Soil carbon modelling as a tool for carbon balance studies in forestry

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Academic dissertation

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ABSTRACT

Soils represent a remarkable stock of carbon, and forest soils are estimated to hold half of the global stock of soil carbon. Topical concern about the effects of climate change and forest management on soil carbon as well as practical reporting requirements set by climate conventions have created a need to assess soil carbon stock changes reliably and transparently. The large spatial variability of soil carbon commensurate with relatively slow changes in stocks hinders the assessment of soil carbon stocks and their changes by direct measurements. Due to these difficulties in measuring soil carbon, models widely serve to estimate carbon stocks and stock changes in soils.

This dissertation aimed to develop the soil carbon model YASSO for upland forest soils. The model was aimed to take into account the most important processes controlling the decomposition in soils, yet remain simple enough to ensure its practical applicability in different applications. The model structure and assumptions were presented and the model parameters were defined with empirical measurements. The model was evaluated by studying the sensitivities of the model results to parameter values, by estimating the precision of the results with an uncertainty analysis, and by assessing the accuracy of the model by comparing the predictions against measured data and by comparing the model results to the results of an alternative model.

The model was applied at the stand level to study the effects of intensified biomass extraction on the forest carbon balance. In another application, the effects of energy use of forest residues on soil carbon were quantified with the model. The model calculated soil carbon deficit was presented as an indirect CO_2 emission. This emission was then compared to other emissions from the forest residue production chain and burning. Finally, the model was applied in an inventory based method to assess the national scale forest carbon balance for Finland's forests from 1922 to 2004.

According to the results of the uncertainty and sensitivity analyses, the soil carbon stock estimates of the model are uncertain, because those parameters that most strongly affect these estimates are poorly known. Carbon stock change estimates, on the other hand, are rather reliable, because the parameters determining these estimates are known better. According to a test conducted with a Canadian litterbag experiment, YASSO managed to describe sufficiently the effects of both the variable litter and climatic conditions on decomposition. When combined with the stand models or other systems providing litter information, the dynamic approach of the model proved to be powerful for estimating changes in soil carbon stocks on different scales. The climate dependency of the model, the effects of nitrogen on decomposition and forest growth as well as the effects of soil texture on soil carbon stock dynamics are areas for development when considering the applicability of the model to different research questions, different land use types and wider geographic regions.

Intensified biomass extraction affects soil carbon stocks, and these changes in stocks should be taken into account when considering the net effects of forest residue utilisation as energy. On a national scale, soil carbon stocks play an important role in forest carbon balances.

Keywords: carbon, decomposition, greenhouse gas inventory, harvest residues, litter, model, soil, YASSO

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I had the pleasure of writing this thesis in a most beautiful and peaceful environment, Suitia castle in Siuntio, where I enjoyed a personal room during these years. I wish to thank the staff of the Suitia Research Farm and Palmenia Centre for Continuing Education for their refreshing lunch and coffee company until the closure of the station at the end of year 2006.

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Siuntio, March 2008, Taru Palosuo

LIST OF ORIGINAL ARTICLES

This thesis consists of an introductory review followed by five research articles. The articles in the review are referred to by their Roman numerals. The articles are reprinted with kind permission of the publishers.

I   Liski, J., **Palosuo, T.**, Peltoniemi M. & Sievänen R. 2005. Carbon and decomposition model Yasso for forest soils. Ecological Modelling 189: 168-182.

II   **Palosuo, T.**, Liski, J., Trofymow, J.A. and Titus B. 2005. Litter decomposition affected by climate and litter quality - testing the Yasso model with litterbag data from the Canadian Intersite Decomposition Experiment. Ecological Modelling 189: 183-198.

III   **Palosuo, T.**, Peltoniemi, M., Mikhailov, A., Komarov, A., Faubert, P., Thuerig, E. & Lindner, M. 2007. Projecting effects of intensified biomass extraction with alternative modelling approaches. Forest Ecology and Management 255: 1423-1433.

IV   **Palosuo, T.**, Wihersaari, M. & Liski, J. 2001. Net greenhouse gas emissions due to the energy use of forest residues - Impact of soil carbon balance. In: Pelkonen, P., Hakkila, P., Karjalainen, T., Schlamadinger, B. (eds.), Woody biomass as an energy source - Challenges in Europe. EFI Proceedings 39: 115-122.

V   Liski, J., Lehtonen, A., **Palosuo, T.**, Peltoniemi, M., Eggers, T., Muukkonen, P. & Mäkipää, R. 2006. Carbon accumulation in Finland's forests 1922-2004 - an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil. Annals of Forest Science 63: 687-697.

AUTHOR'S CONTRIBUTION

Taru Palosuo is responsible for the summary of this thesis. She participated in the planning and writing of article I, conducted the parameter estimation in co-operation with Risto Sievänen, and took part in the planning and analysis of the results of the sensitivity and uncertainty analyses. The YASSO model structure was developed by Jari Liski; Taru Palosuo has been involved in the further development of the model. She was the main author of article II and was responsible for the model runs of the test. The test measures and figures were planned together with Jari Liski, and the CIDET Working Group provided the measurement data. In paper III, Taru Palosuo led the planning and writing of the article; Mikko Peltoniemi and Alexey Mikhailov ran the models. In paper IV, Taru Palosuo was fully responsible for the soil modelling and analysis of the study as well as for most of the writing. In article V, Taru Palosuo was responsible for the soil modelling part of the study and participated in planning the study, analysing the results and writing the paper.

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ABBREVIATIONS

Symbol	Description
C	Carbon
CO_2	Carbon dioxide
D	Drought
DD0	Effective temperature sum over the 0 °C threshold
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land use, land-use change and forestry
MAT	Mean annual temperature
NBP	Net biome production
NEP	Net ecosystem production
NFI	National forest inventory
NPP	Net primary production
PET	Potential evapo-transpiration
SOC	Soil organic carbon
SOM	Soil organic matter
UNFCCC	United Nations Framework Convention on Climate Change

1 INTRODUCTION

1.1 Soil carbon in a changing climate

Soils hold the largest stock of terrestrial organic carbon in the biosphere. The global soil organic carbon stock in the top 1 m and 3 m of mineral soil has been estimated to be 1500 Pg (1 Pg = 10^{15} g) and 2300 Pg, respectively (Jobbágy and Jackson 2000). In addition, peatlands and permafrost soils both hold about 400 Pg in the top 3 m (Davidson and Janssens 2006). All these stocks are considerable when compared to the carbon in the atmosphere (~800 Pg) and vegetation (550 Pg) (Houghton 2007), the two stocks that directly exchange carbon with soils.

Soil carbon stock is determined mainly by the balance of the flow of carbon into the soil as dead organic matter and of carbon output as heterotrophic respiration. Litter input varies in its amount, quality and vertical distribution within soil depending on the vegetation. Decomposition in soils is a complex and diverse set of processes. It involves physical, chemical and biological mechanisms that continuously transform organic matter from compound to compound, finally leading to the release of carbon as carbon dioxide (CO_2) or methane (CH_4) from soil to atmosphere (Berg and McClaugherty 2003). The time scales and pathways of these processes vary considerably (Amundson 2001). Most of the organic material entering the soil decomposes rapidly, but a small portion forms recalcitrant compounds or is stabilised by adsorption or aggregation to soil mineral particles (Krull et al. 2003). This slowly decomposing portion comprises the majority of the organic carbon in soils. Decomposer organisms involved in the decomposition process vary from microbes, fungi and bacteria to soil fauna. Environmental factors such as temperature, moisture and soil properties affect both the productivity of the vegetation, which affects litter production, and decomposition.

The stability of the carbon stock of soils in a changing climate has recently seen considerable discussion and active study in the scientific community (e.g. Giardina and Ryan 2000, Bellamy et al. 2005, Davidson and Janssens 2006, Kirschbaum 2006), due to concern about the effect of positive feedback on climate change. Feedback is positive, when warming accelerates decomposition in soils more than it increases plant-derived litter production to soils. On the other hand, negative feedback may result when the rate of litter production exceeds that of the decomposition. A consensus on the direction of the feedback has not yet been reached mainly due to the variability of observed patterns driven by huge variations in soils and their organic matter. At the same time, different options for using soils as carbon sinks have been studied widely both in agriculture (Jarecki and Lal 2003) and forestry (Jandl et al. 2007).

