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Swedish Environmental Emissions Data

Measurements and models – a comparison of quantification methods for SOC changes in forest soils

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Preface

In order to develop the international reporting under the Climate convention and the Kyoto protocol, it is recommended that parties verify their calculations of greenhouse gas emissions and removals. This is the final report of the project "Verifiering och metodjämförelse för skattningar av förändringar i markkolspoolen i mineraljord på skogsmark". The project was initiated and funded by the Swedish Environmental Agency in order to compare the precision and the uncertainty in the determination of litter and soil carbon pool changes using different methods and to analyze possibilities for enhancing the precision in the estimate of soil organic carbon pool fluxes of forest land in the reporting under the Climate Convention and the Kyoto protocol.

Uppsala 12 August 2009

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Summary

The Swedish UNFCCC[1]-reporting of the LULUCF[2]-sector is based on methods in compliance with the "Good practice" as described by the Intergovernmental Panel on Climate Change (IPCC). Biomass and soil inventory data from the Swedish Inventory of Forests is the major source of information used to quantify changes in the various carbon pools on forest land. Even if the reported uncertainties in soil carbon changes are small from a statistical perspective, they are large in relation to the total Swedish emissions of green house gases. This is due to the fact that the soil carbon pool is so large, that even small and statistically non-significant changes may have an impact on the Swedish CO_2 balance. Sampling based methods may also result in considerable inter annual variations that may look conspicuous in the reporting. Because of the uncertainty and inter annual variations there has been a discussion on the methods used and if there are possibilities to lower the uncertainty and to get more stable estimates of soil carbon changes by combining measurements and models. In this study results from the two soil carbon models, Yasso07 and Q, were compared with repeated measurements of the soil inventory during the years 1994 to 2000. Soil carbon fluxes were simulated with the two models from 1926 to 2000 with Monte Carlo methodology to estimate uncertainty ranges. The results from the models agreed well with measured data. The simulations of Yasso07 and Q resulted in a soil organic carbon stock in year 2000 of 1600 Mton C and 1580 Mton C, respectively while the measured carbon pool was 1670 Mton C. The annual change in soil organic carbon varies substantially between the three methods mainly due to different assumptions regarding annual climate variation. However, the five year averaged mean of annual soil organic carbon change for the two periods 1994-1998 and 1996-2000 indicate the size and direction of the estimated annual changes agree reasonable well. The mean annual change for the two periods was for the Q-model 5.5 Mton C yr^{-1} and 5.6 Mton C yr^{-1} with a confidence interval of 2.1-10.7 Mton C yr^{-1}, and for the Yasso07-model 3.7 Mton C yr^{-1} and 0.9 Mton C yr^{-1} respectively with a confidence interval ranging between -5 to 12.6 and -7 to 9.8 Mton C yr^{-1} respectively. The mean annual change for the two periods estimated using NFI-data was 1.6 M ton C yr^{-1} and 2.5 M ton C yr^{-1} with a standard error of 2 The general conclusion drawn from this study is that both sampling and the models Yasso07 and Q are possible tools to predict the soil organic carbon accumulation and annual changes for Swedish forest soils. The estimates based on measurements as well as the modelled results indicate an increase in carbon stocks in Swedish forest soils. This study does not support a change of method from inventory to model predictions. However, the agreement between the methods shows that the models are suitable as a complement to other soil carbon estimation methods. They are particularly useful for projections and we recommend a further development of the modelling tools.

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[1] UNFCCC, United Nations Framework Convention on Climate Change
[2] LULUCF, Land Use and Land Use Change and Forestry

Background

The United Nations framework convention on climate change (UNFCCC) came into force in 1994. The long-term goal was to stabilize the amount of greenhouse gases in the atmosphere at a level where harmful anthropogenic climate changes are prevented. The most important addition to the convention was negotiated in 1997 in Kyoto, Japan. The Kyoto protocol involves binding obligations for the Annex I countries to decrease their emissions of greenhouse gases during 2008-2012 with at least 5% compared to the base year 1990.

According to Articles 4 and 12 of the United Nations Framework Convention on Climate Change (UNFCCC), parties are required to annually submit national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol. The reporting comprises six sectors, Energy, Industrial processes, Solvents, Agriculture, Land Use, Land Use Change and Forestry (LULUCF) and Waste and the anthropogenic emissions of direct greenhouse gases CO_2, CH_4, N_2O, HFC, PFC, SF_6 and indirect greenhouse gases NO_X, CO, NMVOC and SO_2.

Of the six sectors, the LULUCF-sector is the sector where development have been most progressive the latest years, mainly because of the very complex requirements for the reporting of land-use changes and the carbon pool changes related to them. The need for improvement of the methods is also due to the large uncertainties connected to the estimation of carbon pool changes.

The Swedish UNFCCC[3]-reporting of the LULUCF[4]-sector is based on methods in compliance with the "Good practice" as described by the Intergovernmental Panel on Climate Change (IPCC, 2003). In the most recent Swedish inventory report (SEPA, 2009), all carbon pool changes are calculated annually from the reference year 1990 until 2007. Data from the Swedish Inventory of Forests are the major source of information used to quantify changes in the various carbon pools. The stock change method is used for the most important pools: living biomass, dead organic matter and soil organic carbon, and the measurements are based on repeated measurements on permanent sample plots.

Sweden has reported carbon stock changes in the litter and soil organic carbon pool since 2006. The estimates have varied considerably between the annual submissions; mainly due to method development and recalculations due to extended data availability. The reason is that new data becomes available each year which makes it possible to use more re-inventoried plots in the estimates. From submission 2008 and onwards all changes are now estimated from re-inventoried plot data. Even within a submission there has been considerable variation between years. This can be explained by the fact that a small relative change of a large carbon pool will contribute significantly to the Swedish carbon budget. Thus, normal random variation between years will look conspicuous in the reporting. There has

[3] UNFCCC, United Nations Framework Convention on Climate Change
[4] LULUCF, Land Use and Land Use Change and Forest

been a discussion on how to improve the estimates and how to get more stable estimates of soil carbon changes from year to year. Some, but not all, of these variations have been dealt with using interpolation of years between inventories and running mean calculations for longer periods

The aim with this study was to compare precision and uncertainty in determination of litter and soil carbon pool changes using two different methods for estimating change; (1) the stock change method using repeated soil carbon pool measurements (current Swedish method) and (2) process oriented soil carbon modelling.

Material and Methods

Uncertainty estimations

Uncertainties of the current measured soil carbon estimations arise from either systematic or random errors. Systematic errors in measurements are mainly caused by imperfect calibration of measurement equipment. Random errors are mainly caused by inherently unpredictable fluctuations, natural and spatial variation, and appear as when measurements are repeated. The random errors are analogue to the concept of precision and the standard deviations. The variation of the reported soil carbon can be explained by both systematic and random errors.

Uncertainty in models can be divided in a similar way by statistical and systematic uncertainty. The statistical uncertainties arise from the variability of input variables and parameters where the variability is known. This variability can be described by probability density functions (PDFs) describing the variability of the input variables and the parameters. Systematic uncertainties arise from variability in input variables and parameters when variability is unknown. Also unknown processes in the model e.g. incorrect model structure contribute to the systematic uncertainties.

In this study we mainly discuss uncertainties in measurements that arise from random errors (natural variation) where the mean values are estimated with a statistical variation, and statistical uncertainties for models including the variability of input variables and parameters. Since the uncertainty are defined differently for measurements and for models the estimated uncertainty intervals s are not directly comparable. The measured uncertainties describe the natural and spatial variation while the models describe the variation in input variables and parameters.

Approach

Two principally different methods were used to estimate carbon stocks and carbon stock change. The first is the present reporting method based on repeated sampling of carbon pools and calculations of the stock change. The second is predictions using parameterized process oriented carbon cycling models.

