estimation for the combined data. Yasso07 model does not take site fertility into account nor the effects of nutrient availability to decomposition. Carbon-nitrogen ratio (C/N ratio) of the soil gives a rough estimation for soil fertility, low ratio indicates fertile site and high ratio poor site. C/N ratio of soil was 22 in OMT forests, 28 in MT forests and 33 in VT indicating significant differences in soil fertility between subgroups.

Uncertainties in the estimation of the input biomass rather than the functionality of the Yasso07 model might be one reason for the differences between measured and modelled carbon stock changes in the subgroups. There is a steep increase in the estimated litter input in OMT forests from 1970s to 1990s i.e. between NFI6 and NFI8 contributing to large modelled carbon stock increase in these sites. The increase in the litter input might be partly due changed definition of site types between inventories and also due to changes in site type distributions in long term (Reinikainen et al. 2000). Furthermore, there are high uncertainties related to estimations of birch litter, especially fineroot litter, because there are no measurements available. Birch is more frequent in OMT forests than in MT or VT forests. Also in the BioSoil data estimate for the carbon change in OMT forests is highly uncertain, because the sample size is smallest of all subgroups (n = 38).

Large variation in the measured soil carbon changes is due to large heterogeneity of soils, and due to differences in the soil carbon accumulation between forests of different ages (Peltoniemi et al. 2004, Häkkinen et al. 2011), and in particular, due to differences in the first and second sampling. In the study by Häkkinen et al. (2011) conducted in the tree stands dominated by either by Scots pine (Pinus sylvestris) or Norway spruce (Picea abies) where the stand age varied between 25 and 65 years at the time of the first sampling the mean carbon stock of the organic layer was 1444±95 g m^{-2}. In the second sampling 16-19 years later the mean carbon stock of the organic layer was 1852±67 g m^{-2} giving increase of the carbon stock 23±2 g C m^{-2} per year. In this study the corresponding results (dataset “All”, southern Finland, BioSoil 1986-2006) were 12±4 g C m^{-2} and in all BioSoil samples 14±5 g C m^{-2}. Large carbon accumulation observed by Häkkinen et al. (2011) is due to selection of tree stands where carbon accumulation was expected to be highest based on stand age.

Site type distributions, tree species distributions, stand age distributions as well as the basal area of the tree stands were similar between BioSoil data and recent NFI data that was used as an input data for the Yasso07 model. Therefore, there is no basis to assume that differences in soil carbon accumulation between measured and modelled results were the consequence of dissimilarity in forest treatment at regional scale. The comparison between measured and modelled was not carried out on the sampling plot scale, so we were not able to determine possible effects of logging to the soil carbon change. However, since stand age distributions as well as the basal area of the tree stands were similar between BioSoil data and with recent NFI data we can assume that the rate of loggings were similar in NFI plots used as an input data for the model and in BioSoil sampling plots.

Comparison between measured (BioSoil) and modelled (Yasso07) soil carbon stocks

Measured carbon stocks based on Peltoniemi et al. (2004) are higher than the carbon stocks estimated by Yasso07 although the simulated carbon stocks are within the error limits of the measured. In Peltoniemi et al. (2004) carbon stocks simulated by old Yasso and measured carbon stocks are similar, probably due to small number of simulated sites enabling detailed estimation of the input litter. Compared to the old Yasso, there is a new feature in Yasso07, where the decomposition of the coarse wood litter depends on the wood dimensions. Therefore, inYasso07 coarse wood litter decomposition is slower than in the older version. Despite the slower decomposition, old Yasso estimated higher carbon stocks than Yasso07. In the previous study the amount of dead wood in forest has been observed to be only 0.14-0.22 tn ha^{-1} (Lehtonen et al. 2011), which is only ~0.15% of the total carbon stock in the forest soil in Southern Finland. Yasso07 model estimation have been compared with measured C stock in afforested and deforested sites in the previous study by Karhu et al. (2011) where simulation results were well in accordance with measured carbon stock on most sites.

Comparison between Yasso07 and old Yasso

Carbon stock changes estimated by Yasso07 were higher than estimations by old version of Yasso, although old Yasso predicted higher carbon stocks. The slower decomposition of the coarse wood litter in Yasso07 than in old Yasso likely contributes to higher carbon accumulation in short term. In long term (both models were run into steady state using 10 000 years as an initiation period), the differences related to the sensitivity to weather conditions probably have more influence to the results than differences in decomposition rate. Yasso07 simulations carried out with Scandinavian parameterisation resulted in carbon change estimations that were closest to the changes predicted by old Yasso.

When comparing the time series simulated by Yasso07 and old Yasso the soil carbon stock changes are of the same magnitude. However, models differ in sensitivity to temperature and precipitation variations. Old Yasso is sensitive to variation in temperature, whereas Yasso07 is more sensitive to variation in precipitation. In old Yasso model variation in annual temperature between years is taken into account, but there is only one index describing soil moisture (effect of drought) that does not take into account differences between years. When using average weather data for estimations, models give similar results.

Comparison between different parameter values (Scandinavian, European and Global)

New parameter sets for Yasso07 model based on Scandinavian, European and Global measurements had similar parameter values. There were, however, differences in climate dependence. This was due to large variation in climate variables in Global data that was used to calculate new parameter values compared to European or Scandinavian data. Parameters based on global measurements gave little higher estimates for soil carbon change than European or Scandinavian parameters, but the differences were small. Global parameters also contributed to slightly higher year-to-year variation in soil carbon changes than the two other parameter sets indicating higher sensitivity to weather conditions. This finding was supported when running the model with either standardised temperature or precipitation: year-to-year changes were somewhat larger with Global parameterisation but the differences between parameterisations were small. Similar parameter values as well as similar estimated soil carbon suggest stability and credibility of Yasso07 model.

Sensitivity of Yasso07 model to variation in climate data and litter input data

Yasso07 simulations carried out by standardising either temperature or precipitation suggest that variation in precipitation changes the estimations for soil carbon more than variation in temperature. Simulations run by annually changing climate parameters gave similar C stock change estimation than simulations run by standardised temperature, whereas simulation run by standardized precipitation decreased annual variation of C stock. Accordingly, variation in precipitation had more pronounced effect on decomposition rate factor (k) than variation in temperature. Year-to-year variation in weather had a more pronounced effect on soil carbon change estimations than the variation in the litter input data further emphasizing the sensitivity of the model to variation in climate input data. Litter decomposition has been shown to be strongly affected by climate conditions (temperature, precipitation) in the previous studies (Meentemeyer, 1978; Berg et al., 1993; Aerts, 1997; Liski et al., 2003; Parton et al., 2007).

Comparison between Yasso07 and other soil carbon models

Soil carbon time series simulated by Yasso07 model were compared with soil carbon series simulated by soil carbon model ROMUL. The soil carbon changes simulated by these two models using the same input litter data were congruent. Although the highest and lowest values predicted by Yasso07 and ROMUL did not always occur in exact same time the overall trends of carbon stock changes over the years were similar. Differences in the timing of peaks might be a consequence of different assumptions between models about timing of the litter input. In Yasso07 all litter input is assumed to occur in the beginning of the year, whereas in ROMUL the litter input follows a more realistic cycle: pine needles in autumn, spruce needles all around the year and birch leaves in autumn. Yasso07 has been applied here (and in the GHG inventory) with annual time step, while ROMUL has been applied with daily time step. However, to make the results more comparable, the carbon stocks at the end of the year were applied for both models. The sensitivity of the Yasso07 model to the variation in annual precipitation becomes evident in this comparison by higher predicted carbon loss by Yasso07 in years with high precipitation.

There are few published studies where Yasso07 model is compared to other soil carbon models. However, in the recently published study by Thum et al. (2011) soil carbon stocks and stock changes in grassland and forest soils were calculated by Yasso07 model and CBALANCE model. Yasso07 model produced soil carbon stock estimates that were much closer to measured values than estimates produced by CBALANCE. Yasso07 also captured better the seasonal cycle of the direct CO_2 exchange measurements at the three grassland sites considered. For the five forest sites also analyzed, the results were ambiguous and the root-mean-square error (RMSE) error was 12% larger for Yasso07 than for CBALANCE.

Updating from Yasso to Yasso07 –Effects on time series of the greenhouse gas inventory

Similar soil carbon stock changes were simulated with the old version of Yasso and Yasso07 for class "All" suggesting that updating from Yasso to Yasso07 will only have minor effects on the soil carbon time series used in the greenhouse gas inventory.

Soil carbon time series of the GHG inventory will be more affected by the application annual or floating mean weather data instead of long term averages.

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Table 1. Litter production rate coefficients.

Tree species	Needles	Brances	Bark of stems	Bark of stumps	Roots > 2 mm	Fineroots
pine	0.245	0.02	0.0052	0.0029	0.0184	0.85
spruce	0.1	0.0125	0.0027	0	0.0125	0.85
deciduous	0.79	0.0135	0.0029	0.0001	0.0135	0.85

Table 2. Annual soil carbon stocks changes between years 1986 and 2006 for OMT, MT and VT forests in Southern Finland (All), OMT forests dominated by Norway spruce (OMT, spruce), MT forests dominated by Norway spruce (MT, spruce), MT forests dominated by Scots pine (MT, pine) and VT dominated by Scots pine (VT, pine) simulated by Yasso07 (Scandinavian, European and Global parameterization), Yasso (old), measured annual soil carbon changes between years 1986-2006 (BioSoil, 86-06) and measured annual soil carbon changes either between years 1986-2006 or between years 1995-2006 (BioSoil, all). Standard errors of mean in parenthesis.

kg C ha^{-1} y^{-1}	All	OMT (spruce)	MT (spruce)	MT (pine)	VT (pine)
Yasso07 (Skand)	92 (16)	206 (40)	91 (17)	40 (8.5)	59 (13)
Yasso07 (Eur)	96 (18)	213 (40)	95 (18)	42 (8.2)	61 (14)
Yasso07 (Glob)	119 (22)	207 (61)	124 (15)	40 (8.5)	76 (17)
Yasso (Old)	76	176	88	25	44
Bio Soil 1986-2006	115 (58)	47 (159)	238 (137)	166 (152)	102 (114)
Bio Soil, all samples	136 (60)	47 (146)	203 (129)	195 (135)	123 (109)