The international community has also noted the significance of soil carbon in the global carbon cycle. First, carbon sinks were included in greenhouse gas inventories for the UNFCCC (United Nations Framework Convention on Climate Change) in Rio de Janeiro in 1992 (UNFCCC 1992). The Kyoto Protocol, which was the first step towards limiting emissions of CO_2 and other greenhouse gases, stated that sinks can serve to compensate emission reductions (UNFCCC 1997). The Marrakesh Accords (UNFCCC 2002) stated that each ANNEX I country (i.e. an Industrial Party of the Kyoto Protocol) should report five carbon stocks for LULUCF (Land use, Land-use change and Forestry) sectors: aboveground and belowground biomass, deadwood, litter and soil organic carbon. All these stocks should be quantified, unless a transparent and verifiable method can show that a stock is not a source of carbon (UNFCCC 2002). The Marrakesh Accords also invited the IPCC (Intergovernmental Panel on Climate Change) to develop guidelines for greenhouse gas inventories in the LULUCF sector. Reporting commitments for the UNFCCC have consequently created a need for the reliable and transparent assessment of changes in these stocks on a national scale.

1.2 Forest soils and greenhouse gas mitigation

Forest soils are estimated to hold 1100 Pg carbon, about half of the global stock of soil carbon (Jobbágy and Jackson 2000). The vertical distribution of carbon in forest soil is shallower than, for example, in shrublands or grasslands, which makes the carbon stock of forest soils sensitive to changes in different environmental factors such as climate. It is important to know the dynamics of carbon in forest soils and its responses to changes in climate or forest management, since large forest areas make small changes in stocks noticeable on a national or continental scale. This is particularly important in Finland, where the forest area (26.3 million hectares in total) covers about 87% of the total land area (Metla 2006). Measurement-based estimates of the soil carbon stock of mineral forest soils in Finland have been 6-7 kg C m^{-2} (Kauppi et al. 1997, Liski and Westman 1997a), which makes the total stock in mineral forest soils about 860-1010 Tg. As little as a 2% change in this carbon stock, when converted to CO_2, is equivalent to the total annual greenhouse gas emissions in Finland in recent years: 69-85 Tg CO_2 eqv. (Statistics Finland 2007).

Attempts to alleviate the human-induced increase in greenhouse gases in the atmosphere have introduced carbon management as one of the multiple objectives of forest management (Brown et al. 1996). Alternative mitigation strategies in forest management include 1) conservation management that aims to protect existing forest carbon stocks to prevent emissions, 2) sequestration management that aims to increase forest carbon stocks by sequestration on new forested land (i.e. afforestation) and increasing the carbon stock on forested land, and 3) substitution management that aims to prevent emissions from fossil fuels, for example, by utilising woody biomass in energy production or by using wood as a building material instead of other, more energy-intensive materials (Lindner and Karjalainen 2007). Substitution management is the only carbon mitigation strategy that offers long-term mitigation potential, since with the other two strategies, this potential will likely saturate and raise the risk of losing the sequestered carbon as forests are subject to natural disturbances.

In Finland, the utilisation of biofuels in energy production has been increasing in recent years. For example, amount of stump biomass used as fuel in thermal power plants increased from 5000 to 367 000 m3 between the years 2000 and 2005 (Metla 2006). The main parts of the used wood-based fuels represent different by-products of the forest industry (Metla 2006). As these other wood-based materials are already being utilised effectively in forest-wood chains, the potential for increasing the use of forest biomass as energy lies mainly in forest residues. This means that continuously increasing demands for utilising bioenergy in Finland will lead to the intensified extraction of forest biomass in harvests. The effects of this intensified biomass extraction on forest soil carbon stocks, however, remain unknown. Because the alternative to energy use of forest residues is to let them decompose in forest sites, the decrease in soil carbon stocks due to such extraction should be taken into account when calculating the net effects of their energy use. This requires a method to assess the dynamics of decomposition.

1.3 Assessing soil carbon stocks and their changes

The large spatial variability of the soil carbon along with the relatively slow changes in stock hinders the assessment of soil carbon changes with direct measurements (Conen et al. 2004). Repeated sampling would be the most straightforward way to assess such changes, but the method is often considered to be too expensive and to require excessive effort. Such is the case with forest soils. Flux based measurements (e.g. Baldocchi 2003) also serve to detect the changes in carbon stocks as a whole, but partitioning the fluxes into vegetation and soils requires additional measurements or modelling. Moreover, extrapolating the results of only a few flux measurement sites to a larger scale is problematic. Remotely-sensed data offer the possibility of spatial and temporal estimates of land cover, land management practices and net plant productivity, all of which impact soil carbon dynamics. However, few studies have focused on the direct measurement of soil carbon using remote sensing, and none of them have dealt with forest soils (Gehl and Rice 2007).

Due to these difficulties in measuring, different kinds of models have been developed to estimate soil carbon stocks and their changes. With empirical, data-based approach static, statistical regression models that combine soil carbon stocks with, for example, soil properties (e.g. texture), variables describing aboveground vegetation or climatic conditions have been created and used to assess the stocks of soil carbon on a national or global scale (e.g. Liski and Westman 1997b, Jobbágy and Jackson 2000, Callesen et al. 2003). The IPCC Guidelines (IPCC 2006) also propose a similar static approach for the lower level (Tier 2) method, where certain land-use types are connected with some default carbon stock values. Changes in soil carbon in such cases are calculated based on area changes in the types of land-use multiplied by the default soil carbon stock values. In addition, several statistical regression models of decomposition have been developed based on decomposition experiments in the field or laboratory (e.g. Trofymow et al. 2002, Kurz-Besson et al. 2006, Mäkinen et al. 2006). The development of these empirical models requires extensive data sets, and consequently is linked to the measurement problems described above. In addition, the applicability of these models is always limited to the domain of data from which they were developed, and using them outside their domain requires assumptions of the similarity of the relations described within the models in the case studied.

An alternative to the empirical, data-based modelling approach is the mechanistic, process-based approach, in which models are built on the conceptual ideas of the processes of the system. These models endeavour to describe the processes with variable driving factors and their interactions as fundamentally as possible. With the assumption of the correct process description, mechanistical models are thought to be applicable outside their data domain as well. In practice, however, most of the models are neither purely mechanistical nor purely empirical, but something in between. These functional models aim to provide a general description of the process without going into great detail to maintain the practical applicability of the models (Addiscott 1993). Due to the dynamic nature of the decomposition process as well as the carbon stock of soils, most soil models nowadays are dynamic system models. A typical feature of the dynamic model is the memory: the state of the system in a certain moment affects its state in the following moments. Dynamic models describing decomposition are typically multi-pool models, where microbial activity is expressed in the decomposition rates of these model pools (McGill 1996).

Perhaps the most widely known dynamic decomposition models are the CENTURY (Parton et al. 1987, Parton et al. 1994) and RothC (Coleman and Jenkinson 1996) models both of which describe soil carbon as a multi-pool system and have been used and tested worldwide for different land-use types (e.g. Kelly et al. 1997, Smith et al. 1997, Peng et al. 1998, Falloon and Smith 2002, Smith et al. 2006). Examples of the models developed particularly for forest ecosystem studies include ROMUL (Chertov et al. 2001), DocMod (Currie and Aber 1997), SOILN (Eckersten and Beier 1998) and Forest-DNDC (Li et al. 2000, Stange et al. 2000). Yet another type of dynamic approach is to describe decomposition as a continuum of varying litter quality (e.g. Bosatta and Ågren 1985, Ågren and Bosatta 1998). All these models include detailed descriptions of the decomposition process as well as other aspects than purely carbon dynamics. In contrast to these detailed models are some very simple soil modules developed for larger modelling frameworks. Examples of such models include the stand-level forest and wood products model GORCAM (Schlamadinger and Marland 1996) and the global vegetation model LPJ (Sitch et al. 2003).

1.4 Soil carbon modelling as a practical tool

Models, and particularly process models, are applied in order to permit examination beyond the limits set by measurements. The idea is that the exact process description of the models makes them applicable beyond the ranges of data behind them. This idea motivates the continuous development of models with a growing number of factors and complex internal structures. Taking into account the heterogeneity of the soil matrix and processes of decomposition in soil, however, one could ask whether our knowledge of these processes will ever reach the level of accuracy needed to model them other than highly approximately. An alternative approach is to accept the incomplete process description and create simple models that adopt only the most important interactions and features of the processes, but which cover the necessary information in their parameters defined on the basis of extensive data.