Two models were used, Yasso07 (Liski et. al. 2005) and Q (Rolff & Ågren 1999). The models simulated the carbon pool changes during the period from 1926 to 2000 based on regionalized annual data on litter input and climate. The uncertainties were taken into consideration by creating uncertainty intervals around the simulated mean values of soil organic carbon. Uncertainties of the carbon pool change determinations were analysed with normal sampling statistics determining the interval. For the models we used Monte Carlo simulations to estimate uncertainty bounds of the organic soil carbon stocks in Swedish forests soils during the inventory period of 1994 to 2000.

Study Area

We divided Sweden into 7 regions representing different climate zones of Sweden (Figure 1). Historical litter input data were aggregated from National Forest Soil Inventory data. The calculations using inventory data and the modelling study will comprise all Forest land according to the UNFCCC-reporting definition with some exceptions. Due to the fact that the statistics on historic litter input only included forest land dominated by either Scots Pine (*Pinus syvestris*) or Norway Spruce (*Picea abies*) forests, broad leaved forests and mixed forests where the coniferous part is less than 70 % were not included in the analysis. Norway Spruce and Scots Pine makes up 81 % of the total Swedish standing stock. In earlier reporting to UNFCCC Sweden has defined Forest land according to the Global Forest Resources Assessment (FRA)[5]. Forest land is defined as land with a tree crown cover (or equivalent stocking level) of more than 10 percent, with a minimum area of 0.50 hectare and the trees should be able to reach a minimum height of 5 m at maturity *in situ*. According to this definition the forest land in Sweden is around 27 million ha. In this study we cover around 23 million ha, which is more than 80 % of the total forest land in Sweden.

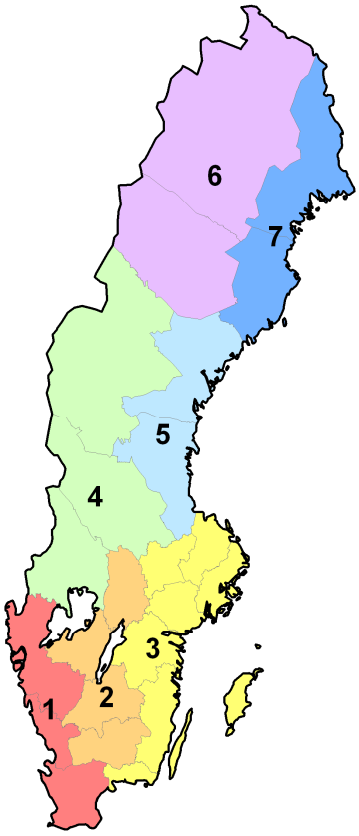

Figure 1. Regions for the SOC-models

[5] FAO, 2006

SOC-changes based on repeated measurements

According to the requirements for reporting under the UNFCCC Sweden is reporting changes in three carbon pools (living biomass, dead organic matter and soil organic carbon). Dead organic matter includes the carbon pools dead wood and litter. Litter includes all non-living biomass not classified as dead wood, in various states of decomposition above the mineral or organic soil. This includes the litter, fumic, and humic layers.

The carbon in the litter pool was estimated based on three different sources (i) coarse litter (ii) annual litter fall and (iii) litter < 2 mm. Coarse litter was defined as dead organic material with a "stem diameter" between 10-100 mm and originating from dead trees. Coarse litter was not inventoried but calculated as 15 % of the aboveground dead wood. Litter fall was calculated using empirical functions based on tree stand properties and litter fall for deciduous species by biomass functions based on leaf biomass. This fraction of litter is regarded as an annual pool. The remaining part of this pool after one year was included in the O horizon and thus measured by the soil inventory. The fine litter (< 2 mm) was estimated by sampling the O or H horizon sample which was taken on an area basis, weighed and analysed for carbon content.

The soil organic carbon pool of forest land and grassland on minerogenic soils includes all carbon below the litter, fumic and humic layers. The carbon pool considered here was soil organic carbon down to a depth of 0.5 m measured from top of the mineral soil and the calculation of changes of the land-use categories Forest land and Grassland was primarily based on soil sampling combined with pedotransfer functions. Histosols were not included in this study because the emissions are not determined by the stock change method and the two models are not suitable for organic soils.

The basic function used to determine the amount of carbon in a soil layer was based on the amount of carbon in a certain soil layer and the fraction of fine earth. The amount of fine earth depends on the bulk density and amount of gravel, stones and boulders in the soil

Each permanent sample plot is revisited in a ten year cycle and each year approximately 500 plots are measured for carbon content. The annual value of each plot was estimated by interpolating the carbon content on the plot for the years in between the measured years. Finally, the total annual value of the SOC-pool was calculated as the mean of all measured and estimated values for the plots. The number of measured plots used in the estimation will increase step-by-step to a maximum of ca 5000 plots when the whole set of plots have been re-inventoried.

Models

Yasso07

The Yasso07 model is a generalization of an earlier Yasso soil carbon model (Liski *et al.*, 2005). The model has been used in various research applications, and, in addition, it has been applied to national green house gas inventories (Monni et

al., 2007). The improvements of Yasso07 consist of more data, more reliable mathematical methods and uncertainty estimates of the results. Yasso07 is based on a larger number of more diverse measurements covering a wider range of climate conditions and ecosystem types worldwide. Yasso07 is also based on more advanced mathematical methods. The output of the Yasso07 is characterized by probability densities that represent uncertainty ranges due to the uncertainty in the parameter values of the model.

The structure of Yass07 (Figure 2) is determined by the following four assumptions of litter decomposition;

(i) Non-woody litter consists of four compound groups (waxes etc., sugars etc., celluloses etc. and lignin etc.), and each group has an own decomposition rate independent of litter origin,

(ii) Woody litter consists of these same compound groups but it decomposes at a lower rate,

(iii) Decomposition rates of the compound groups depend on temperature and precipitation and

(iv) Decomposition of the compound groups results in mass losses from the system, mass flows between the compound groups and formation of more recalcitrant humus.

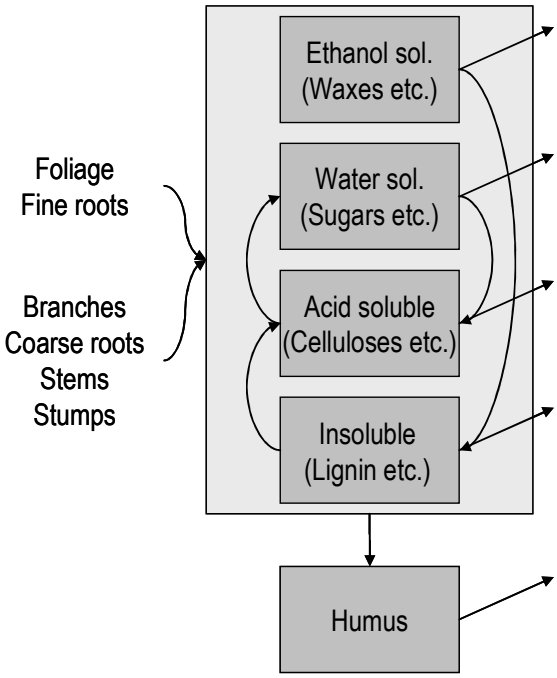

Figure 2. Flow chart of Yasso07 model.

The parameter values of Yasso07 model was developed using different sets of measurements in Europe and North and South America from Berg *et al.* (1991), Berg *et al.*(1993), Gholz *et al.*(2000), Trofymow (1998), Makinen *et al.* (2006), Palviainen *et al.*(2004), Tarasov & Birdsey (2001), Liski & Westman (1995), Liski & Westman (1997) and Liski *et al.*(1998). With the Markov Chain Monte Carlo

method, the model was calibrated to all the measurements available and the probability densities of the parameters were established (Table 1).