Table 3. Standard errors of the mean for the simulated annual soil carbon stocks changes between years 1986 and 2006 simulated by Yasso07 (Scandinavian, European and Global parameterization), including both uncertainty from the litter input data and uncertainty originating from the parameters. Uncertainty originating from parameters is presented separately in parenthesis. Standard errors of the mean for measured soil carbon changes between years 1986-2006 (BioSoil, 86-06) and measured annual soil carbon changes either between years 1986-2006 or between years 1995-2006 (BioSoil, all). Abbreviations for the subgroups as in Table 2.

kg C ha^{-1} y^{-1}	All	OMT (spruce)	MT (spruce)	MT (pine)	VT (pine)
Yasso07 (Skand)	16 (4.2)	40 (7.4)	17 (5.2)	8.5 (3.1)	13 (3.3)
Yasso07 (Eur)	18 (3.8)	40 (7.1)	18 (4.9)	8.2 (3.0)	14 (2.8)
Yasso07 (Glob)	22 (2.5)	61 (4.6)	15 (3.5)	8.5 (1.9)	17 (1.9)
Bio Soil 1986-2006	58	159	137	151	114
Bio Soil, all samples	60	146	129	135	109

Table 4. Simulated soil carbon stocks in Southern Finland simulated by Yasso07 (Scandinavian, European and Global parameters), Yasso (old) and measured soil carbon stocks (Peltoniemi et al. 2004). Abbreviations for the subgroups as in Table 2. Standard errors of mean in parenthesis.

tn C ha^{-1}	All	OMT (spruce)	MT (spruce)	MT (pine)	VT (pine)
Yasso07 (Skand)	48 (9.7)	48 (10)	51 (11)	50 (11)	44 (9.7)
Yasso07 (Eur)	51 (11)	51 (10)	55 (11)	54 (11)	47 (10)
Yasso07 (Glob)	53 (11)	54 (12)	57 (11)	56 (13)	49 (10)
Yasso (Old)	66	65	68	71	60
Bio Soil			80 (22)	66 (21)	63 (30)

Table 5. Standard errors of the mean for the simulated annual soil carbon stocks calculated with Yasso07 (Scandinavian, European and Global parameterization), including both uncertainty originating from the parameters (in parentheses) and the combined uncertainty from the litter input data and parameters. Standard errors of the mean for measured soil carbon stocks (Peltoniemi et al. 2004). Abbreviations for the subgroups as in Table 2.

tn C ha^{-1}	All	OMT (spruce)	MT (spruce)	MT (pine)	VT (pine)
Yasso07 (Skand)	9.7 (2.2)	10 (2.2)	11 (2.3)	11 (2.4)	9.7 (2.1)
Yasso07 (Eur)	11 (2.0)	10 (2.0)	11 (2.1)	11 (2.2)	10 (1.9)
Yasso07 (Glob)	11 (1.5)	12 (1.4)	11 (1.5)	13 (1.6)	10 (1.3)
Bio Soil			22	21	30

Table 6. Simulated soil carbon stocks changes 1972-2008 simulated by Yasso07 using average weather data (1972-2008). Abbreviations for the subgroups as in Table 2.

kg C ha^{-1} y^{-1}	All	OMT (spruce)	MT (spruce)	MT (pine)	VT (pine)
Yasso07 (Skand)	147	265	164	97	109
Yasso07 (Eur)	150	270	168	99	110
Yasso07 (Glob)	194	362	229	118	143
Yasso (Old)	135	239	151	86	97

Table 7. Parameter values of Yasso07 model and their 95% confidence limits based on Global, European and Scandinavian litter-bag data.

	Global	European	Scandinavian	Unit	Interpretation
αA	-0.462±0.0003	-0.517±0.0002	-0.665±0.0004	a^{-1}	decomposition rate of A
αW	-4.802±0.003	-4.724±0.001	-5.182±0.003	a^{-1}	decomposition rate of W
αE	-0.307±0.0003	-0.266±0.0002	-0.397±0.0005	a^{-1}	decomposition rate of E
αN	-0.205±0.0001	-0.264±0.0001	-0.336±0.0002	a^{-1}	decomposition rate of N
*p*1	$2.27*10^{-4}±5*10^{-5}$	$0.048±5*10^{-5}$	0.017±0.0001	-	relative mass flow, W → A
*p*2	$0.014±7*10^{-5}$	$0.003±7*10^{-5}$	$0.030±9*10^{-5}$	-	relative mass flow, E → A
*p*3	$0.985±4*10^{-5}$	$0.968±5*10^{-5}$	$0.990±6*10^{-5}$	-	relative mass flow, N → A
*p*4	$0.844±6*10^{-5}$	$0.855±5*10^{-5}$	0.790±0.0001	-	relative mass flow, A → W
*p*5	$0.229±6*10^{-5}$	$0.215±5*10^{-5}$	0.166±0.0001	-	relative mass flow, E → W
*p*6	$0.003±2*10^{-5}$	$0.020±7*10^{-5}$	$0.001±2*10^{-5}$	-	relative mass flow, N → W
*p*7	$0.021±4*10^{-5}$	$0.003±3*10^{-5}$	$0.003±5*10^{-5}$	-	relative mass flow, A → E
*p*8	$2.07*10^{-4}±2*10^{-5}$	$0.002±2*10^{-5}$	$0.010±6*10^{-5}$	-	relative mass flow, W → E
*p*9	$0.009±4*10^{-5}$	$0.005±7*10^{-5}$	$0.006±5*10^{-5}$	-	relative mass flow, N → E
*p*10	$0.132±5*10^{-5}$	$0.137±5*10^{-5}$	0.200±0.0001	-	relative mass flow, A → N
*p*11	$0.198±7*10^{-5}$	$0.193±7*10^{-5}$	0.189±0.0001	-	relative mass flow, W → N
*p*12	0.266±0.0001	$0.099±7*10^{-5}$	0.070±0.0001	-	relative mass flow, E → N
β_1	$0.060±4*10^{-5}$	$0.096±9*10^{-5}$	0.059±9*10-5	$ºC^{-1}$	temperature dependence
β_2	$-2.79*10^{-4}±1*10^{-6}$	$-0.003±5*10^{-6}$	-0.001±5*10-6	$ºC^{-2}$	temperature dependence
γ	-1.166±0.0009	-2.458±0.002	-1.858±0.001	m^{-1}	precipitation dependence
ω_1	$-0.170±4*10^{-5}$	$-0.071±7*10^{-5}$	-0.100±7*10-5	$a^{-1}m^{-1}$	precipitation induced leaching (Europe)
ω_2	$-1.43*10^{-4}±4*10^{-6}$	*	*	$a^{-1}m^{-1}$	precipitation induced leaching (Americas)
ω_3	-1.120±0.0004	*	*	$a^{-1}m^{-1}$	precipitation induced leaching (Benin)
φ_1	-0.964±0.0004	-0.433±0.0006	-0.819±0.0004	cm^{-1}	first order size dependence
φ_2	0.915±0.0004	1.421±0.0004	1.153±0.0004	cm^{-2}	second order size dependence
r	$-0.155±6*10^{-5}$	$-0.269±5*10^{-5}$	-0.264±6*10-5	-	size dependence power
αH	$-0.001±1*10^{-6}$	$-0.001±7*10^{-7}$	-0.0008±1.3*10-6	a^{-1}	humus decomposition rate
*P*H	$0.002±3*10^{-6}$	$0.002±2*10^{-6}$	0.002±3*10-6		mass flow to humus

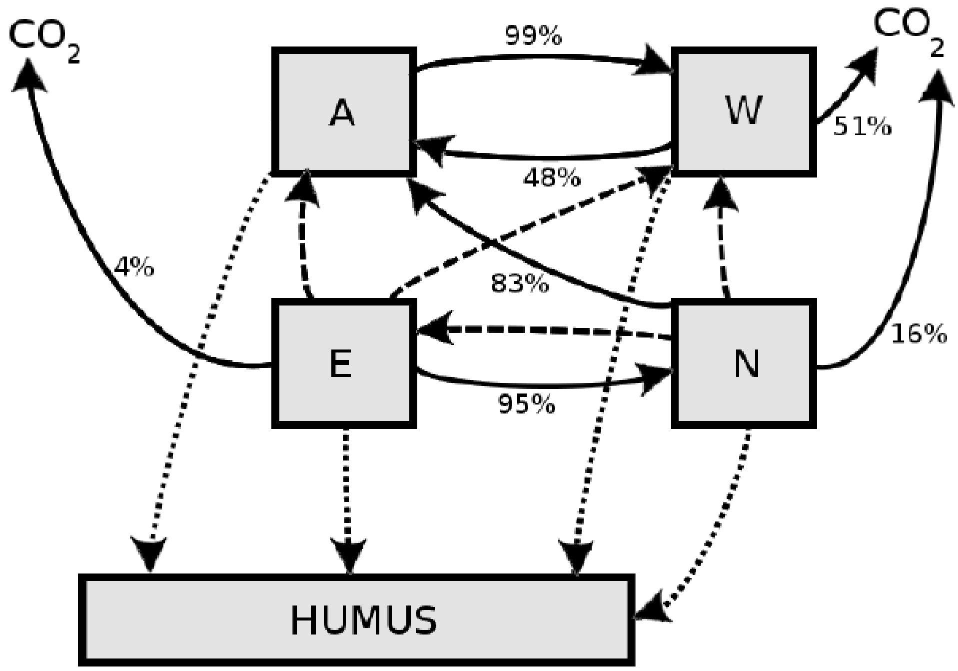

Figure 1. Flow diagram of the Yasso07 model. The carbon flows whose magnitudes differ statistically (95% confidence) from zero (solid arrows) between and out of the AWEN (A compounds hydrolysable in acid, W compounds hydrolysable in water, E compounds hydrolysable in ethanol or dichloromethane, N compounds neither soluble nor hydrolysable at all) fractions (square boxes) and their magnitudes; the small flows (dotted arrows) into humus (bottom box), each approximately 0.5%; and the mass flows (dotted arrows) into humus (bottom box), each approximately 0.5%; and the mass flows whose maximum *a posterioiri* estimates were indistinguishable from zero but whose 95% Bayesian confidence interval was boarder then 0.05 (dashed arrows) (Tuomi et al. 2010).