Which of these above-mentioned modelling approaches would then be favourable when developing models as tools for practical purposes or supporting tools for decision making? Haag and Kaupenjohann (2001) have suggested that modelling for decision-making and modelling for theoretical scientific purposes may need to follow separate paths. The construction of complex models to gather and combine available information, theories and data, as well as to test hypotheses can be fruitful. Modelling for decision-making, on the other hand, must take into account requests for transparency and participation, and the validity of the model products will be judged according to their capacity to provide context-sensitive knowledge for specific decision problems. The aspect of transparency clearly supports the use of simple rather than complex models. The transparency of complex models is weak, since their complexity hinders the model user in perceiving the workings of the model and the assumptions behind it. Model results should always be interpreted with caution. However, when compared to decisions based purely on subjective guesses or political will, using models represents a step forward.

Models in general are useful as tools of synthesis (Rastetter 1996, Haag and Kaupenjohann 2000) and can guide further study (Oreskes et al. 1994). The modelling process itself is a learning process in which modellers must explicitly define their notions about the modelled system, thus rendering the model a catalyst of interdisciplinary communication.

Timely research questions about forest soil carbon stock dynamics focus on the development of reliable and functional assessment methods for practical reporting purposes and the analysis of responses of stocks to changes in climate and management. These purposes required an easy-to-use and relatively simple modelling tool to assure the transparency of the modelling process. To be widely applicable, the tool should cover the most important processes controlling the dynamics of carbon in forest soils. As the relevant spatial scale varies from regional to global, the availability of the model input data restricts the factors that the model takes into account. The model should also be tested as widely as possible to evaluate the reliability of the model-calculated soil carbon and soil carbon change estimates.

For these purposes, however, we found the above-mentioned models unsuitable. The detailed input information that the detailed models required, as well as their internal complexity, compromised their applicability. Moreover, their monthly or daily time steps were considered inappropriate for forestry purposes. The simple models, on the other hand, were considered too simple to cover the most important aspects of the dynamics modelled, and their reliability has not been thoroughly tested. This dissertation presented, evaluated and applied a new modelling tool for the practical forestry purposes.

1.5 Model evaluation

An important step in the modelling process is model validation or evaluation. The objectives, meaning and proper terminology that should be used for the evaluation, however, remain debatable. Oreskes et al. (1994) claimed that the validation of environmental models is impossible, since the mathematical components of the models are always closed systems, whereas the environmental systems they describe are open. Oreskes et al. also relied on Popper's argument (e.g. in Popper 1995) that, in principle, to prove a theory false is possible, but even in principle, to prove a theory true is impossible.

However, the requirement of thorough model evaluation for practical applications still exists. The interpretation of evaluation in this context is that the model is acceptable for its intended use if it meets specific performance requirements (Rykiel 1996). This does not mean that the model structure or the modelled results would be correct, however. Refsgaard and Henriksen (2004) state in their modelling guidelines that the question of suitable performance criteria should be set in the socio-economic context, and Rykiel (1996) stressed the importance of clearly written evaluation criteria.

But how shall we evaluate the models in practice? Vanclay and Skovsgaard (1997) adopted the viewpoint that the modeller should provide as much information as possible about the model's behaviour and predictive ability. Model users should then decide, based on this information, how suitable the model is for their purpose. This dissertation applied different means to evaluate the model in order to provide a greater insight into the model's behaviour and performance as well as the reliability, precision and accuracy of the model's results and factors affecting them. In addition to these model tests, the model user should perform a targeted evaluation of the model separately for each intended model application. This is particularly important when applying the model to conditions very different from those for which the model was developed.

1.6 Objectives of this dissertation

The overall aim of this thesis was to develop and evaluate a dynamic soil carbon model for upland forest soils and to apply the model in different types of practical forest carbon assessment studies.

The specific objectives were:

- to present the model structure, to explain the assumptions behind the structure, and to determine the model parameters with empirical data (Study I).
- to evaluate the model with sensitivity and uncertainty analyses (Study I), and by testing the model against measured data (Studies I and II) as well as by comparing the results of the model with those of an alternative model (Study III).
- to use the developed model, combined with an empirical forest stand simulator, as well as an alternative model combination, to analyse the effects of intensified biomass extraction on the forest carbon balance at the stand level (Study III).
- to apply the model to simulate the decomposition dynamics of harvest residues in order to assess the indirect CO_2 emissions resulting from diminished soil carbon due to the energy use of forest residues (Study IV).
- to use the model in the nation wide forest carbon balance assessment based on forest inventory data (Study V). The carbon stocks and flows of Finland's forests were assessed from 1922 to 2004.
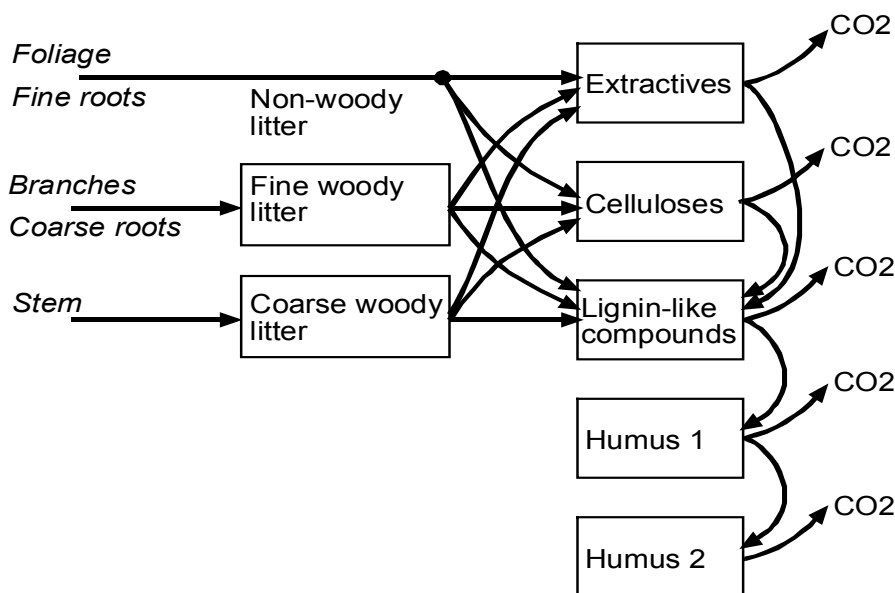
Figure 1. Flow chart of the YASSO model. The boxes represent carbon compartments, the arrows carbon fluxes.

2 MATERIAL AND METHODS

2.1 Soil carbon model YASSO

Assumptions

The conceptual model structure for YASSO (Figure 1) was set according to some basic assumptions about decomposition. The assumptions are listed below as they appeared in Study I, along with some added clarifications.

Assumption 1*. Litter and soil organic matter consists of different compound groups that decompose at their own typical rates independent of their origin. The decomposition rate of these groups decreases with the increasing complexity of the compounds.*

According to this assumption, the soil organic matter can be divided into unique cohorts that are dynamically homogeneous. Cohorts are thus not assumed to consist of chemically homogenous material, but the material within these compartments is assumed to decompose at the same rate. Dynamically homogenous and unique compartments are a challenge when trying to identify measurable counterparts to the model compartments (Smith et al. 2002). Clearly, chemical extraction procedures typically used (such as the one applied in Study II) provide no dynamically homogenous chemical fractions. This is therefore a simplifying assumption, as the soil organic matter consists of a myriad of compounds with different chemical properties affecting their vulnerability to microbial, physical or chemical decomposition. This simplification, however, is an important tool to handle and approximate easily the exceedingly complex characteristics of soil organic matter, and serves widely in different compartment models describing the decomposition of soil organic matter (e.g. Parton et al. 1994, Coleman and Jenkinson 1996, Currie and Aber 1997, Chertov et al. 2001).