Input uncertainty was taken into concern by 1) the error in the chemical composition according to deviation between measurements and average values of coefficients of variation calculated from a plant species specific data set of Liski et al. (2006) and 2) by the error in the quantity of litter input with coefficients of variation calculated from a nation-wide study in Finland by Peltoniemi et al. (2006) and Monni et al. (2007). 100 Monte Carlo simulations were made within the parameter ranges in Table 1 and the input uncertainties of chemical composition and input. The uncertainty bounds are formed by the 95 confidence limits of all the Monte Carlo simulations made.

Table 1. The parameter probability densities of Yasso0707

Parameter	Description	Unit	Range (PDF)
α_A	Decomposition rate of A	a^{-1}	0.62, 084
α_W	Decomposition rate of W	a^{-1}	5.0, 6.6
α_E	Decomposition rate of E	a^{-1}	0.24, 0.35
α_N	Decomposition rate of N	a^{-1}	0.027, 0.042
p_1	Mass flow from W to A	-	0.41, 0.54
p_2	Mass flow from E to A	-	0, 0.16
p_3	Mass flow from N to A	-	0.60, 0.98
p_4	Mass flow from A to W	-	0.94, 1
p_5	Mass flow from E to W	-	0, 0.08
p_6	Mass flow from N to W	-	0, 0.21
p_7	Mass flow from A to E	-	0, 0.004
p_8	Mass flow from W to E	-	0, 0.003
p_9	Mass flow from N to E	-	0, 0.25
p_{10}	Mass flow from A to N	-	0, 0.007
p_{11}	Mass flow from W to N	-	0, 0.031
p_{12}	Mass flow from E to N	-	0.79, 0.99
β_1	Temperature dependence parameter	$℃^{-1}$	0.078, 0.122
β_1	Temperature dependence parameter	10^{-3} $℃^{-2}$	-2.4, -0.8
γ	Precipitation dependence parameter	m^{-1}	-1.06, -1.36
p_H	Mass flow from A, W, E, N to humus	10^{-3}	3.7, 5.6
α_H	Humus decomposition coefficient	10^{-3} a^{-1}	1.4, 1.9
δ_1	Size dependent parameter	cm^{-1}	-1.9, -1.5
δ_2	Size dependent parameter	cm^{-2}	0.76, 0.96
r	Size dependent parameter	-	-0.321, -0.290

The Q-model

A central concept in the model is the quality of the organic matter in the soil, which varies between different litter fractions and changes gradually during the process of decomposition. Further, the decomposition processes are controlled by the microbial community and the parameters of the model explicitly describe features of the microbial community. The Q-model consists of a family of functions that describes the decomposition of organic material, and here we used a version that takes into account the invasion rates of litter types for both new and old litter

(Agren *et al.*, 2007). Litter enters the soil in litter fractions that originate from needles, branches, stems, fine roots, coarse roots, stumps and under ground vegetation. The model describes the quality of organic material during decomposition, where litter has initially higher quality than humus (Figure 3). The decomposition of litter is regulated by decomposition functions that describe the fraction remaining during time. These functions are empirically developed and are specific for each litter fraction. Needles and fine roots are decomposed faster than stems, stumps and coarse roots. The decomposition is dependent on litter type but also on initial quality of the litter, invasion time of the micro organisms (for coarse litter fractions), climate and soil properties. These factors are described in the model parameters (f_C, q_{0n}, q_{0w}, e_0, η_{11}, β, *T*, *max*b, *max*s *and* u_0).

The parameter f_C is the carbon concentration in decomposer biomass, q_{0n} and q_{0w} are initial litter quality in needles and coarse woody litter, e_0 is microbial decomposer growth efficiency and describes the fraction of carbon that is incorporated into new decomposers biomass per unit used carbon, η_{11} is the rate of decrease in quality for each decomposition cycle. When carbon of a certain quality is assimilated, the new carbon will have a new quality that is decreased by η_{11}. The parameter β controls the shape of the decomposer quality response and controls how fast the decomposition rate changes with quality. This will be influenced by soil texture and β increases with clay content. The parameters *max*b and *max*s are the invasion times, i.e. when the branches and the stems are totally invaded by microorganisms. Finally, the parameter u_0 is the decomposer growth rate and is related to the average temperature at the site. The parameterization of the model was made with probability density functions (pdf's) and thus not only one single value for each parameter was assumed. The pdf's were based on expert's judgement and earlier parameterizations of the model (Hyvonen et al., 1998).

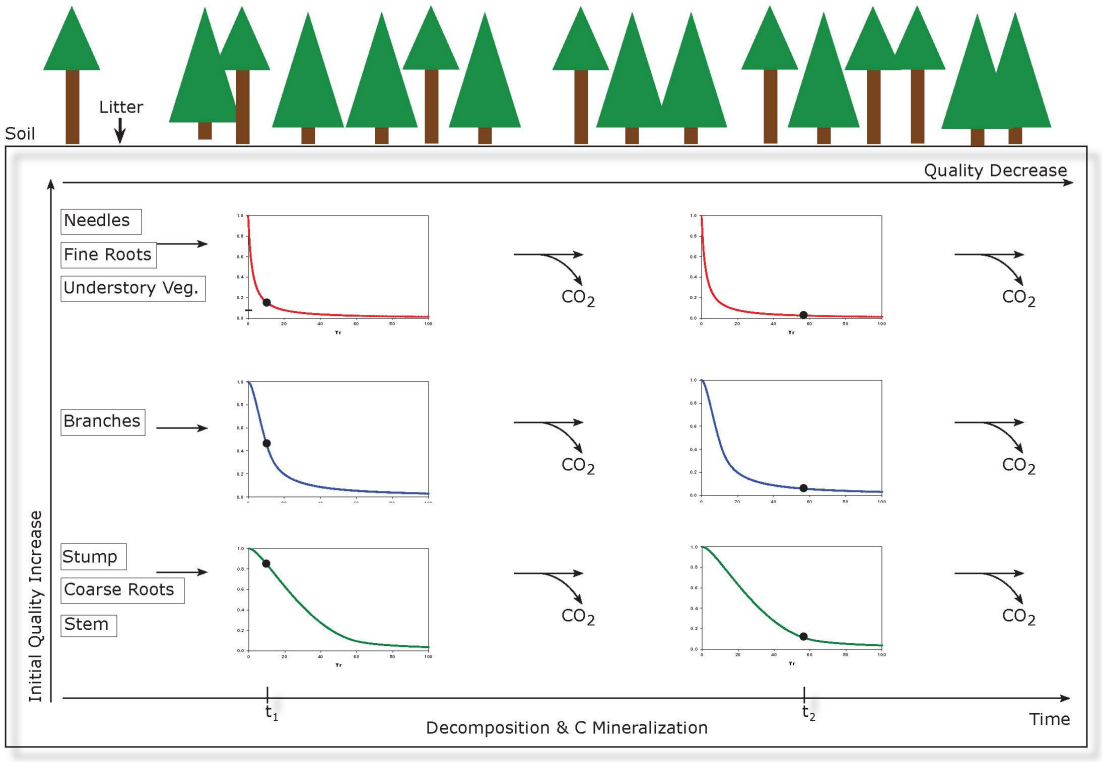

Figure 3. A conceptual picture of a version of the Q model. The graphs in the box represent the decomposition of the organic matter. The y-axis is the mass remaining as the organic material decomposes through time by different decomposition rates depending on the initial quality of the litter input and the time step.