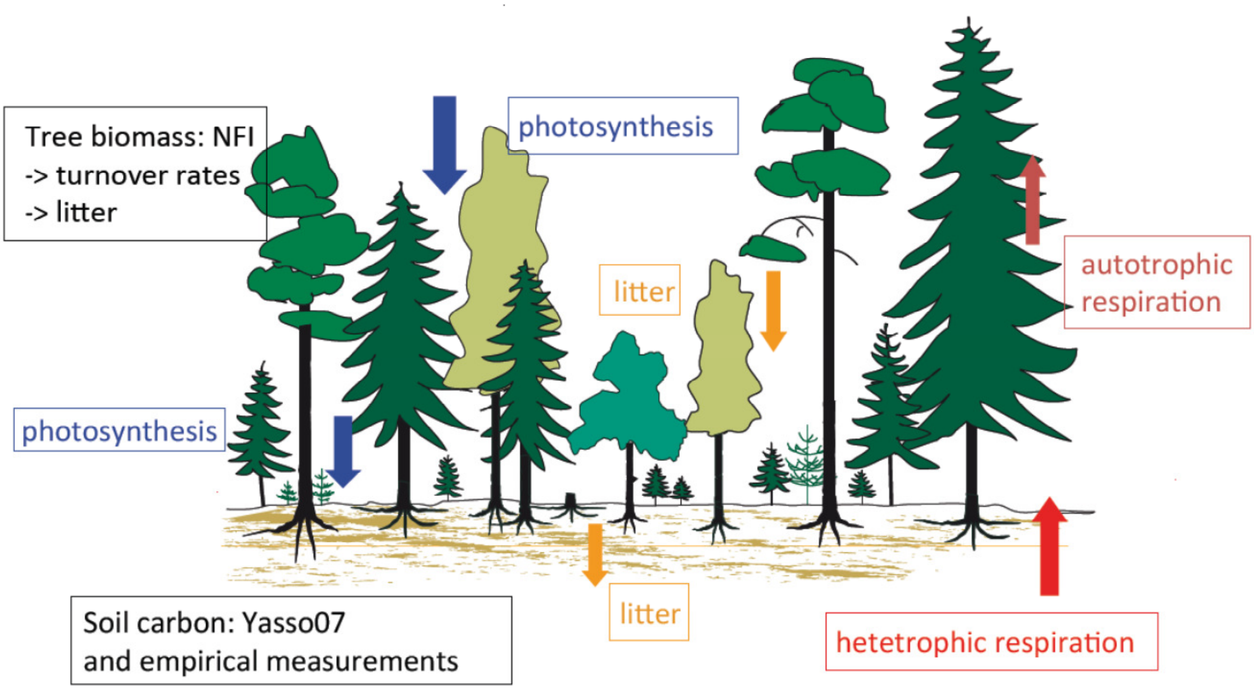

Figure 2. Illustration of the studied system.

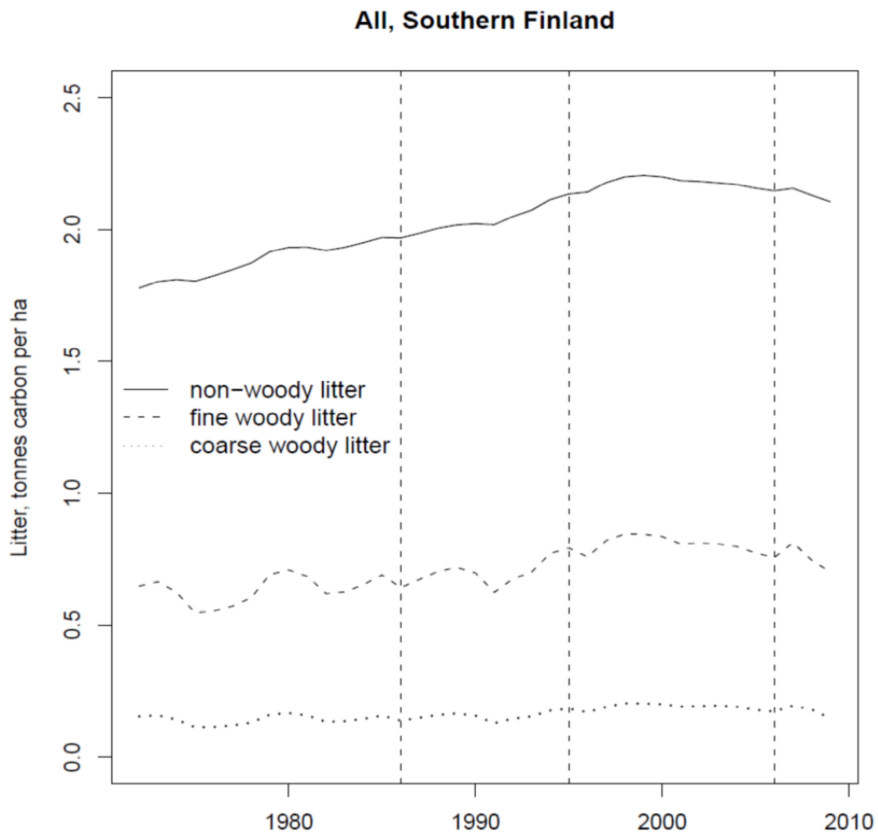

Figure 3. Time series of litter input to soil 1972-2008 divided into non woody litter (nwl), fine woody litter (fwl) and coarse woody litter (cwl) in OMT, MT and VT forests in Southern Finland (subset All). Vertical lines represent BioSoil sampling years 1986, 1995 and 2006.

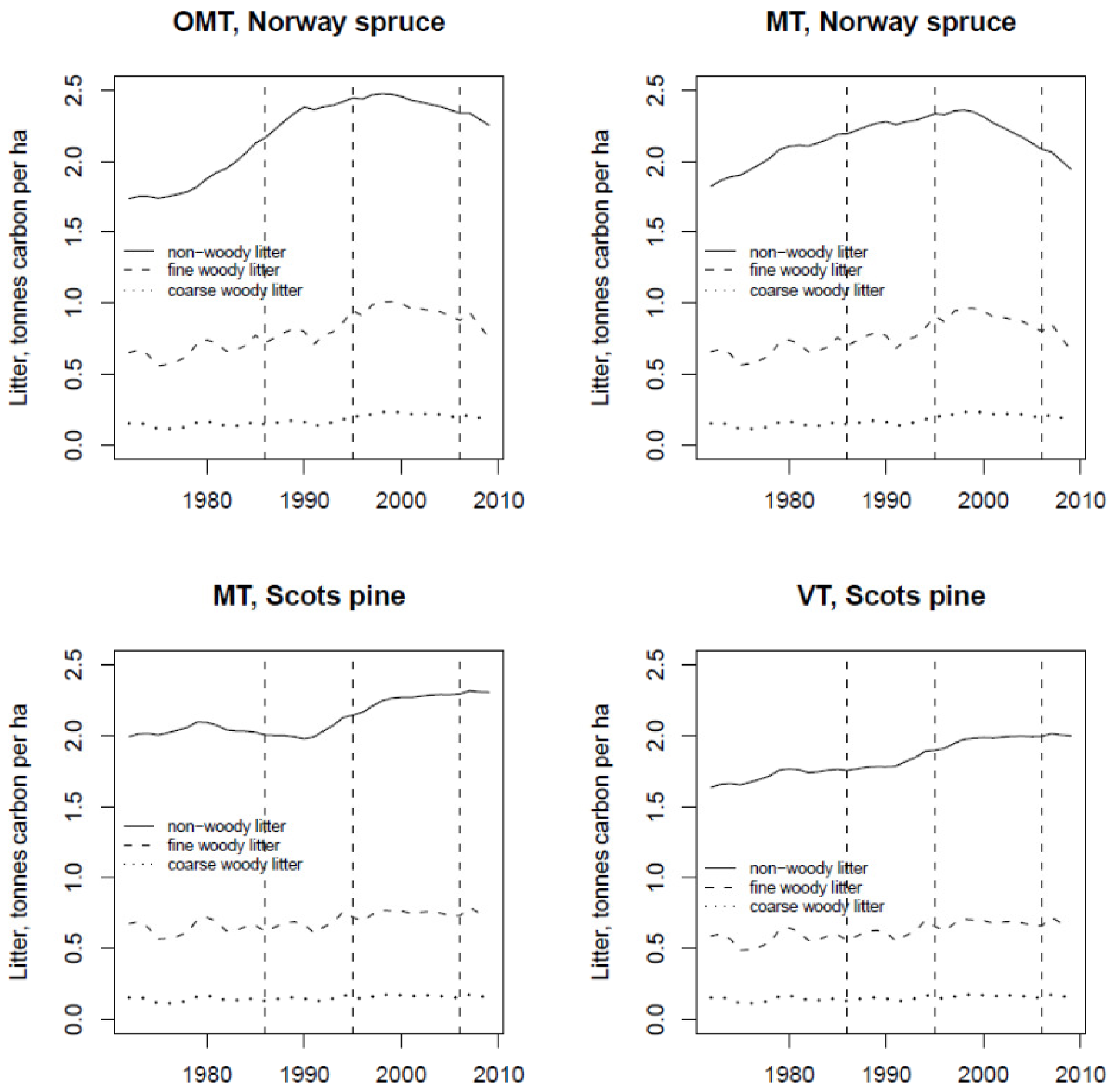

Figure 4. Time series of litter input to soil 1972-2008 divided into non woody litter (nwl), fine woody litter (fwl) and coarse woody litter (cwl) in OMT forests dominated by spruce, MT forests dominated by spruce, MT forests dominated by pine and VT forests dominated by pine. Vertical lines represent BioSoil sampling years 1986, 1995 and 2006.