Another assumption here is that no interactions occur within the model compartments in the sense that the amount of some modelled compounds would affect the decomposition of the other compounds. In addition, the availability of any other chemical compounds, such as nutrients, in no way affects the decomposition of the compartments. In other words, the decomposition of the organic compounds is assumed to be independent of the material from which they originate. There is, however, one exception to this assumption. Study I provides two decomposition rates for the extractives compartments, which differ for coniferous and deciduous plants. Figure 2a shows that the empirical evidence supports this exception. The fact that the parameter values must differ for different species indicates the need to divide the compartment into two separate compartments. In the YASSO applications, this has been implemented either by driving a couple of models one for coniferous and another for deciduous species side by side, or by making one additional model compartment for the extractives. Both of these practical implementations lead to the same aggregated results.

Decomposition is also assumed to be independent of the location of the material within the forest stand. The decomposition of roots is therefore assumed to be similar to the decomposition of branches if they share a similar chemical structure.

Assumption of the decreasing decomposition rates along with the complexity of the compartments helped us to determine the decomposition rates during parameterisation (Section 2.4).

Assumption 2. *Decomposition of woody litter is delayed because of its physical characteristics mean that not all woody litter is immediately exposed to microbial decomposition.*

This assumption takes into account particle size as a physical attribute of litter quality. The decomposition of fine and coarse woody litter is separated (i.e. the decomposition of branches and roots is distinct from the decomposition of large stems and stumps). As Laiho and Prescott (2004) state, diameter as a factor affecting the decomposition of woody litter is only a derivative of substrate quality and environmental factors. The connection between the diameter and decomposition of woody debris is controversial (Yin 1999), but many empirical studies also support this rough division (Edmonds 1987, Taylor et al. 1991, Næsset 1999).

Implementation of the delay in woody debris decomposition in the YASSO model occurs through the use of separate compartments for the woody litter from where the material flows into the following decomposition compartments, which is where the decomposition within the model occurs. The implementation of the delay compartments is a simplification yielding model compartments with no measurable counterparts. To determine the fractionation rates of these compartments, the measured remaining mass of the woody litter has been linked to the sum of decomposition compartments and the corresponding woody litter compartment of the model. In short, the litter compartments as such do not represent the woody debris in forests. To estimate the woody debris, one should calculate the flow of carbon originating from the woody litter through the model, and use the sum of all model compartments with this carbon as an estimate.

Assumption 3. *Decomposing compounds lose a certain proportion of their mass per unit of time.*

This can be written with the simple first-order decay model

$$\frac{dX}{dt} = -kX \qquad (1)$$

where the mass loss is directly proportional to the decomposing mass (X).

Assumption 4. *A part of the decomposed mass is removed from the soil as heterotrophic respiration or leaching while the reminder forms more recalcitrant compounds.*

This assumption describes the division of the decomposition products of the model compartments. In most applications, the carbon leaving the system is assumed to leave as CO_2 through heterotrophic respiration, but this is not explicitly defined within the model itself. This model can also include carbon transferred from the system studied through leaching or otherwise across the system boundaries set in the application.

This assumption, precludes the formation of more easily decomposable products during the decomposition process. As this model is used with the one-year time step, the flows within the model can be considered as net flows over one year, which makes the return flows to fast decomposing compartments less important.

Assumption 5. *Microbial activity, and thus decomposition rates, as well as the exposure rate of the decomposition depend on temperature and moisture conditions.*

The climate dependency of the decomposition is implemented in the current YASSO version so that selected climatic variables, such as temperature and drought, affect a rate modifier that multiplies the decomposition or fractionation rates of all compartments. Therefore, the decomposition of each model compartment is similarly dependent on the climate, except for humus, which is assumed to be less sensitive to temperature than the decomposition of more recalcitrant compounds.

Structure

The YASSO model consists of five compartments describing decomposition and humification processes in the soil, and two woody litter compartments describing the physical fractionation of woody litter (Figure 1). Non-woody litter (foliage, fine roots, non-woody plants, etc.) is separated directly into the first three decomposing compartments (extractives, celluloses and lignin-like compounds) according to its chemical composition (given by parameters c_{ij}). Each decomposition compartment has a specific decomposition rate (k_j) that determines the proportion of their content that leaves the compartment. Proportions (p_j) of the flows from these compartments are transferred into the subsequent decomposition compartments while the rest (1-p_j) is removed from the system. The two humus compartments with different dynamical properties describe the slow soil organic carbon dynamics. Woody litter is separated into coarse (stems and stumps) and fine woody litter (branches and coarse roots) compartments from which the carbon flows according to the fractionation rates (a_i) and its chemical composition to the decomposition compartments.

Mathematically, the YASSO model is a linear (time-invariant) compartmental system. The model can be expressed as a set of differential equations (as in Study I) or as matrix equations (below).

The model can be written in matrix form as follows:

$$\mathbf{x}'(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \qquad (2)$$

where $\mathbf{x}'$ is the time derivative of the state vector

$$\mathbf{x} = \begin{bmatrix} x_{fwl} & x_{cwl} & x_{ext} & x_{cel} & x_{lig} & x_{hum1} & x_{hum2} \end{bmatrix}^{\mathrm{T}}$$

that describes the model compartments: two woody litter compartments (fine woody litter (x_{fwl}) and coarse woody litter (x_{cwl})) and five decomposition compartments (extractives (x_{ext}), celluloses (x_{cel}), lignin-like compounds (x_{lig}), faster decomposing humus (x_{hum1}), and slower decomposing humus (x_{hum2})).

Initial conditions appear as $\mathbf{x}(0) = \mathbf{x}_0$.

The system matrix

$$\mathbf{A} = \begin{bmatrix} -a_{fwl} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -a_{cwl} & 0 & 0 & 0 & 0 & 0 \\ a_{fwl}c_{fwl\_ext} & a_{cwl}c_{cwl\_ext} & -k_{ext} & 0 & 0 & 0 & 0 \\ a_{fwl}c_{fwl\_cel} & a_{cwl}c_{cwl\_cel} & 0 & -k_{cel} & 0 & 0 & 0 \\ a_{fwl}c_{fwl\_lig} & a_{cwl}c_{cwl\_lig} & k_{ext}p_{ext} & k_{cel}p_{cel} & -k_{lig} & 0 & 0 \\ 0 & 0 & 0 & 0 & k_{lig}p_{lig} & -k_{hum1} & 0 \\ 0 & 0 & 0 & 0 & 0 & k_{hum1}p_{hum} & -k_{hum2} \end{bmatrix}$$

includes constant parameters. The a_i parameters describe the invasion rate of woody litter i by microbes, k_j the decomposition rate of compartment j, and c_{i_j} the proportion of compounds j in litter type i.

The input

$$\mathbf{u} = \begin{bmatrix} u_{nwl} & u_{fwl} & u_{cwl} \end{bmatrix}^{\mathrm{T}}$$

consists of the litter input of non-woody (u_{nwl}), fine woody (u_{fwl}), and coarse woody (u_{cwl}) material. The input matrix represents the allocation of carbon from the litter input

$$\mathbf{B} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ c_{nwl\_ext} & 0 & 0 \\ c_{nwl\_cel} & 0 & 0 \\ c_{nwl\_lig} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

Climate dependencies

Environmental factors influencing decomposition in YASSO are restricted to selected climatic factors: temperature (T) and drought (D). The climatic dependencies of the model are currently based on empirical linear regression models developed by Liski et al. (2003). The models serve as rate modifiers of the decomposition and fractionation rates of the compartments

$$k_j(T, D) = k_{j0}(1 + s_j\beta(T - T_0) + \gamma(D - D_0)) \qquad \text{and} \qquad (3)$$

$$a_i(T, D) = a_{i0}(1 + \beta(T - T_0) + \gamma(D - D_0)) \qquad , \qquad (4)$$

where k_{j0} and a_{i0} are the decomposition and fractionation rates of the model in the reference conditions, and β and γ are parameters describing the proportional change in decomposition rates when temperature and summer drought variables change. Values for these parameters appear in Table 2 of Study I. The temperature sensitivity of the humus decomposition is slowed down by rate modifier s_j, which is less than 1 for humus compartments and 1 for the other compartments. The linear regression models are initialised with reference conditions (T_0, D_0), which are the climatic conditions of the data used for basic parameterisation used in the model.

The temperature variable (T) is either mean annual temperature (MAT) or, depending on the application, the effective temperature sum over the 0 °C threshold (DD0). Drought (D) is restricted to the summer months and represents the difference between the accumulated precipitation and the accumulated potential evapotranspiration (PET) from May to September. Only the negative values of this difference are used, since the positive values indicate the no-drought effect, and thus favourable moisture conditions for decomposition.