The uncertainties of the model outcome were investigated with the GLUE (Generalized Likelihood Uncertainty Estimation) framework developed by Beven & Binley (1992). GLUE is an uncertainty estimation method that describes the uncertainties of the model outputs by calibrating to measured observations with Monte Carlo simulations and uses the whole parameters probabilities to illustrate the uncertainty of the simulations.

The PDFs of the Q model parameters for the GLUE analysis are found in table 2.

Table 2. The parameters of Q ranges for the GLUE, all uniform densities

Parameter	Description	Range (PDF)
q_{0n}	Initial litter quality needles	0.8, 1.5
q_{0w}	Initial litter quality weed	0.8, 1.5
e_0	Microbial decomposer growth efficiency	0.1, 0.4
η_{11}	Rate of decrease in quality	0.1, 0.45
β	Shape of decomposer quality response	2, 10
maxb	Time when the branches are totally invaded	1, 40
maxs	Time when the stems are totally invaded	10, 60
u_{00}	Parameter in u0, the basic decomposer rate	0.04, 0.09
u_{01}	Parameter in u0, the basic decomposer rate	0.01, 0.02

In this study the "limits of acceptability" approach described in (2006) was applied were a triangular distribution around the measured value was used. The simulations that preformed within the triangular distribution were kept to form the uncertainty bounds of the final aggregated simulations. The triangular distribution was estimated by the 95th confidence interval around the mean value of the repeated soil measurements in each region and year.

The Monte Carlo simulations that met the criteria described above were analyzed by the Weighted Likelihood, *WL*, based on the Model Efficiency (ME) (Smith *et al.*, 1996) according to

$$WL = 1 - \frac{\left(ME_i - ME_{\min}\right)}{\left(ME_{\max} - ME_{\min}\right)} \quad , \qquad \text{Eq. 2}$$

were the Model Efficiency is defined by

$$ME = \frac{\left(\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n}\left(P_i - O_i\right)^2\right)}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \quad , \qquad \text{Eq. 3}$$

so that the *WL* varies between 0 and 1, with values near 1 indicating highest likelihood performance of the model. The measure provides a percentage term for the total difference between the predicted and the observed. $\overline{O}$ is the mean of the observed data, P_i is the predicted values and O_i is the observed data and n is the population number. The 5th, 95th percentiles and the mean of the accepted simulations are finally aggregated to form the prediction uncertainty bounds of the models performance at the national level. The WL was further used to analyze the parameter uncertainty of the accepted simulations.

Input Data

The litter production was compiled by forestry statistics on actual standing tree and harvested volumes to estimate the standing stock of tree components for every year from 1926 to 2002 divided in the 7 regions defined for this study. The litter components included are for above ground needles, branches, stems and understory vegetation divided in top and bottom layers. The under ground litter components are the fine roots and the coarse roots. Harvest residues originate from all above ground components due to clear cuttings of the largest trees (> 25 cm diameter), since it is the main form of harvest and the only statistics available for the whole period. The species considered were Norway spruce and Scots pine. With allometric functions (Marklund, 1988) standing stock was divided in the different tree components. For each tree component the litter production was estimated with the turnover rate of needles correlated to latitude (Agren *et al.*, 2007). The litter compiled represents litter in forests dominated by either Norway spruce or Scots pine. The litter production was greater for Pine forests in southern regions. Norway spruce volume has increased has increased rapidly from 1926 and onwards. During the 70s there were large cuttings that resulted in a decrease of litter production. The contribution of understory vegetation to litter input was estimated from data on

coverage of the bottom and field layer from the Swedish National Forest Soil Inventory during 1994 to 2002, together with the biomass models developed by Muukkonen *et al.*(2006) and turnover rates for understory vegetation from Peltoniemi *et al* (2004) and in Kleja *et al* (2008). The bottom layer consisted of bryophytes and lichens and the field layer of herbs and grasses and dwarf shrubs (Figure 5c).

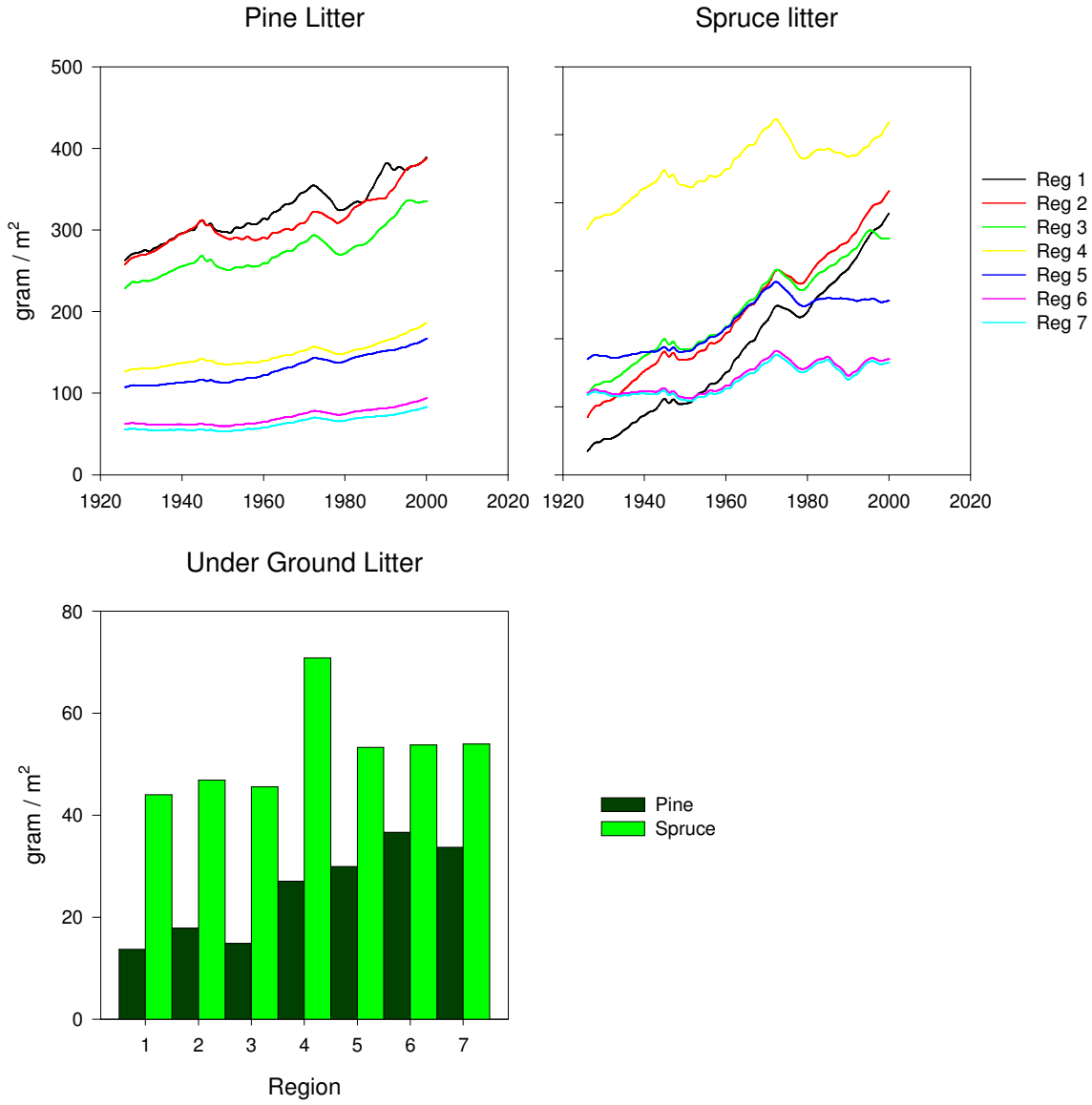

Figure 4. Litter input by region in g C/m^2. a) Tree litter input in Pine and b) Spruce forests. c) Under ground litter input by Pine and Spruce forests.