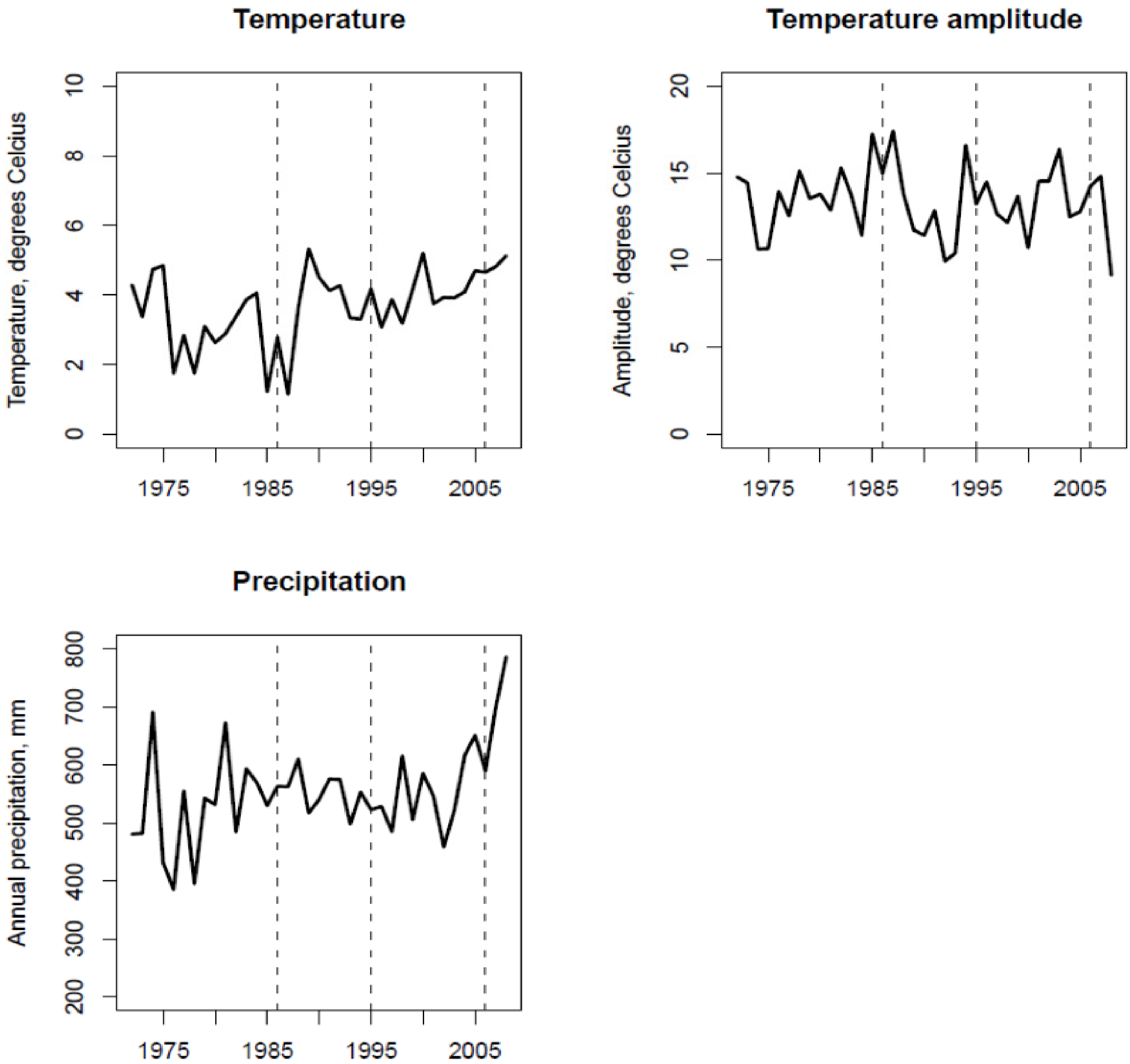

Figure 5. Time series of weather variables (mean annual temperature, mean annual temperature amplitude and mean annual precipitation) for years 1972-2008. Vertical lines represent BioSoil sampling years 1986, 1995 and 2006.

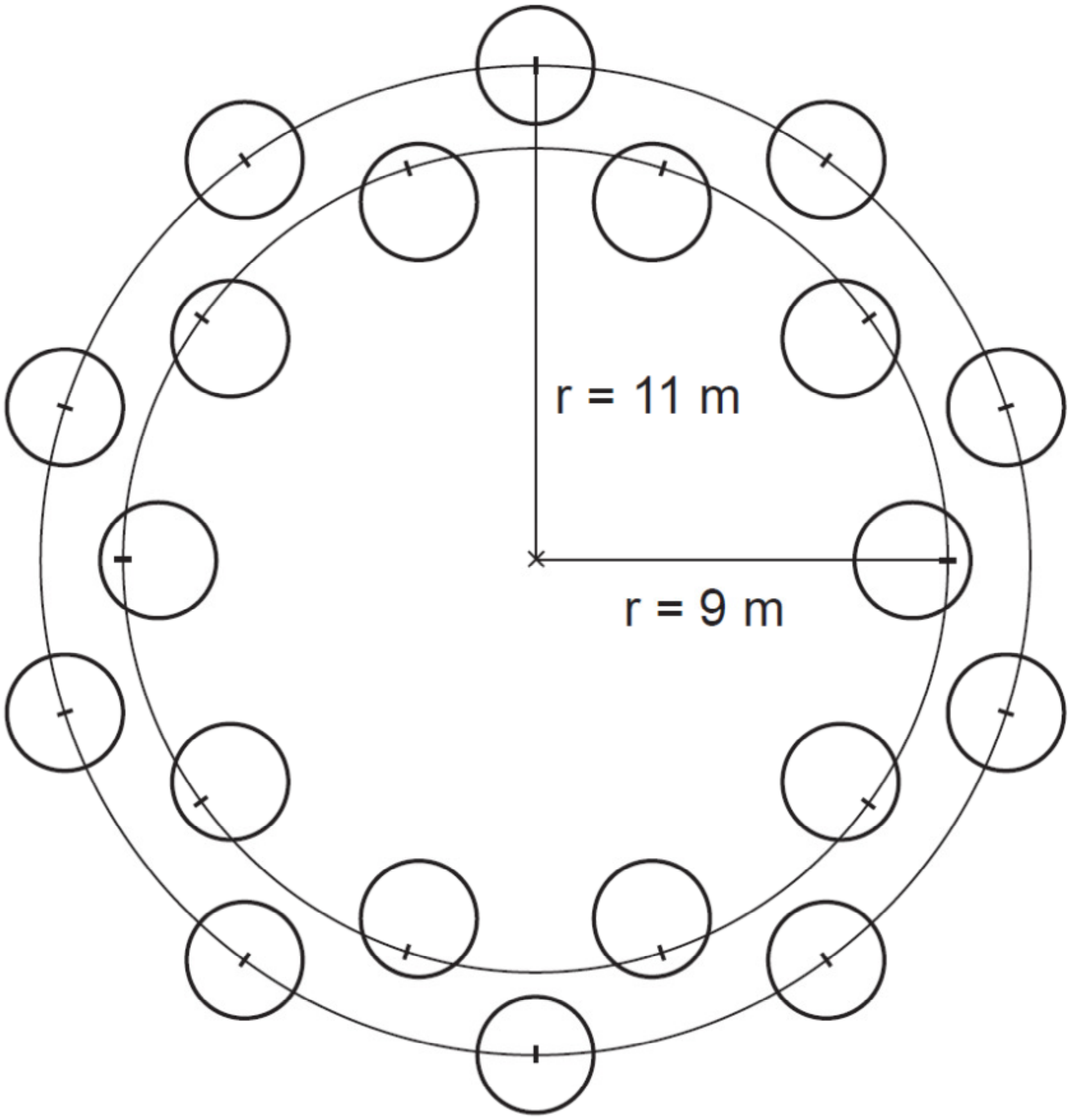

Figure 6. National forest inventory (NFI) sampling plot and the locations of the soil sampling points (BioSoil). Outer sampling circle is for first sampling (1986-88 and 1995), while inner is for second sampling (2006).