2.2 Data used in model parameterisation and evaluation

Parameterisation, evaluation and applications of the soil carbon models require different kinds of data on decomposition and soil carbon. The data used in this dissertation originate from the litterbag experiments, which provide information on the short term (typically a few years) decomposition of leaf-litter, mass loss or density data on woody litter decomposition and total soil carbon measurements.

Litterbag data

In the litterbag experiments, a small amount of leaf-litter or other litter material is put into a small bag, placed on the study plot in contact with the underlying litter layer, and incubated for a certain period of time. After the incubation period, the content of the litterbag is weighted, and selected chemical analyses are conducted on the remaining litter material to study the content of different nutrients and other selected properties of the material. In typical litterbag experiments, several litterbags are placed in the field and a certain number of litterbags is then removed for analysis between the fixed time periods. These types of experiments are rather costly and laborious, which is why they usually last no longer than a few years. Only recently have a few longer and geographically wide litterbag experiments taken place (e.g. Long-term Intersite Decomposition Experiment Team (LIDET) 1995, Trofymow and the CIDET Working Group 1998). Testing decomposition models, such as YASSO, with litterbag studies is rather straightforward. Model runs are simple, with no model input other than the initial states of the model variables taken from the measured characteristics of litter initially placed into the litterbags.

In Study I, Swedish litterbag data with length from two to five years (Berg et al. 1991a, Berg et al. 1991b) (Figure 2) served to determine the parameter values of the fast decomposing model compartments. The data involved 18 litterbag experiments with Scots pine (*Pinus sylvestris* L.) and 2 experiments with birch (*Betula pendula* Roth).

In Study II, the YASSO model was tested against the Canadian Intersite Decomposition Experiment (CIDET), one of the widest existing litterbag data sets. The test covered mass remaining data for 10 different leaf-litter types (Table 1 in Study II) in 18 upland forest sites (Table 2 in Study II) across Canada over a six-year period.

Woody litter data

Mass loss or density measurements of logs or branches typically serve to acquire information on the decomposition of woody material. In Study I, the parameter values of the woody litter compartments were determined based on mass loss estimates calculated from the density measurements of Norway spruce (*Picea abies* (L.) Karst.) logs of two diameter classes in the Leningrad region of Russia (Tarasov and Birdsey 2001) (Figure 3). No similar data on the decomposition of fine woody litter, such as branches, were available.
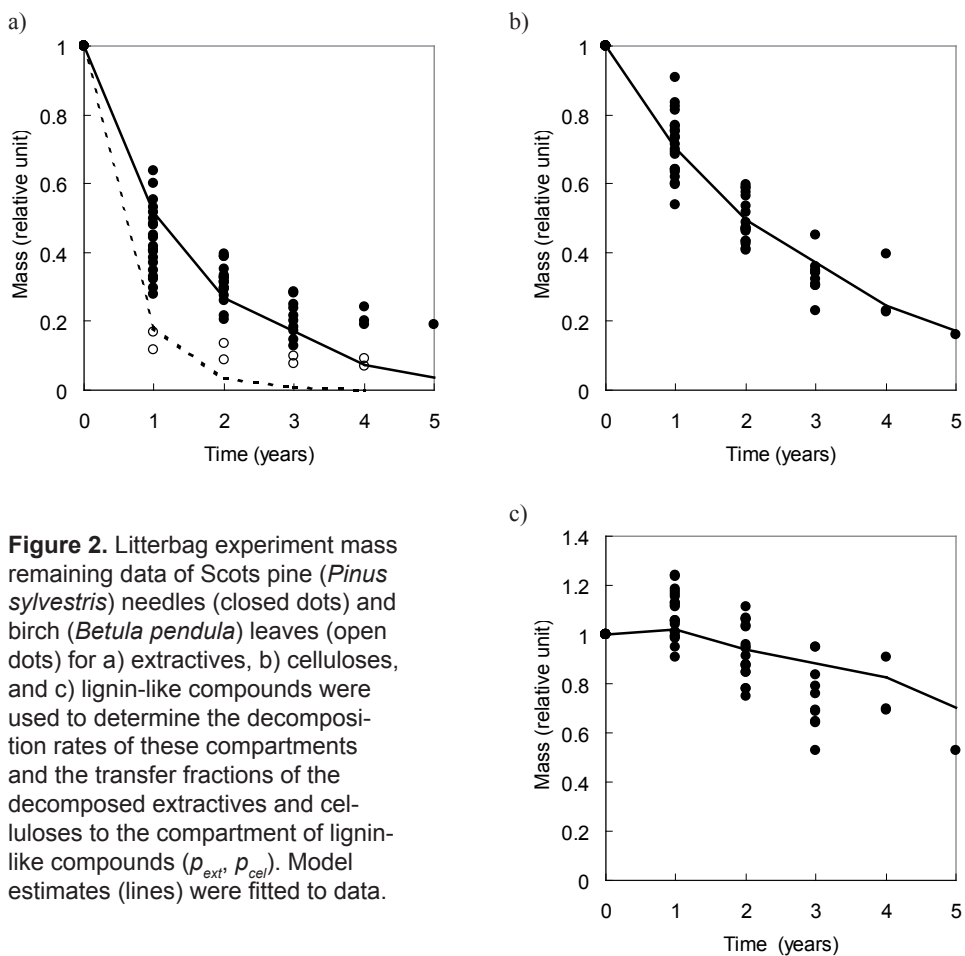
Figure 2. Litterbag experiment mass remaining data of Scots pine (*Pinus sylvestris*) needles (closed dots) and birch (*Betula pendula*) leaves (open dots) for a) extractives, b) celluloses, and c) lignin-like compounds were used to determine the decomposition rates of these compartments and the transfer fractions of the decomposed extractives and celluloses to the compartment of lignin-like compounds (p_{ext}, p_{cel}). Model estimates (lines) were fitted to data.

Total soil carbon measurements

Total soil carbon estimates are usually based on samples taken from different soil layers and from different locations within the study plot. The stock is then calculated with the information acquired on soil organic carbon concentrations, bulk density and the content of rock fragments. Model parameterisation and testing the total carbon stock estimates of the YASSO model in Study I used total soil carbon measurements of the carbon in the organic layer and down to a depth of 1 m in the mineral soil. These data used in the model parameterisation actually anchor the current model version to describe the soil carbon stock down to a depth of 1 m. The parameterisation used soil carbon measurements from 26 Scots pine sites along a 5300-year soil chronosequence in Southern Finland (Liski et al. 1998) (Figure 4). The test involved similar measurements from six forest sites of different productivity and tree species in southern Finland (Liski and Westman 1995).

Figure 3. Mass remaining of Norway spruce (*Picea abies*) logs of 5-20 cm in diameter (closed dots) and 20-60 cm in diameter (open dots) were used to determine the exposure of coarse woody litter to microbial decomposition (a_{cwl}).
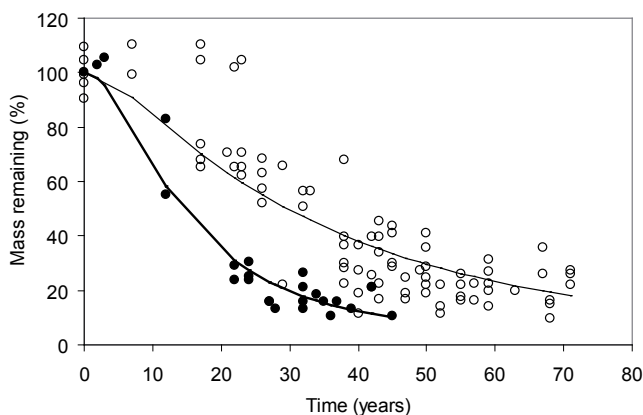
Figure 4. Soil carbon measurement data (litter excluded) along a soil chronosequence (Liski et al. 1998) were used to determine the decomposition rates of humus compartments (k_{hum1}, k_{hum2}).
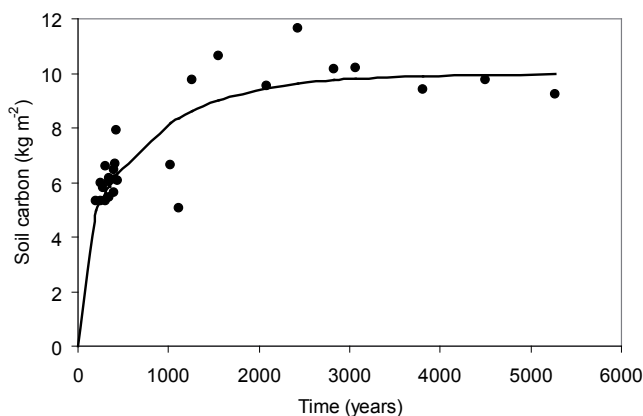
2.3 Data needed to run the model

Litter amounts

Litter input estimates are necessary to run the YASSO model in applications, to test the model or to determine its parameters with total soil carbon measurements. The method applied to generate these estimates usually depends on the availability of the information required and on the scale of the application.