For the year 1926, the year when simulation started, the litter production was assumed to be the same in both Q and Yasso simulations. Furthermore, decomposition and production were assumed to be in steady state. In the Q model the accumulation of steady state carbon (old carbon) in wet soils was estimated by correcting for wet soils in the models parameter u_0, by a factor 0.65.

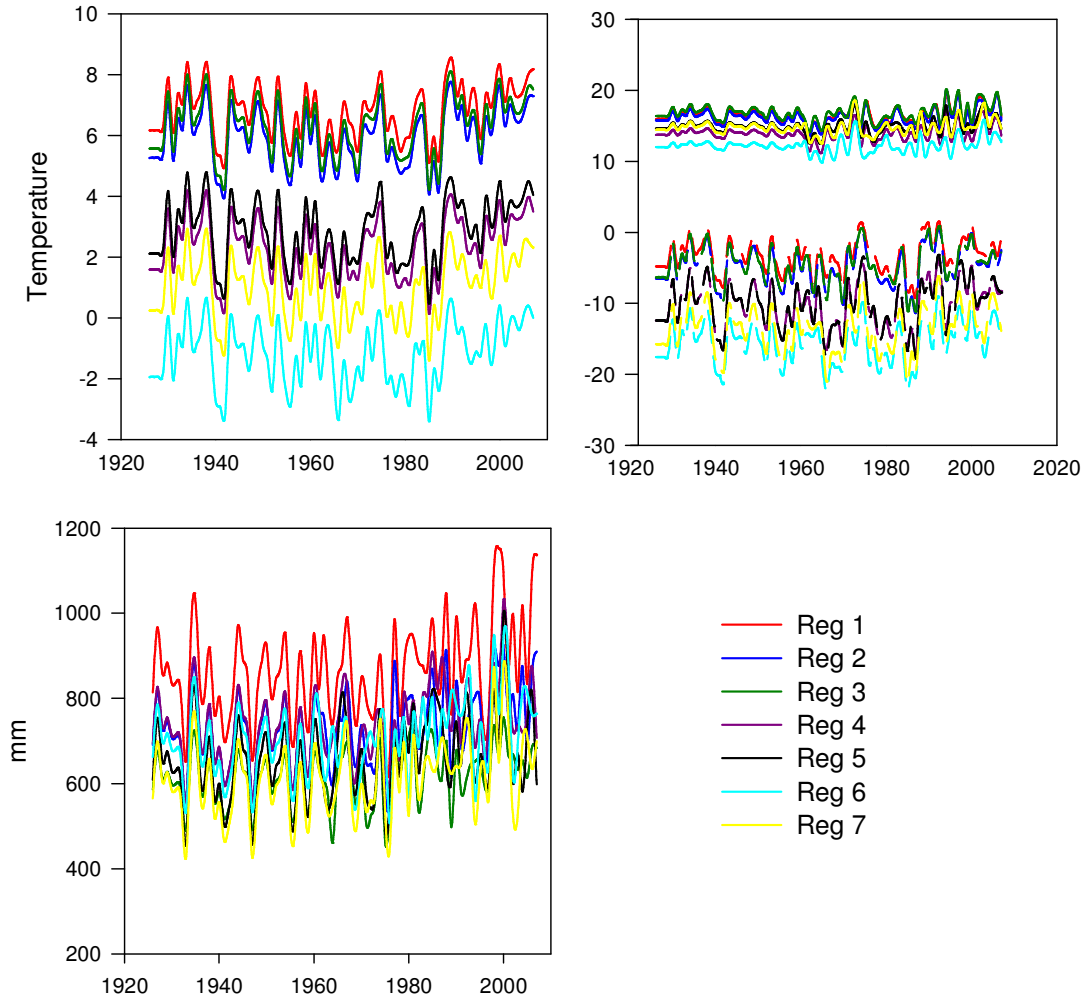

Figure 5. Climate input a) mean annual temperature (℃) , b) min monthly mean temperature and max monthly mean temperature (℃) and c) annual precipitation (mm).

County level climate data for the period from 1961 to 2007 were obtained from the Swedish Meteorological and Hydrological Institute(Johansson, 2000; Johansson & Chen, 2003). Regional data according to the regions in Figure 1 was calculated using area weighted means of the data representing the counties in each region. Linear regression functions based on relationships established relating regional data to the national mean for the period 1967 to 2007 were used to calculate the climate data for the period 1926 to 1960 (Figure 5).

Results & Discussion

Comparison of soil organic carbon pools

The soil carbon pools of the models differ in their definitions compared to the reported figures to the UNFCCC. Figure 6 illustrates the differences between the three methods regarding input and output and definitions of soil compartments included in the study. The comparison in this study included the litter layer (including litter and humus) and the SOC layer in the UNFCCC reporting. This could be compared to the whole set of output compartments in the two models.

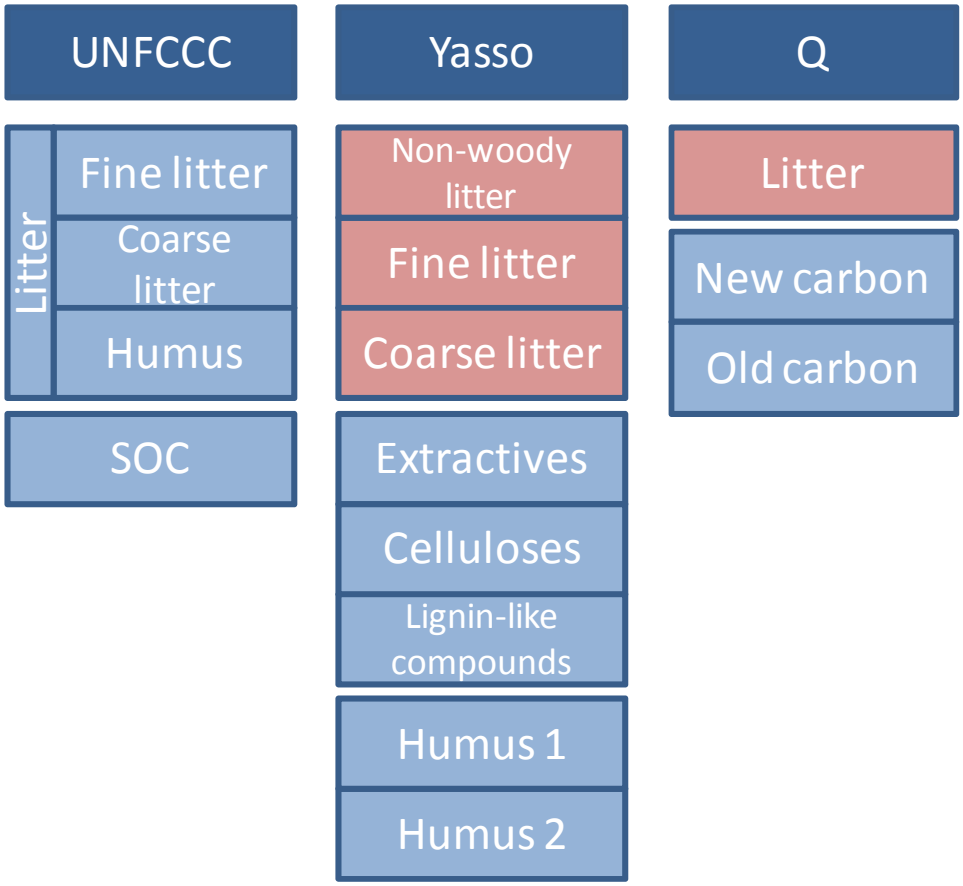

Figure 6. The different compartments of the three methods to estimate SOC changes. Red shaded boxes represent input to models and blue shaded represent output from models or calculated pool changes from the UNFCCC reporting system.