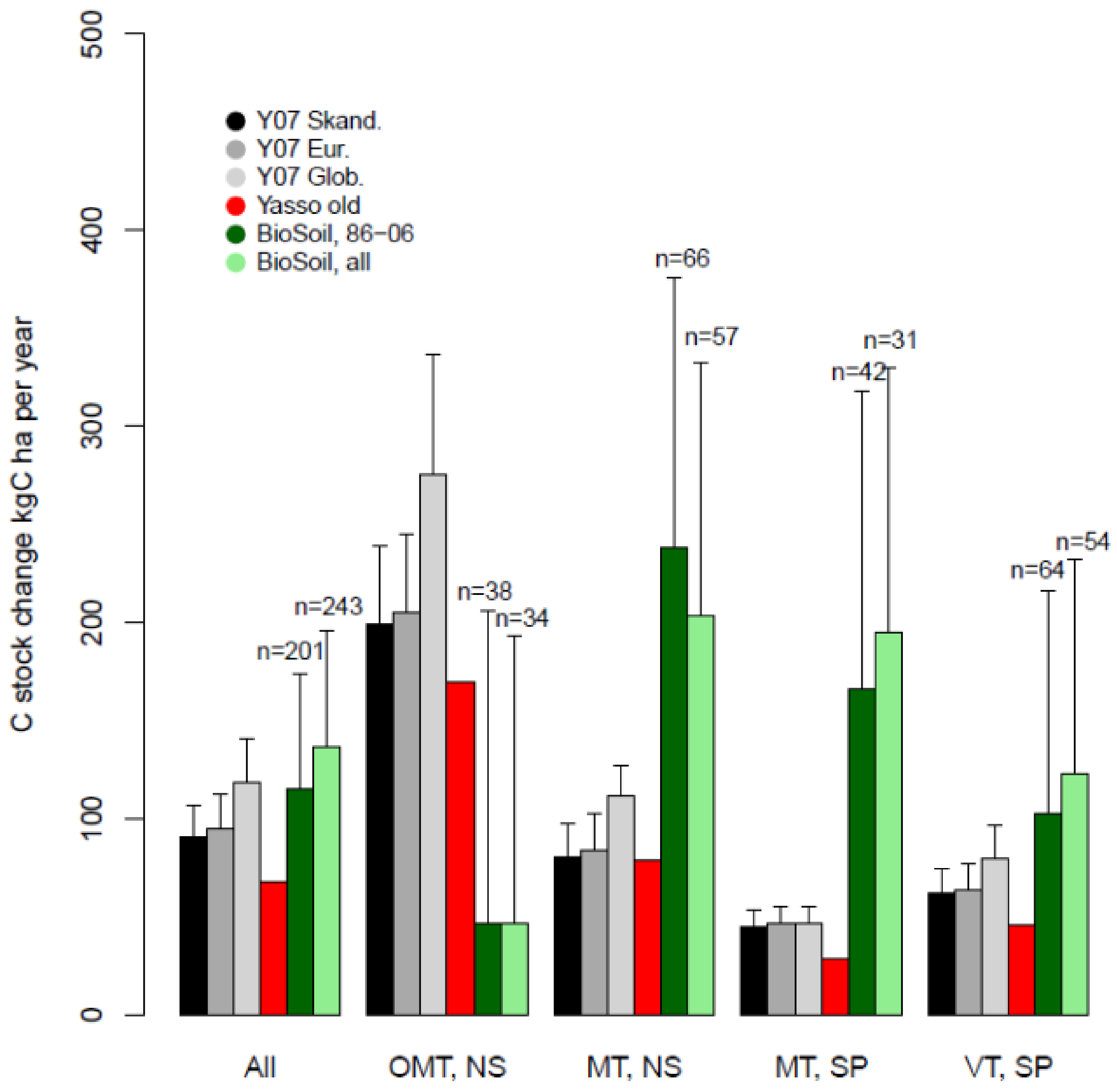

Figure 7. Simulated annual soil carbon stocks changes between years 1986 and 2006 calculated with Yasso07 (Scandinavian, European and Global parameters), Yasso (old) and measured annual soil carbon changes between years 1986-2006 (BioSoil, 86-06) and measured annual soil carbon changes either between years 1986-2006 or between years 1995-2006 (BioSoil, all) in OMT, MT and VT forests in Southern Finland. Abbreviations for the subgroups: OMT, MT and VT forests in Southern Finland (All), OMT forests dominated by Norway spruce (OMT, NS), MT forests dominated by Norway spruce (MT,NS), MT forests dominated by Scots pine (MT,SP) and VT dominated by Scots pine (VT,SP).

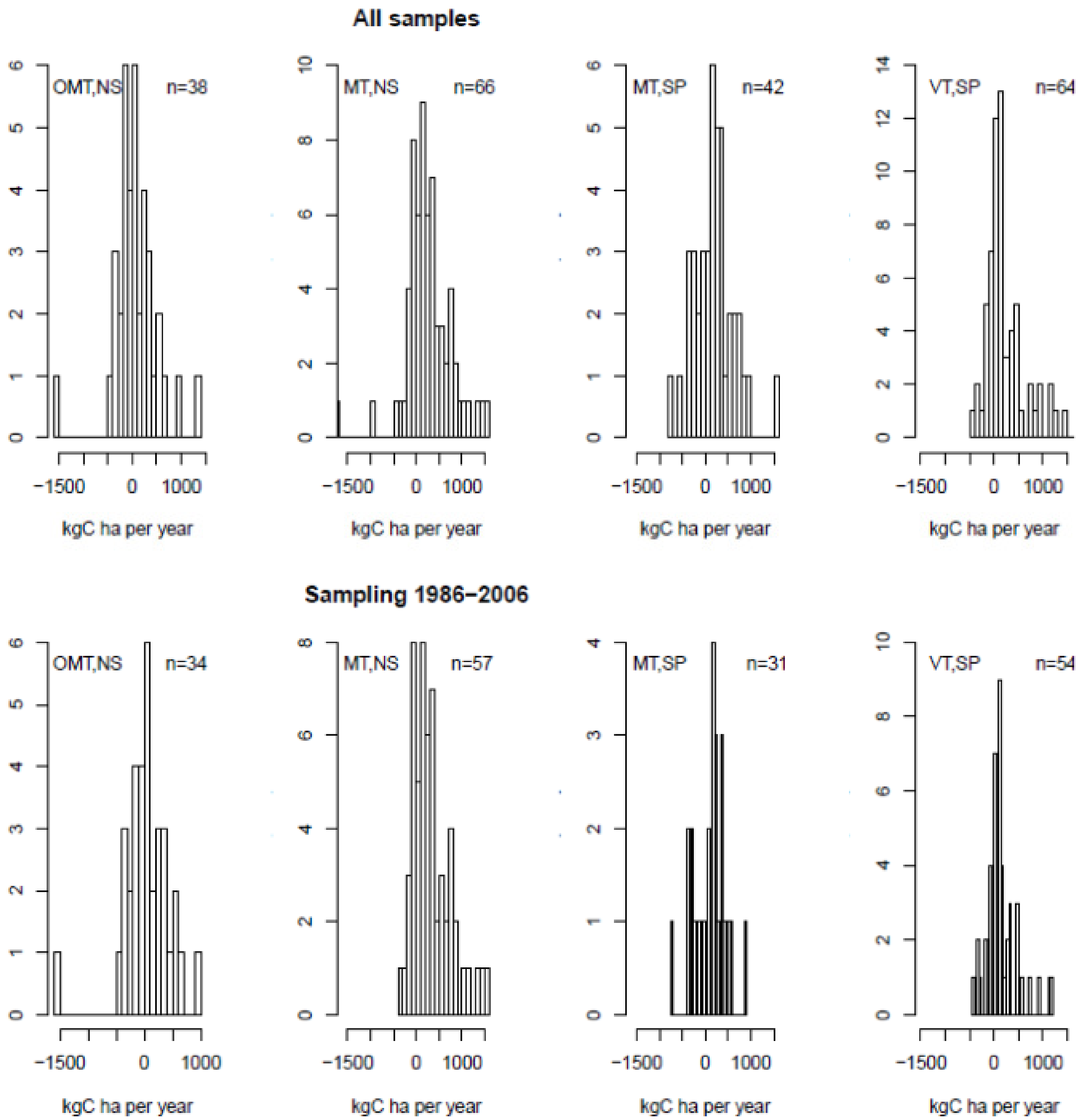

Figure 8. Frequency histograms of soil carbon accumulation (kg ha^{-1} y^{-1}) in BioSoil data for the subgroups determined by forest site types in the whole data (the first sampling either 1986-1988 or 1995) and in subpopulation with 1995 sampling excluded (the first sampling in 1986-1988). Abbreviations for the subgroups as in Figure 7.

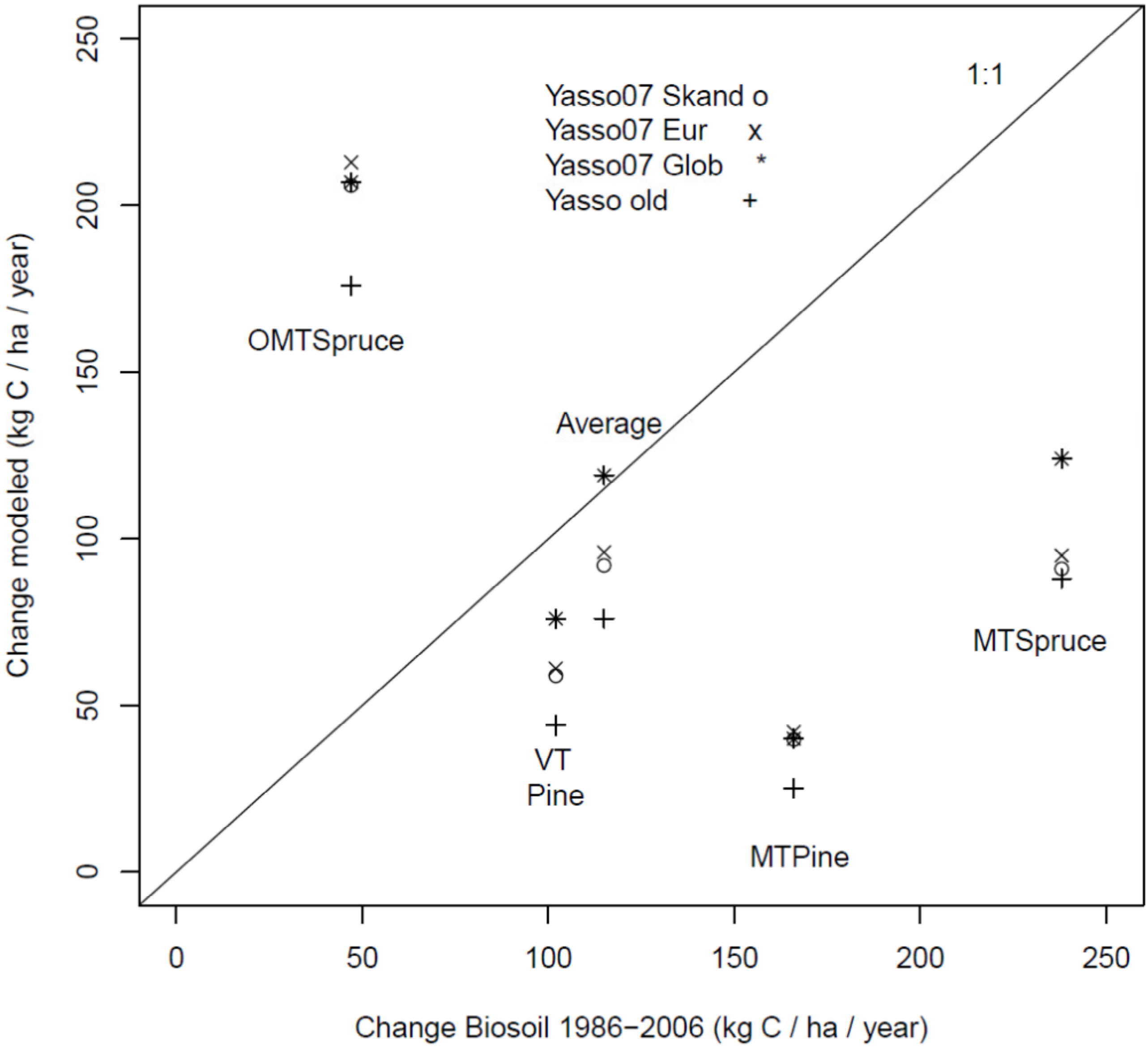

Figure 9. Measured (BioSoil) and modeled soil carbon change (kgC ha per year) plotted against 1:1 line. Modeled soil carbon change calculated with Yasso07 (Scandinavian, European and Global parameters) and measured annual soil carbon changes between years 1986-2006 in OMT, MT and VT forests in Southern Finland (Average), OMT forests dominated by Norway spruce (OMT, Spruce), MT forests dominated by Norway spruce (MT, Spruce), MT forests dominated by Scots pine (MT, Pine) and VT dominated by Scots pine (VT, Pine)