Study I involved rough, average long-term litter production estimates, when the model was parameterised against the soil chronosequence data. Litter estimates were calculated based on literature values of the typical biomass production of southern Finland and on the turnover rates of different biomass compartments (Mälkönen 1974, Persson 1983, Liski and Karjalainen 1997, Liski et al. 1998).

When testing the model in Study I, and in the stand scale application of the model (Study III), the biomass production was estimated with empirical forest stand simulator MOTTI (Hynynen et al. 2002, Matala et al. 2003, Hynynen et al. 2005, Salminen et al. 2005). MOTTI is a decision support tool based on extensive data from Finnish forests and developed to assess the effects of forest management practices on stand dynamics and the profitability of forest management. It includes several model components, both static and dynamic. Growth in MOTTI is predicted with empirical distance-independent individual-tree growth models that predict tree diameter and height growth over five-year periods. Mortality is predicted with an individual-tree survival model, and a stand-level model for self-thinning. Biomass estimates within MOTTI are based on Marklund's biomass equations (Marklund 1988), and are calculated separately for each tree. Fine root biomass (< 2 mm) estimates used in Studies I and III were calculated using an empirical relation with foliage biomass (Vanninen and Mäkelä 1999). For litter production estimates from living trees, the biomass estimates were multiplied by turnover rates (e.g. Table I in Study V). The amounts of harvest residues were taken from the biomass estimates of the year of harvest.

Study V was an example of the model application on a national scale. The litter estimates for the soil model were calculated based on national forest inventory (NFI) data. Aggregated forest inventory measurements (Ilvessalo 1927, Tomppo 2000) of stem volume and forest area and drain estimates reported by national forestry statistics (Metla 2005) served as basic information. Calculations were conducted at the sub-national level, separately for the southern and northern Finland, and for the main tree species (i.e. Scots pine, Norway spruce and aggregated broadleaved species) and their age-classes. The interannual variation of tree growth was estimated with growth indices based on tree ring measurements of the tree species studied in the area (Henttonen 1998). The biomasses of the various tree components were assessed with biomass expansion factors (Lehtonen et al. 2004), and the biomass of ground vegetation was obtained with other statistical models (Peltoniemi et al. 2004, Muukkonen and Mäkipää 2006). To calculate the litter production from living vegetation to soil, the biomass estimates were multiplied by compartment-specific turnover rates (Table I in Study V). The biomass of harvest residues was calculated as a sum of biomasses of all compartments, except that of the bole.

Litter quality

Litter quality within the model is defined with *c*-parameters that tell how non-woody, fine-woody and coarse-woody litter is divided between extractives, celluloses and lignin-like compounds. Values for these parameters can be determined by varying methods of chemical analysis such as those applied within the sub-studies of this dissertation. Litterbag data in Study I were divided between the model compartments according to reported extractable substances, sulphuric acid soluble substances and sulphuric acid insoluble substances (Berg et al. 1982, Berg et al. 1991b). In Study II, initial chemistry of the studied litters was taken from the conventional elemental and proximate analysis by Preston et al. (2000). A large number of applicable values for different species and plant compartments also appears in the literature. For example, the chemical composition of litter input used in the model parameterisation, tests and applications in Studies I, III, IV and V were literature values (Berg et al. 1982, Berg et al. 1984, Hakkila 1989).

Climatic data

Climatic data needed to run the model include temperature and drought. In practise this usually means that monthly temperature and precipitation values are needed in order to calculate the DD0 and drought. Liski et al. (2003) noted that DD0 is an effective predictor of decomposition rate and Study II showed that DD0 is a preferable variable in the YASSO model, whereas MAT data are usually more readily available for different model applications. In model applications (for example in Studies II, III and V), the DD0 has been calculated from mean monthly temperatures by assuming that the mean temperatures occurred in the middle of each month; mean daily values were then linearly interpolated from these. This is how the effective temperature sums were calculated when creating the empirical climate models used in YASSO (Liski et al. 2003).

When creating the climate regression models, Liski et al. (2003) used the Priestly-Taylor equation (Priestly and Taylor 1972) to calculate PET. In many applications, the Thornthwaite method (Thornthwaite 1948), with the approximation developed by Palmer and Havens (1958), has been used because it is easier to use and requires less input data. The Thornthwaite method was also used in Study II, where the climatic dependency of the model was tested with the large Canadian litterbag dataset.

The current basic parameter set was determined in central Sweden and southern Finland (Study I), and the reference climatic conditions used in all the sub-studies of this dissertation are $T_{0,MAT}$ = 3.3 °C, $T_{0,DD0}$ = 1903 °C days and D_0 = -32 mm. These are also the climatic conditions assumed when no climatic dependency was taken into account in the model (Studies I and IV in Finland).

The climatic data in Study II in Canada were the thirty-year climate-normal (long-term) data gathered from the climate stations nearest the CIDET sites. In Study III, the climatic variables for the sites were taken from a model that calculates monthly temperature and rainfall surface for Finland using long-term monthly weather station data (Ojansuu and Henttonen 1983). In Study V, in a national-scale model application, the YASSO model was run using temperature as the only climatic variable, which varied annually. The regression model, which included temperature as the only independent variable, was taken from Liski et al. (2003) because temperature alone has been shown to explain more than 85% of the climatic effect on annual decomposition in Finnish conditions (Mikola 1960). Climatic data for the study period originated from the CRU TS 1.2 data set (Mitchell et al. 2004), which is also based on long-term data.

Model initialisation

With dynamic models, the model results of each time step depend not only on the model parameters and input, but also on the previous values of the state variables. The model initialisation (i.e. giving initial values for the state variables) is therefore an important step in model applications.

The model compartments, lack of measurable counterparts hampers initialisation of YASSO. Typically, the rare information measured concerns total stocks, and no basis exists for allocation of the total stocks to model compartments. A means often used for initialisation is to assume the state variables to be in a steady-state with certain input estimates given to the model. Within this dissertation, steady-state assumption was applied in Studies I, III and V. In practise, the equilibrium states were calculated with analytical equations with the assumption of stable input (Study V) or with spin-up runs with certain period of input, such as when litter input over the forest rotation was used in Study III. Alternatively, allocating the measured total soil carbon stock with some additional assumptions, as in Study V when transferring the soil carbon over different land-use types, could serve to initialise the model.

2.4 Model parameterisation

Parameter estimation, or model calibration, is an important part of the modelling process, since it enables the numerical model results and their reliable use in tests and applications. In the best case, the model parameters can be determined directly from separate measurements. This is not always possible, however, and in such cases the parameters must be determined with measurements of the whole system (i.e. the system variables or their functions are measured). This is how the parameters of the YASSO model were determined in Study I. The parameterisation approach was such that the parameters were first determined for certain climatic conditions (here for southern Finland and central Sweden) and were then scaled with the help of climatic dependencies to be applicable to other climatic conditions.

The parameterisation procedure of the model consisted of separate steps. First, the decomposition rates and proportions p_j of the extractives, celluloses and lignin-like compounds were determined by minimising the sum of the squared errors between the measured and the model-calculated mass remaining values of these compounds in leaf-litter and by anchoring the p_j values according to qualitative criteria (Figure 2). These parameter values were then anchored and used to determine the parameters of the slowly decomposing humus compartments by minimising the sum of the squared errors between the model-calculated and the measured values of total soil carbon along the soil chronosequence (Figure 4). All these parameter values were then used to determine the last parameters (the fractionation rates of woody litter) by minimising the sum of the squared errors between the model-calculated and measured mass remaining values of the logs (Figure 3). Because no data were available for parameterisation of the fractionation rates of the fine woody litter, a mid-point value between the value for coarse woody litter and a value equal to one was applied for them. Model parameters obtained with this procedure appear in Table 1.