Soil carbon stocks and changes

The total soil organic carbon stock of Swedish forest soils were estimated to 1670 Tg C (M ton C) in 2000. Both models simulated carbon stock near the reported values with 1580 for Yasso07 and 1600 by Q. The average rate of change of the both models during the whole simulation period is for Yasso07 1.3 Tg yr^{-1} and for Q 2.8 Tg yr^{-1}. Both Yasso07 and Q simulated the carbon stock satisfactory compared to the repeated measurements. The Q model used the results from the repeated measurements to calibrate the simulation using the GLUE method. This explains why the Q model simulates higher rate of change during the whole simulation period in comparison to 1.74 reported by Agren *et al* (2007). The stocks were also higher than in Agren *et al* (2007) (1047 T g C), which is explained by including the understory vegetation and the correction of the carbon accumulation difference in wet soils of the old carbon for the Q model. The understory vegetation in northern regions contributes to around 30 % of the tree litter input (Figure 4), and has considerable impact on the national C stock due to a large area proportion of forest land located in northern Sweden.

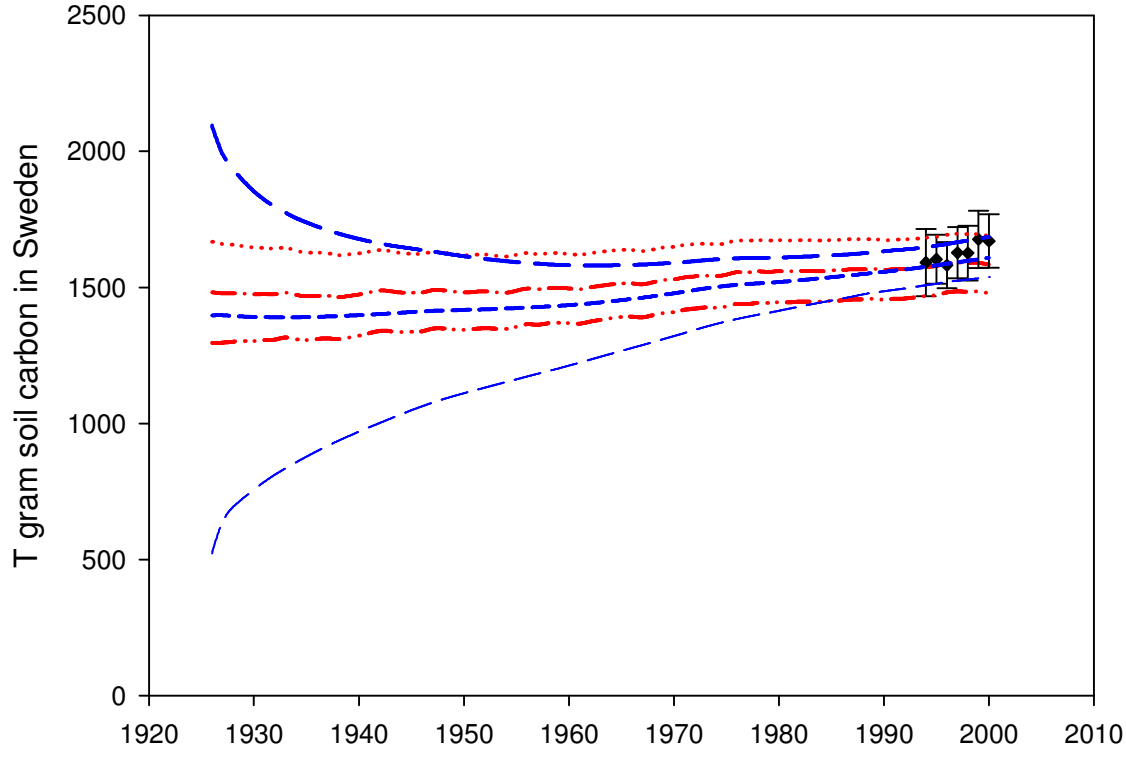

Figure 7. Total amounts in T gram of soil carbon in Swedish forest soil development since 1926 to 2000. Yasso07 (dotted red lines), Q (dashed blue lines) and repeated measurements (error bars & 1994 to 2000 only), including the confidence limits bounds of Yasso07 and Q, and standard error for the repeated soil measurements.

The soil organic carbon change for the period 1994 to 2000 varied between the methods. In Figure 8 mean values for five year periods are shown for the three methods in two periods 1994 to 1998 and 1996 to 2000. The simulated uncertainties were described as distribution of the Monte Carlo simulations reflecting variation of input and parameters while the uncertainties of the measured stock changes are based on random error estimations. Therefore the uncertainty bounds in the figure represent different types of uncertainty. The estimate based on repeated measurements of the Swedish National Forest Soil Inventory showed high annual variation with a mean value of 1.6 Tg yr^{-1} during the five year period of 1994 to 1998 and with a standard error of 2. In the second period (1996-2000) the mean was 2.5 Tg yr^{-1} with a standard error of 2. The soil organic carbon annual change for the Q simulation was 5.5 Tg yr^{-1} for the first period and 5.6 Tg yr^{-1} the second with a confidence limit bound of 2.1 to 10.7 Tg yr^{-1} for both periods. Yasso07 simulated a soil organic carbon change of 3.7 Tg yr^{-1} and 0.9 Tg yr^{-1} the second period with a confidence limit bound of -5.2 and 12.6 Tg yr^{-1} and -7.9 and 9.8 Tg yr^{-1} respectively. Yasso07 simulations showed a higher variation in the annual changes of soil organic carbon than Q for the two studied periods. This is mainly due to the fact that the Yasso07 models used variable climate input while the Q model that used a constant temperature for the whole simulated period. A variable climate input has an evident effect on the annual soil organic C changes.

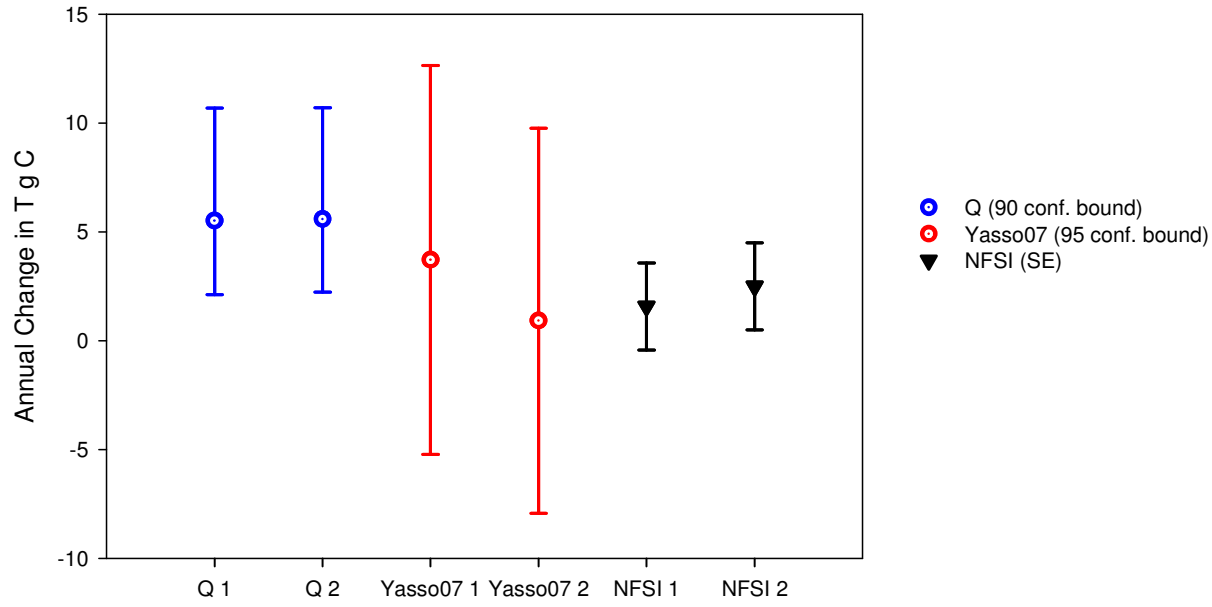

Figure 8. Change of SOC in T grams per year. Average of a 5 year period for 1994 to 1998 (1) and 1996 to 2000 (2) together with the uncertainty bounds of the modelled change and the standard error of the repeated measurements. To the left Q(blue), middle Yasso07 (red) and to the right (black) repeated measurements.