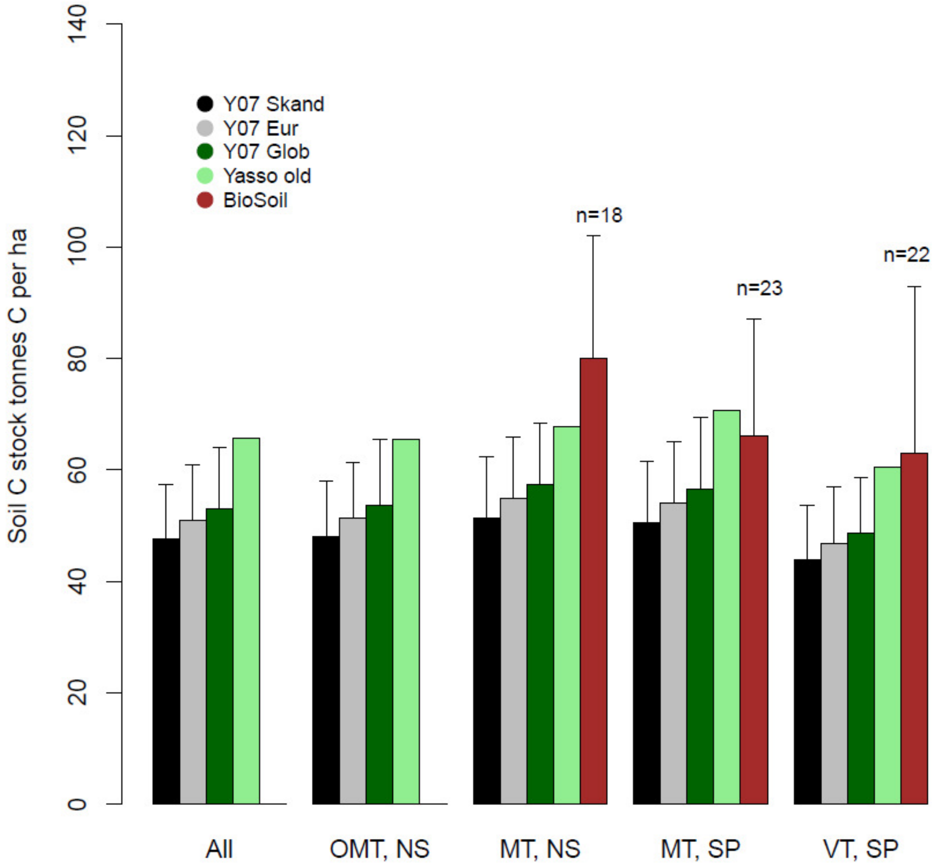

Figure 10. Simulated soil carbon stocks calculated with Yasso07 (Scandinavian, European and Global parameterization), Yasso (old) and measured soil carbon stocks (Peltoniemi et al. 2004.). Abbreviations for the subgroups as in Figure 7.

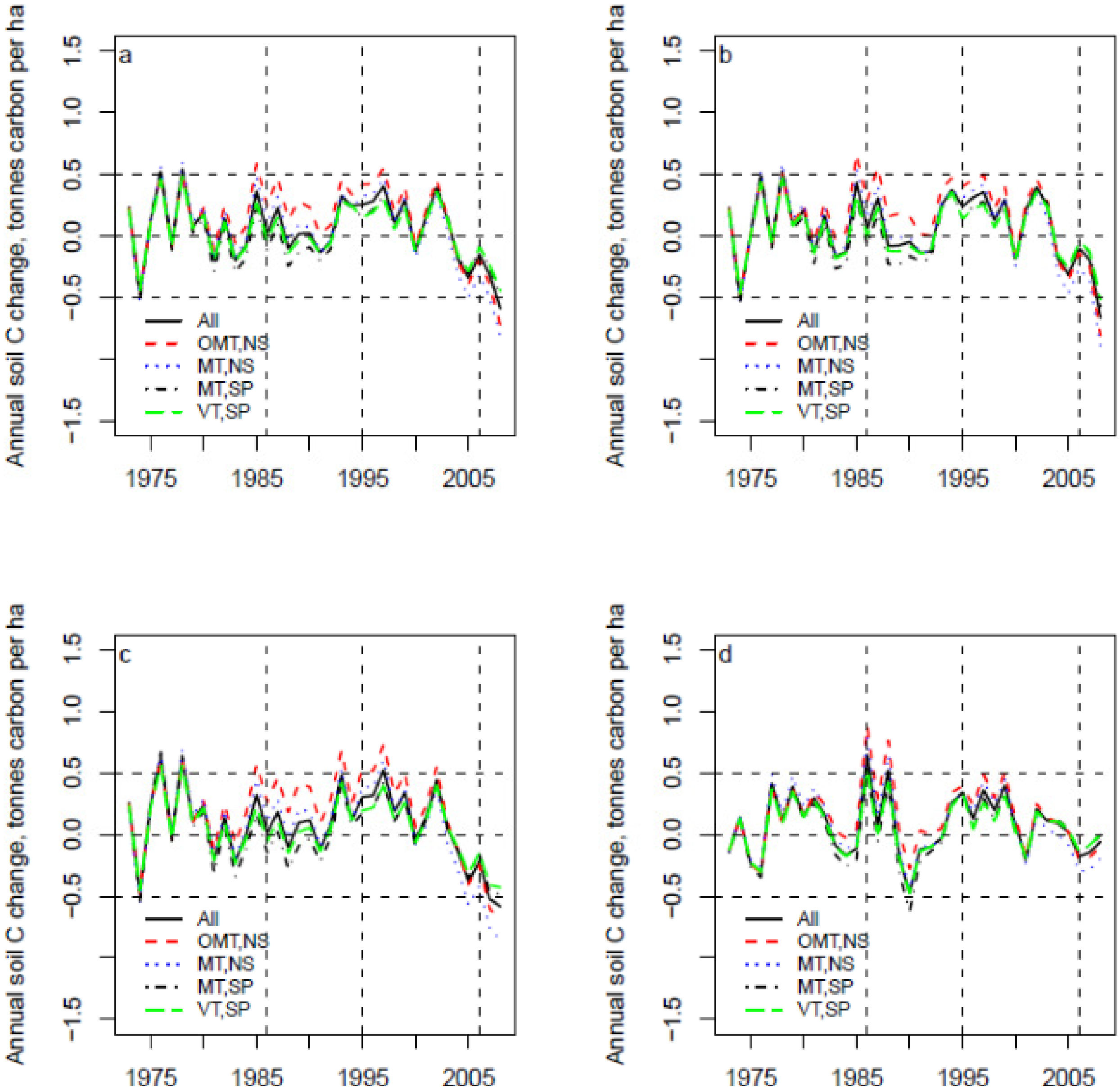

Figure 11. Simulated soil carbon change 1972-2007 calculated with a) Yasso07, Scandinavian parameterization, b) Yasso07, European parameterization, c) Yasso07, Global parameterization and d) Yasso (old), Global parameterization. In all the simulations, the annual weather data for the corresponding years was used. Vertical lines represent BioSoil sampling years 1986, 1995 and 2006. Abbreviations for the subgroups as in Figure 7.