Table 1. Parameter values of the model and their estimated uncertainties under chosen standard conditions (mean annual temperature 3.3 °C, effective temperature sum (0 °C threshold) 1903 °C days and precipitation minus potential evapotranspiration from May to September –32 mm).

Parameter	Value	Uncertainty Absolute	Relative	Notes
Invasion rates of woody litter by microbes (year^{-1})				
Fine woody litter (a_{fwl})	0.54	0.077 – 1.0	± 86 %	
Coarse woody litter (a_{cwl})	0.030 or 0.077	0.028 – 0.032 or 0.072 – 0.083	± 5 % or ± 7 %	Smaller value for larger logs (∅ 20 – 60 cm), larger value for smaller logs (∅ 5 – 20 cm)
Decomposition rates (year^{-1})				
Extractives (k_{ext})	0.48 or 0.82	0.45 – 0.51 or 0.71 – 0.93	± 6 % or ± 14 %	Smaller value for conifers, larger value for deciduous plants
Celluloses (k_{cel})	0.30	0.28 – 0.31	± 5 %	
Lignin-like compounds (k_{lig})	0.22	0.17 – 0.29	–23 – +32 %	
Faster humus (k_{hum1})	0.012	0.002 – 0.02	–83 – +67 %	
Slower humus (k_{hum2})	0.0012	0.0017 – 0.0008	–33 – +42 %	
Formation of more complex compounds in decomposition (proportion of decomposed mass)				
Extractives to lignin-like compounds (p_{ext})	0.2	0.1 – 0.3	± 50 %	
Celluloses to lignin-like compounds (p_{cel})	0.2	0.1 – 0.3	± 50 %	
Lignin-like compounds to faster humus (p_{lig})	0.2	0.1 – 0.3	± 50 %	
Faster humus to slower humus (p_{hum1})	0.2	0.1 – 0.3	± 50 %	

Climatic parameters β and γ (Equations 3 and 4) (Table 2 in Study I) for the model were derived from the study by Liski et al. (2003). The decrease in the temperature sensitivity of humus decomposition (parameter s) was determined based on the data gathered along a temperature gradient in Finland (Liski and Westman 1997b). Model-calculated total soil carbon amounts in equilibrium were fitted to the measured soil carbon amounts along this gradient. Litter input estimates given to the model followed the pattern of stem wood production along the gradient. The value of s for the second humus compartment was assumed to be the square of the value for the first humus parameter in order to show that the slower decomposing humus compartment was less sensitive to climate than the first compartment. Values equal to 0.6 and 0.36 were obtained for the s-parameters of the faster and slower decomposing compartments, respectively.

2.5 Model evaluation

Model performance was evaluated in this dissertation with sensitivity analysis, uncertainty analysis, tests with measured data on decomposition and total soil carbon, and with a model comparison. These tests highlight different aspects of the model's performance.

Sensitivity analysis

Sensitivity analysis has acquired a strong position as a method for evaluating models (IAEA 1989, Prisley and Mortimer 2004, Medlyn et al. 2005, Nalder and Wein 2006, Tatarinov and Cienciala 2006) as it addresses issues such as model robustness, the stability of model parameters, and the variability of model outputs. Sensitivity analysis is also an important part of model uncertainty analysis as it identifies the components of a model that are potentially important contributors to the overall uncertainty of the model. The procedure used in Study I represents the most traditional form of sensitivity analysis: the local constant fraction analysis. The response of the model output to small, constant fraction changes in each input parameter (model parameters, initial states of the model variables or model input) is evaluated one at the time. Mathematically, it means a partial derivative of the studied model output function with respect to one of those parameters with the others held constant. Analytical calculation of these derivatives is not, however, always simple. Consequently, simulations are used instead. The analysis highlights those parameters that most influence the model outputs around a certain position in the parameter space.

In Study I, sensitivity analysis was conducted for the YASSO model around the determined basic parameter set (Table 1). We studied the sensitivity of the steady-state soil carbon stock of low productivity Scots pine stand and examined the effect of a 1% increase in each parameter and input value by running the model with stable, average annual input to the steady-state, (i.e. until the simulated model variables no longer changed).

Uncertainty analysis

The Monte Carlo simulation is an effective means to combine uncertainties in model parameters and input when models are complex with non-linearities and different types of correlations (Morgan and Henrion 1990). In the Monte Carlo method, random numbers are generated from input distributions, and the output distribution is calculated based on each set of random numbers. Assuming a correct model structure the method thus provides information on the precision of the model results.

In study I, we determined the uncertainty of the YASSO model results for a 90-year forest rotation of Scots pine stand with two thinnings. The stand information used was the same as that used in the sensitivity analysis. The uncertainty was assessed by determining the uncertainty of the parameter values of the model and by conducting a Monte Carlo simulation of a forest rotation. Uncertainty ranges for the parameters were, as much as possible, defined on the basis of measured information. Parameter values from these uncertainty ranges were sampled, assuming an even distribution, for 250 times, and the model runs were performed with these sampled values. Correlations between the model parameters created by the parameterisation procedure were taken into account by calculating the decomposition rates of lignin-like compounds and of two humus compartments based on the other parameters.

Test of decomposition estimates

In Study II, the extensive Canadian litterbag data set was used to test how accurately the model predicts the mass loss of different leaf-litter types over six years. The test was performed for two different temperature variables (MAT and DD0). The initial litter quality taken from the measured data and climatic data served as input information for the model runs. The model was run with the basic parameter set (defined in Study I) and climatic dependency regression models. The sum of simulated carbon in YASSO's compartments and measured ash served as the model's prediction for the mass remaining, which was then compared to the measured mass remaining values.

Test of soil carbon estimates

In Study I, YASSO's estimates for the amount of soil carbon in equilibrium were compared to measured soil carbon estimates for forest sites of various productivities. The stand simulator MOTTI served to generate the litter production for these sites, and the information required as input for MOTTI regarding the study sites were taken from Liski and Westman (1995) or assumed to be typical for the region.

Model comparison

Model comparisons offer the means to study the effect of different model properties that cause discrepancies in the output of different models. Factors causing these differences include, for example, model structure, specific equations that alter process rates, calibration procedures, and the quality of the data used for model parameterisation (Homann et al. 2000). Model comparisons are especially valuable when the measured information to test the models is rare. Alternative model results also highlight the overall uncertainty related to the modelled values if neither of the models is known to be particularly weak.

In Study III, the YASSO model was linked to the stand simulator MOTTI, and simulated impacts of the biomass extraction in final felling on subsequent biomass and soil carbon stocks were compared to the simulation results of EFIMOD-ROMUL. EFIMOD is an individual-based process model (Komarov et al. 2003), and ROMUL is a soil module describing soil organic matter dynamics (Chertov et al. 2001). The most relevant difference between the model approaches, with regard to the subject under study, was that EFIMOD-ROMUL includes the nitrogen dynamics omitted in MOTTI-YASSO. Table 2 in Study III covers model inputs and run time assumptions of the models. The soil models studied are both linear compartment models, but in ROMUL, other soil and litter properties, in addition to temperature and moisture, also affect the decomposition and humification processes described with a set of empirical regression models.

Model runs were conducted for six typical Finnish forest sites on mineral soils from different parts of the country, representing various forest site types and dominant tree species (Table 1 in Study III). The stand data required for the initialisation of the stand models, and the soil data required by ROMUL, were taken from the measurements since the sites were part of the Finnish National Forest Inventory's (NFI) permanent monitoring grid.

In this summary, Study III presents both a model comparison and a model application. In the results section, only a pure comparison of decomposition dynamics of soil models is presented in the model evaluation; the other results of the Study III are presented in the model application section. The decomposition dynamics projected by the models were studied by supplying both models with similar litter material and following the decomposition dynamics of these litters at different study sites.