Uncertainty in simulations

The contribution of the uncertainty in parameters, climate variability and litter input differ for the Yasso07 simulations (Figure 9 a-d). The example is from simulations for Pine forests in region 1. From 1926 to 2000 the litter input together with the parameter uncertainty stands for most of the uncertainty analyzed here (9c) with 0.5 kg C m^{-2}. The climate variability together with the parameters contributes with 0.3 kg C m^{-2} (9b) to the uncertainty. The parameters alone contribute to the uncertainty of the Yasso07 simulations by 0.2 kg C m^{-2}.

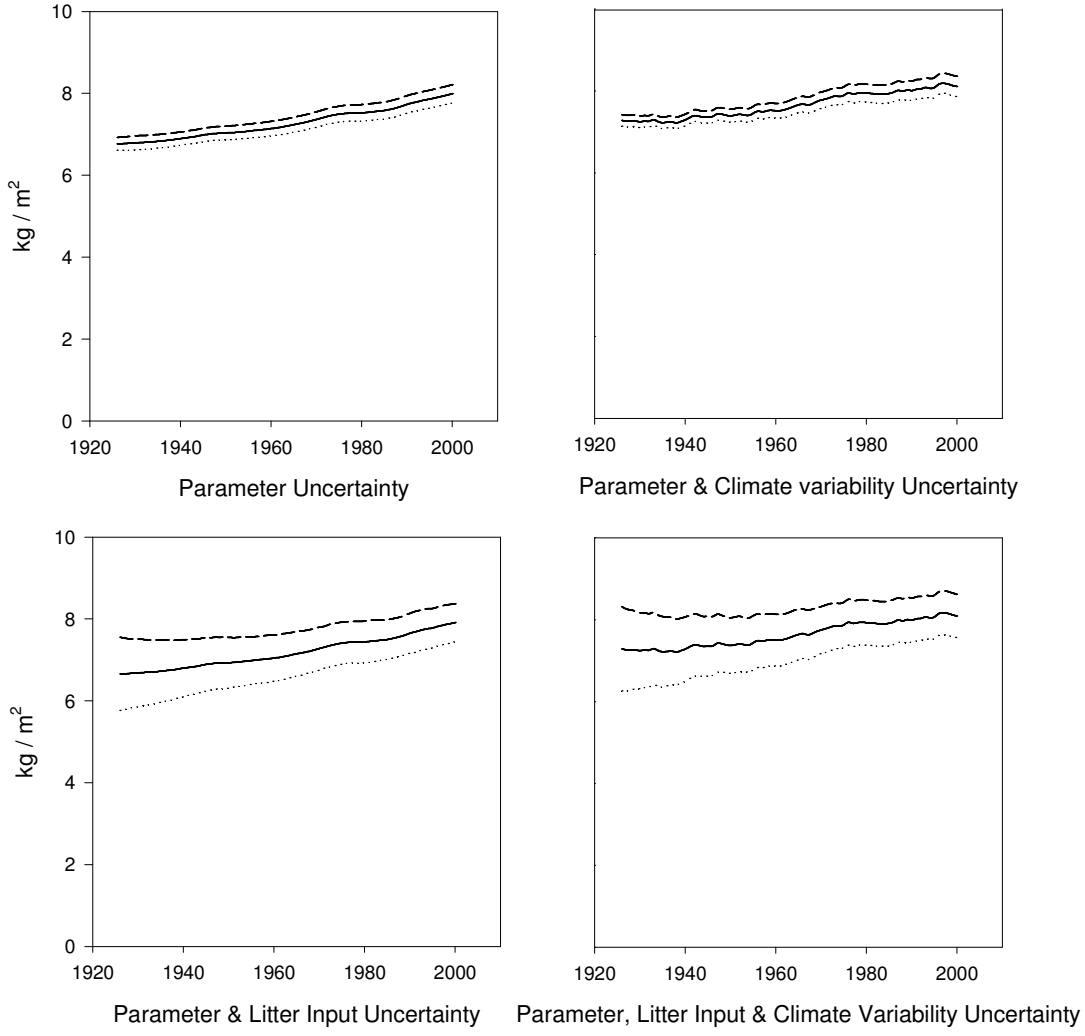

Figure 9. Uncertainty contribution of a) parameters, the variability of b) climate variability and c) the litter input in Yasso07. The dashed lines represent the upper 95 confidence interval, the lines are the mean and the dotted lines are the lower 95 confidence interval.

Parameter uncertainty in the Q simulations is illustrated by the weight likelihood of the accepted simulations (Figure 10) for all forest (Pine and Spruce) for region 2. Each dot n a plot represents one simulation and the dots with the highest WL (close to 1) are the simulations that fitted the observations most. Good simula-

tions (according to the WL measure chosen here) range through the whole parameter space for several parameters, indicating that the model is not sensitive to the parameterization. The dot plots also give information if the parameterization can be improved after calibration. Only the parameters β and e_0 were able to be better defined. Maybe η_{11} and $q0_{\mathrm{n}}$ might be better defined if more simulations were carried out. These are the parameters that contribute most to the uncertainty in the Q simulations. Those uncertain parameterizations give raise to unstable starting values that affects the uncertainty bounds of the Q simulations (shape of curve in the beginning, Figure 7). The calibration exercise also showed that the parameters were correlated to each other. This explains why the Q model simulated good results through the whole parameter range for some parameters. Given this information, more accurate simulations can be made in the future with updated parameter densities taking the correlation between the parameters into concern.