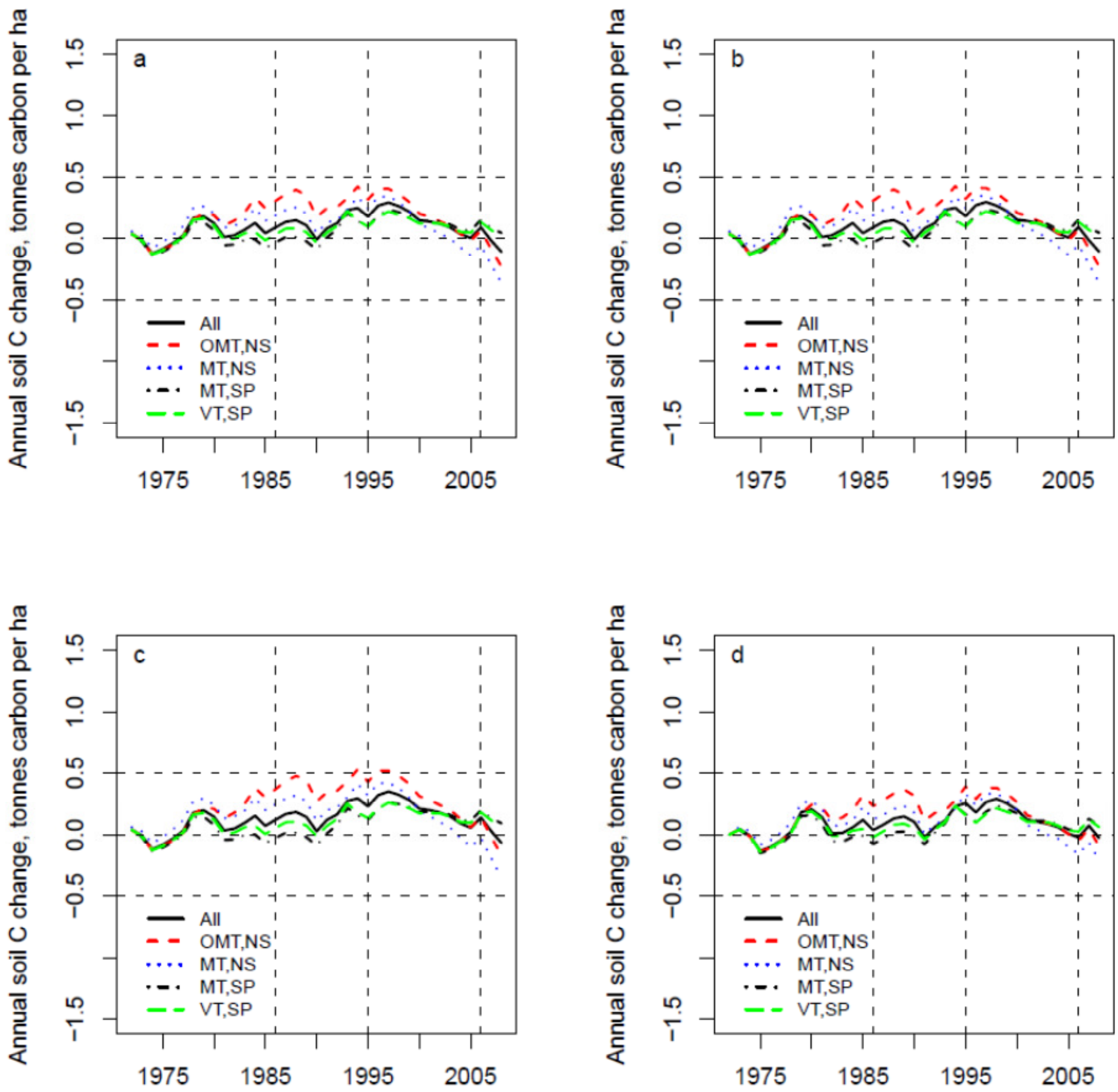

Figure 12. Soil carbon change 1972-2007 simulated by a) Yasso07, Scandinavian parameterization, b) Yasso07, European parameterization, c) Yasso07, Global parameterization and d) Yasso (old), Global parameterization. In all simulations, average long term weather over 36 years (1972-2008) was used. Vertical lines represent BioSoil sampling years 1986, 1995 and 2006. Abbreviations for the subgroups as in Figure 7.

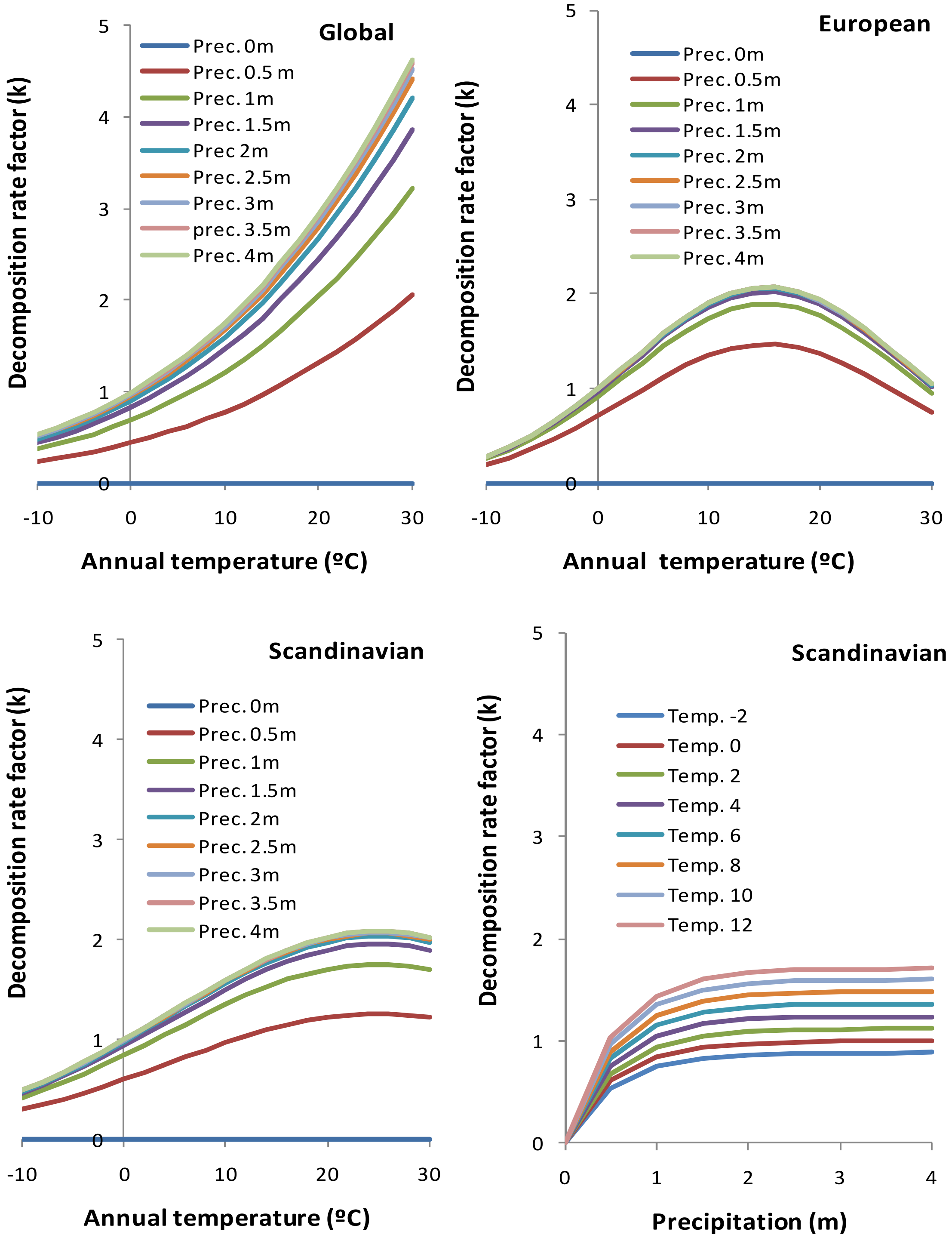

Figure 13. Climate dependence (average annual temperature and average annual precipitation) of decomposition rate factor (k) with the parameters β_1, β_2 and γ in parameter sets Scandinavian, European and Global expressed by function:

The decomposition rate factor (k) = exp(β_1*temperature+β2*[temperature]^2) * (1-exp[γ*precipitation]) (Tuomi et al. 2009). Global and European parameters plotted with different precipitation rates and Scandinavian parameters plotted both with different precipitation rates and with different annual temperatures.

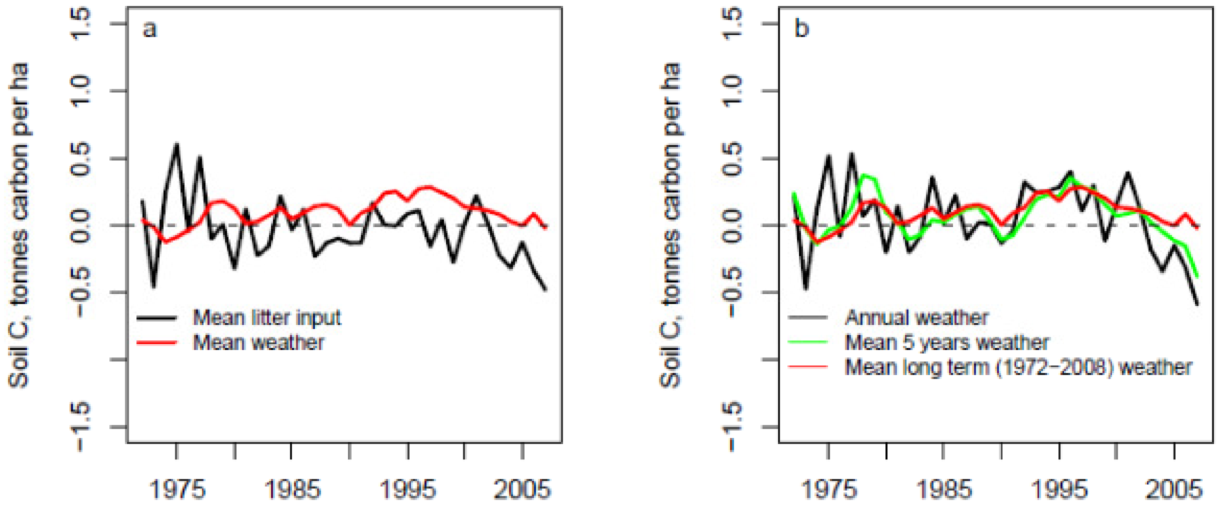

Figure 14 A) Soil carbon stock changes in subgroup “All” 1972-2007 simulated by Yasso07 model with Scandinavian parameterisation using average long term weather data (1972-2008) and annually determined litter input or annual weather data and fixed litter input (litter input for year 1972). B) Annual soil carbon changes (tnC ha^{-1}) simulated by Yasso07 model with Scandinavian parametrisation using either average annual weather data, average weather data over 5 years or average long term (36 years) weather data.

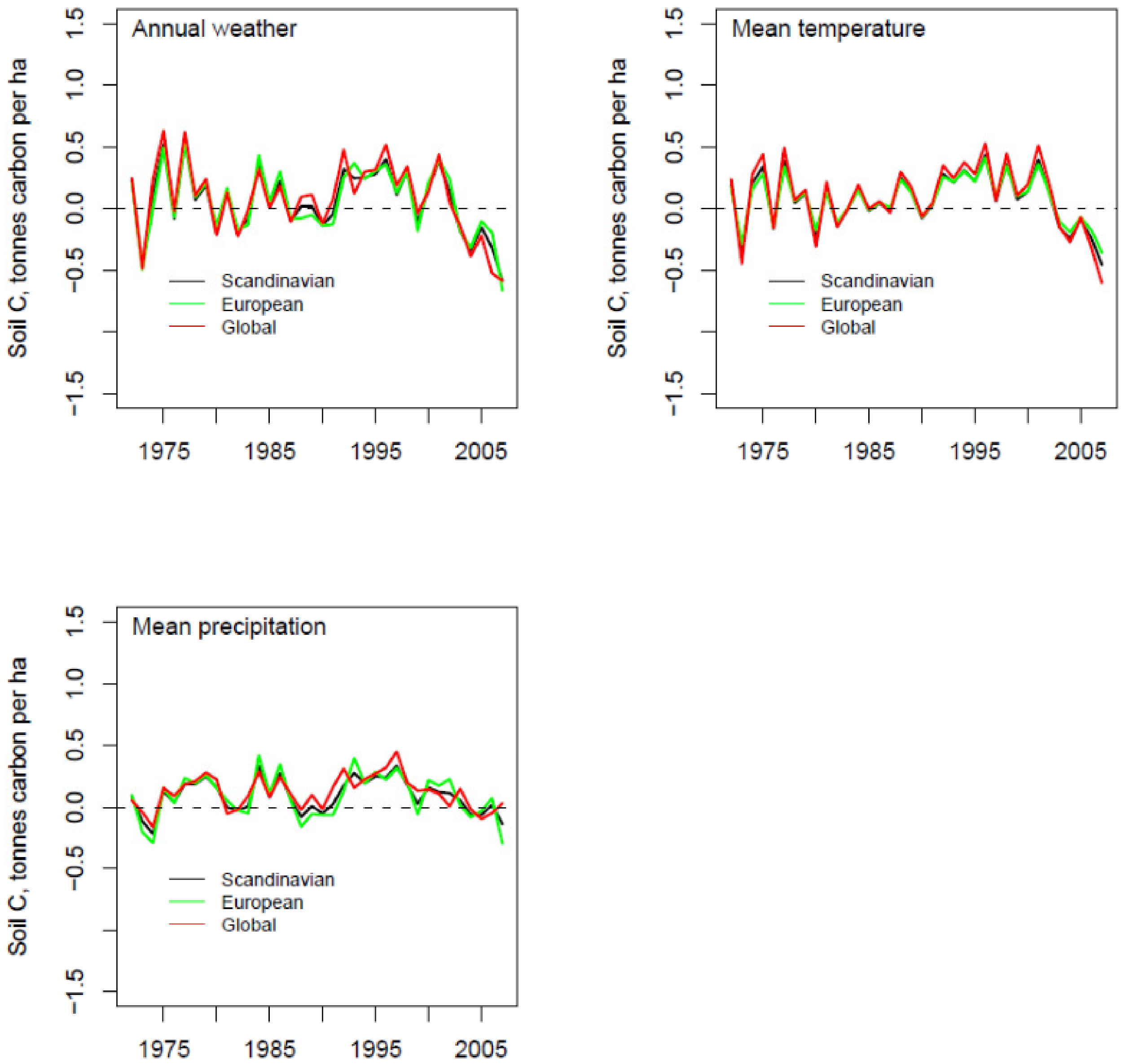

Figure 15. Sensitivity analysis of annual soil carbon change (tnC ha^{-1}) 1972-2007 in OMT, MT and VT forests in Southern Finland (subgroup “All”) simulated with Yasso07 either by Scandinavian, European or Global parametrisation varying input climate data. Alternate input weather datasets were annually varying temperature, temperature amplitude and precipitation (Annual weather), annually varying precipitation, but average long term (1972-2008) temperature and temperature amplitude (Mean temperature) and annually varying temperature and temperature amplitude but average long term (1972-2008) precipitation (Mean precipitation).

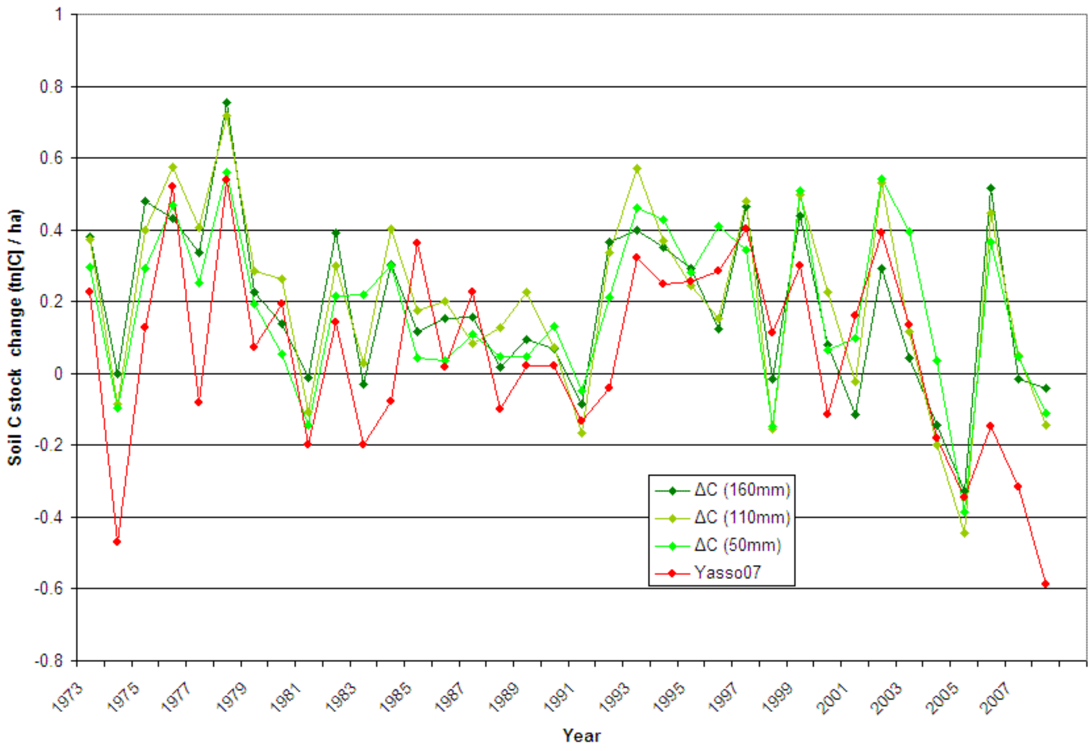

Figure 16. Annual soil carbon stock changes in OMT, MT and VT forests of Southern Finland simulated by YASSO07, Scandinavian parametrisation (red line) and ROMUL soil carbon model (green lines). ROMUL simulations have been carried out with three different soil water retention capacities (ΔC), 160 mm, 110 mm and 50 mm. Although the time steps of the models differ, the comparison have been carried out by using the situation in soil at the end of the year.

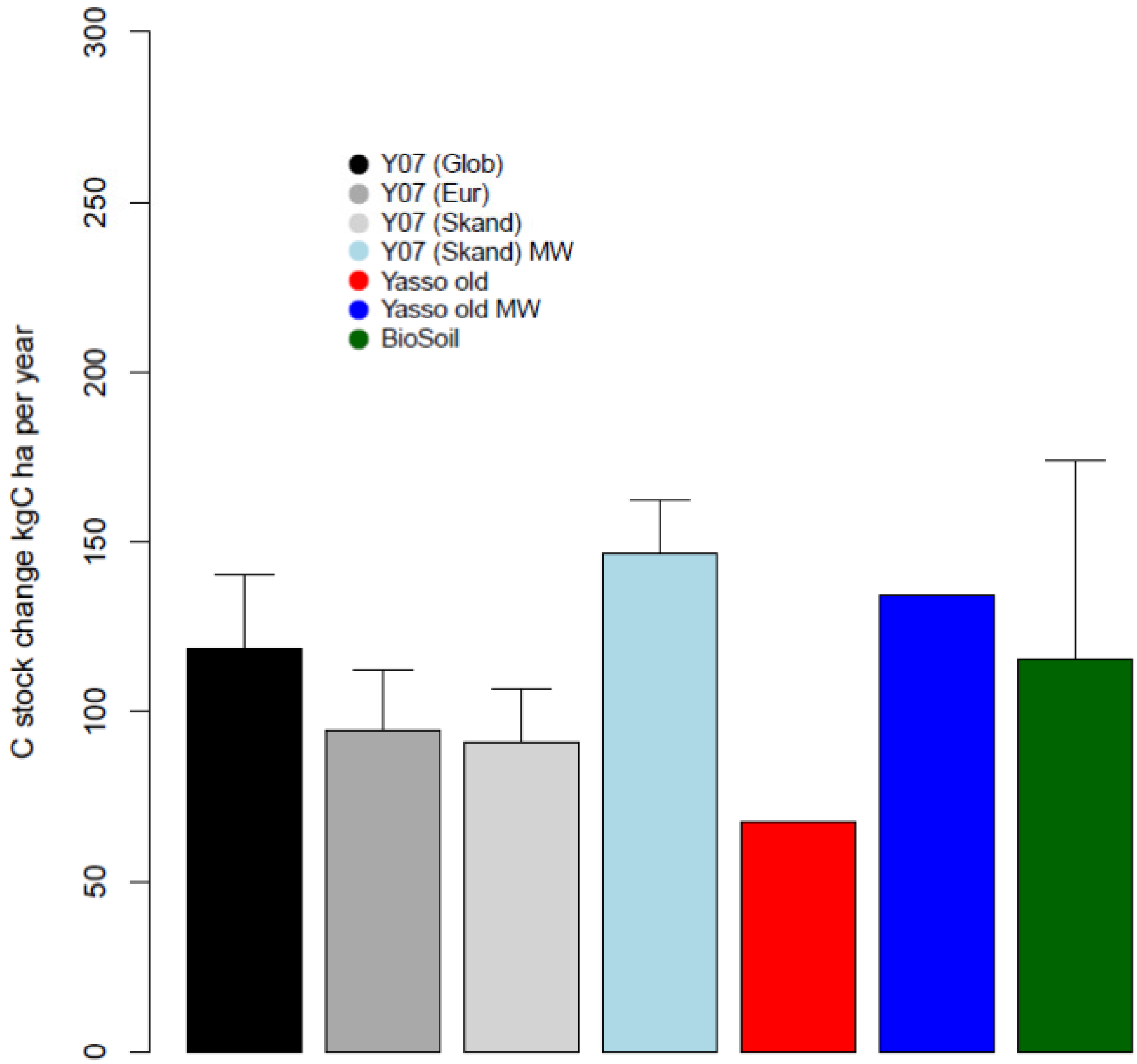

Figure 17. Simulated annual soil carbon stocks changes between years 1986 and 2006 calculated with Yasso07 (Scandinavian, European and Global parameters), Yasso (old) using annually varying weather data, and simulated annual soil carbon stocks changes between years 1986 and 2006 calculated with Yasso07 (Scandinavian parameters) and Yasso (old) using long term mean (1972-2008) weather data (MW), and measured annual soil carbon changes between years 1986-2006 (BioSoil)