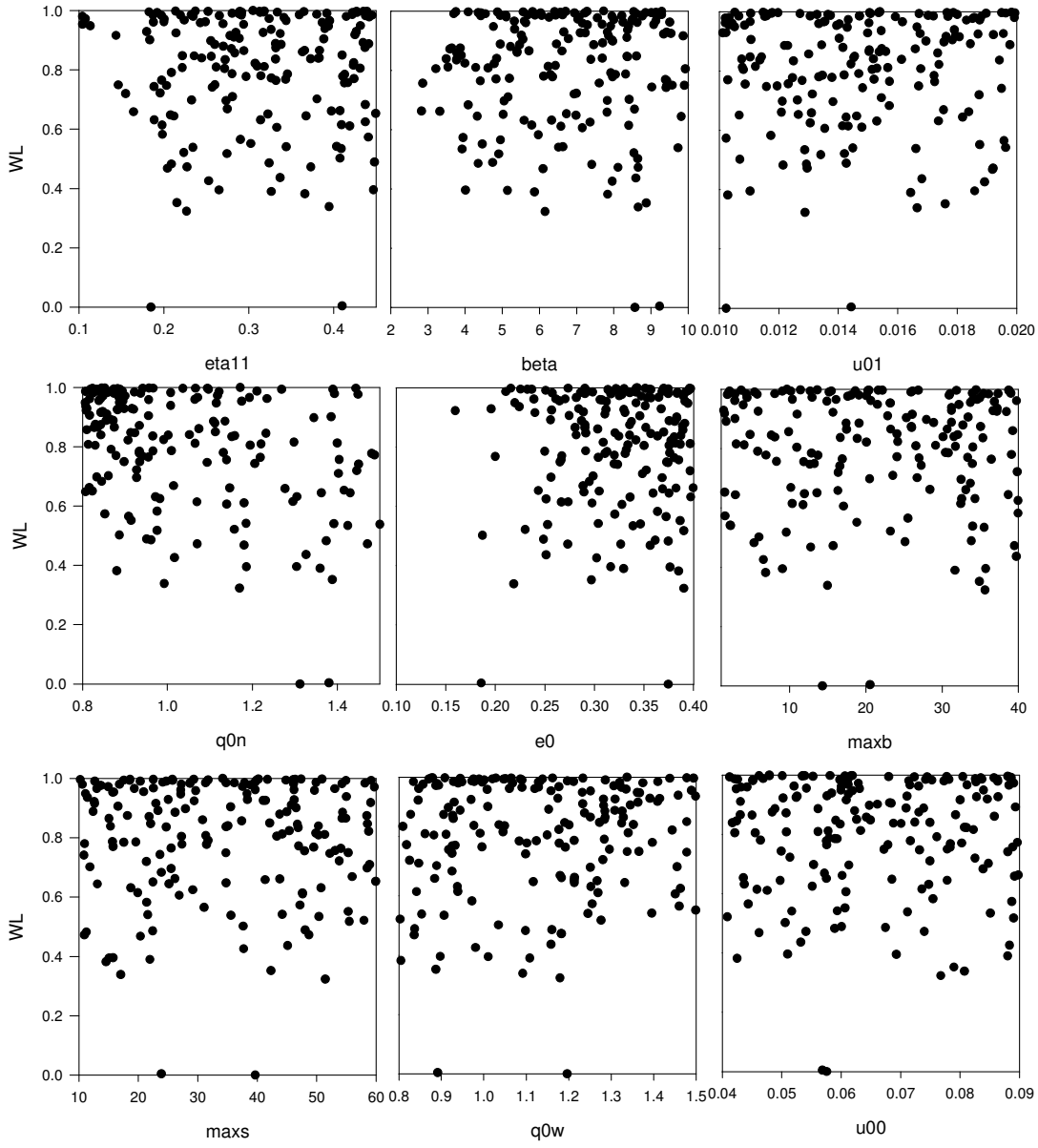

Figure11. Parameter uncertainty in Q. On the y-axis the weighted likelihood of the accepted simulations and on the x-axis the parameter ranges (pdf). The parameters are explained in table 2.

One source of parameter uncertainties in both Q and Yasso07 is the use of air temperature to describe the soil temperature. Some reasons for using air temperature are the difficulty of assessing the soil temperature at a greater scale than plot scale and that the temperature is different at different depths, which in turn means that the dissolved organic carbon in different soil layer has to be described. Another uncertainty source is the variable temperature used by the Yasso07 simulations. We have noted here that the annual variation in temperature affects the annual soil organic carbon change. IPCC recommends using averaged mean temperature to reduce the annual variations. We believe that it is fair to average out the

variation of the temperatures to decrease the yearly variation of the changes, but only after simulating with the yearly variable temperature to reflect the system in a more correct way and to be able to include the temperature trend in the models.

Systematic uncertainty (structural error) in the models, which were not taken into account here, is the interactions between the decomposition of soil organic matter and the nitrogen availability in the soil. Recent research points out that nitrogen availability is of great importance for the rate of decomposition of the organic material (Hyvonen *et al.*, 2007; Knorr *et al.*, 2005).

Concerning the significance of the uncertainties of the annual soil carbon changes in Figure 8, it is important to state that the uncertainties values presented here are not comparable between the methods. The reason for this is due to the fact that the sources of uncertainties arise differently for models and for the repeated measurements. For the inventory estimates, important sources of uncertainty are sampling errors and measurement errors. For the Yasso07 estimates, the important sources are uncertainty in input data to the model, especially litter input, and uncertainty in parameter values of the model. For the Q model only the parameter uncertainties are taken into account when calculating the uncertainty interval.

The uncertainties related to the estimated soil organic carbon pool changes are high. It may be noted that the SOC change of 5 Tg yr^{-1} is equivalent to 18 M ton CO_2, which in turn is almost the same amount of CO_2 as the reported CO_2 emissions for the national transport sector (20 M ton CO_2) which is the sector that stands for the greater part of the Swedish CO_2 emissions (SEPA, 2009). This will also imply a great impact on the overall global climate change estimates when taking the soil carbon into account as feedback in the global models. So, the need to decrease the uncertainties in the estimation of the soil organic carbon changes is high. The modelled uncertainties that we have shown in this study has so far been extremely cost efficient since they build on earlier studies but also non specific since these uncertainties were not aimed to serve the reporting and cover its uncertainties. In order to decrease the uncertainties of the reporting to the UNFCCC and the Kyoto protocol in the future more specific investigations regarding the uncertainties of the reporting is needed.

The comparison between the stock change method and the models show that (i) the estimations of the carbon stock is in good agreement between the two methodological approaches and (ii) uncertainty in estimating change is considerable also when using models. Both measurements and models indicate increased carbon stocks in soils although the level differs. The results verify that the Swedish method of estimating carbon changes is not affected by higher uncertainties than the models. It is of importance to clarify that this modelling exercise is a simplification of the reported soil organic carbon changes, e.g. we have only estimated the changes in Pine and Spruce dominated stands. In order to increase the precision of the SOC changes, the models need to be developed to include all forest soils and the litter input estimations need to be improved. Future verification like this one is of great interest in the future. In addition the understory litter production also contains uncertainties due to the estimation method. The biomass functions used for this study are taken from Finnish conditions and therefore the litter production of

the understory litter in the southern regions of Sweden are most likely underestimated, since the Finnish conditions are applied and tested for lower temperatures. We also assume that the litter produced by the understory vegetation during 1994-2000 is the same during the whole simulation period since it is all the information we could get at the moment. We also believe that the forests were less dense in 1926 and that the understory litter production therefore may be under estimated during the first half of the simulated period.

Conclusions

The general conclusion drawn from this study is that both sampling and the models Yasso07 and Q are possible tools to predict the soil organic carbon accumulation and annual changes for Swedish forest soils. The estimates based on measurements as well as the modelled results indicate an increase in carbon stocks in Swedish forest soils.

Considerable uncertainties (statistical variation) are found in modelled as well as in measured estimates. The problem with an uncertainty that is large due to small changes in large carbon pools affects all the tested methods. However, the inventory based estimate represents all forest land in Sweden while it was necessary to reduce the number of plots that could be used in the modelling since input data and biomass functions are lacking for some tree species. The use of models is also limited by the less comprehensive historic data on forest properties that is necessary for determining the steady-state starting value and the carbon pool development during the dynamic simulations.

This study does not support a change of method from inventory to model predictions. However, the agreement between the methods shows that the models are suitable as a complement to other soil carbon estimation methods. They are particularly useful for projections and we recommend a further development of the modelling tools. They are also valuable as a tool to reveal possible sources of uncertainty. One example of this is the large variation due to the use of annual weather data that might explain inter-annual variations in the inventory data.

To be able to estimate the forest soil carbon changes in the future, with the models used in this study or other similar models, our recommendations for further development are:(i) reduce uncertainties in litter input, especially turnover rates for different litter fractions and root litter estimations, (ii) develop models to include all forest soils and (iii) separate the output from the models into carbon pools comparable to the carbon pools used for reporting to UNFCCC.

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