2.6 Model applications

Several studies in different countries have applied the soil carbon model YASSO (Table 2). These applications can be divided into three classes: those where the model serves to study the effects of different forest management activities on the forest carbon balance or follows the development of the carbon balance along the stand development (e.g. Study III, Kaipainen et al. 2004, Thürig et al. 2005, Schmid et al. 2006), those that apply the model only to quantify the decomposition process (Study IV), and those where the model serves in regional- or national-scale carbon accounting (e.g. Study V, Peltoniemi et al. 2006, Monni et al. 2007). Sub-studies III, IV and V of this dissertation are presented as examples of these different types of model applications.

Effects of intensified biomass extraction on forest carbon balance

Study III focuses on the effects of two alternative forest management scenarios with different intensities of biomass extraction on the forest carbon balance. Model were run according to the latest silvicultural recommendations in Finland (Hyvän metsänhoidon suositukset 2006). In the standard scenario (STA), only stems were assumed to be removed from the study sites after thinning interventions and in final felling. In the scenario of intensified biomass extraction (IBE), we followed the recommendations for harvest residue extraction given in the silvicultural recommendations in Finland (Hyvän metsänhoidon suositukset 2006) by assuming that 60% of the harvest residues (i.e. needles, branches, and tree tops) and tree stumps was to be extracted from the final fellings. The same forest management scenarios were simulated with both MOTTI-YASSO and EFIMOD-ROMUL model combinations, and we studied differences between scenarios and model simulations.

Net greenhouse gas emissions due to energy use of forest residues

The utilisation of biofuels, such as forest residues, is generally assumed to release no carbon to the atmosphere. For example, CO_2 emissions from burning wood are excluded from the guidelines regarding country reporting to the UNFCCC (IPCC 2006). This is because carbon released in the burning of fuel is taken up again by growing plants. This consideration, however, disregards the effect of residue removal on forest soil carbon stocks. Residues decomposing in forests form a continuously diminishing carbon stock for decades that is lost when residues are burned.

Table 2. (facing page) Studies where the YASSO model has been applied.

Study	Studied subject	Study area, scale	Time of the study	Litter production method	Evaluation done for YASSO model within this application
Study III	The effect of intensified biomass extraction on forest carbon, model comparison.	Finland, 6 study sites	One forest rotation	Forest simulator MOTTI	Model simulations compared with EFIMOD-ROMUL
Study IV	Impact of soil carbon balance on net greenhouse gas emissions due to energy use of forest residues	Finland, 1 study site	One forest rotation	Average mature forest stand information	-
Study V	Carbon balance of Finland's forests	Finland, national scale	1922-2004	NFI with statistical biomass models	-
De Wit et al. 2006	Carbon budget of forests in southeast Norway	Southeast Norway, sub-national scale	1971-2000	NFI with statistical biomass models	Comparison with 1) litterbag data, 2) soil carbon stock estimates
Peltonieni et al. 2006	Factors affecting the uncertainty of sinks and stocks of carbon in Finnish forest soils and vegetation	Finland, national scale	1989-2004	NFI with statistical biomass models	Uncertainty analysis for the whole calculation scheme
Monni et al. 2007	Effect of the uncertainty of forest carbon stock changes on the total uncertainty of GHG inventory in Finland	Finland, national scale	1990-2003	NFI with statistical biomass models	Uncertainty analysis for the whole calculation scheme
Thürig et al. 2005	Impacts of forest management and wind disturbance on carbon sequestration	Switzerland, 4400 sample plots	1986-2036	Forest scenario model MASSIMO	Comparison with 1) litterbag data, 2) soil organic carbon measurements
Schmid et al. 2007	Carbon balance of Swiss forests with 4 alternative forest management scenarios, model comparison	Switzerland, 1256 sample plots	1995-2095	Forest scenario model MASSIMO and semi-empirical, individual-based forest model SILVA	-
Kaipainen et al. 2004	Effects of changing rotation lengths on carbon stocks of trees, soil and forest products	Finland, Germany, UK and Spain, stand scale	One forest rotation	Biomass module of CO2FIX	-
Peltoniemi et al. 2007	Stratification of regional sampling by model-predicted changes of carbon stocks in forested mineral soils	Finland, national level	Model simulations over forest rotations	Forest simulator MOTTI	-

In Study IV, the YASSO model was applied to simulate the decomposition of harvest residues in forest to assess the average size of the carbon stock in residues over the rotation. To obtain a broader picture of the net effects of residue extraction on greenhouse gas emissions, this soil carbon deficit was converted to a CO_2 emission and compared to emissions from burning the fuel and with the emissions from the fuel production chain as well as to estimates of the emissions from fossil fuels in energy production. The simulations were done for a typical mature *Myrtillus*-type (MT) spruce stand in southern Finland. The amount of harvest residues from different biomass compartments was calculated using Marklund's (Marklund 1988) allometric biomass functions. Fine root biomass was estimated using a constant needle-fine root-ratio (Nikinmaa 1992, Vanninen et al. 1996).

Carbon balance of Finland's forests

In Study V, YASSO served as part of a method developed for estimating the total carbon balance of forests based on national forest inventory (NFI) data. The approach of this study is similar to those of earlier studies by Kurz and Apps (1999) and Liski et al. (2002), which integrated biomass estimates, litter production, disturbances and the soil decomposition model. The method served to assess the carbon balance of the forests of Finland from 1922 to 2004 within the current national borders. We studied the variability of the carbon balance and the role of natural and human-induced factors affecting it.

The YASSO model served to determine the carbon stocks of litter and soil organic matter, the annual changes in these stocks, and heterotrophic respiration (Rh) resulting from decomposition. The results of the biomass covered both uplands and peatlands, but due to the limitations in the applicability of YASSO, the results for soil carbon covered only upland mineral soils, which comprised 74-79% of the total forested area during the study period.

Estimating the amounts of carbon transferred between forests and other land use types covered changes in soil carbon brought by the land-use changes. These estimations were calculated by assuming a constant carbon content (6.1 kg m^{-2}, the mean carbon content of soil and litter at the beginning of the calculations in 1922) for afforested and deforested land. This effect was allocated to YASSO's compartments according to the division of carbon of the steady-state stock in 1922.

To compare the results of the study to those of other studies with ecological concepts, the values of these concepts were derived from the inventory-based estimates of the study. Net primary production (NPP) was calculated as the sum of carbon stock changes of trees (ΔC_{trees}) and ground vegetation (ΔC_{gv}), the litter production of trees (L_{trees}) and understorey (L_{gv}), natural losses (M), and fellings (F).

$$NPP = \Delta C_{trees} + \Delta C_{gv} + L_{trees} + L_{gv} + M + F \qquad (5)$$

Estimates of the heterotrophic respiration (Rh) of YASSO served to calculate net ecosystem production (NEP) from net primary production (NPP).

$$NEP = NPP - Rh \qquad (6)$$

The net biome production (NBP) was then calculated from NEP by deducting removals (RE) from NEP (Eq 6). These removals contain roundwood removed from the forests.

$$NBP = NEP - RE \qquad (7)$$

3 RESULTS

3.1 Model evaluation

Sensitivity of the steady-state carbon stock

The model-calculated soil carbon stock estimate was most sensitive to the humification fractions (p_{lig}, p_{hum1}) and decomposition rates of humus (k_{hum1}, k_{hum2}) (Table 3 in Study I). These parameters determine the amount of humus in the model, and as the majority of the carbon of the model in the steady state is in the humus compartments, this result is reasonable. Temperature was also identified as an important factor for the model-calculated steady-state carbon stock. Different litter types (non-woody, fine woody and coarse woody) affected the simulated steady-state soil carbon stock according to their shares of the total input. Generally, steady-state carbon stocks of the model are directly proportional to the litter input.

Uncertainty in annual stock and stock change estimates

Uncertainties in the model parameters were determined as 95% confidence intervals based on data used to determine those parameters and some additional assumptions (Table 1). The uncertainty in the model's results for carbon stocks and stock changes over a forest rotation were then studied with Monte Carlo simulations. The coefficient of variation in the soil carbon stock estimates of the simulated forest stand varied between 12% and 15% depending on the year. Uncertainties in the annual soil carbon stock changes varied more due to changes in the litter input during the rotation. The main source of uncertainty in carbon stock change estimates was the fractionation rate of the fine woody litter compartment for which the estimated uncertainty range was large due to the lack of measurement data. This particularly affected the uncertainty in carbon stock ranges after harvest when the stand contained a lot of decomposing woody material (Figure 5b in Study I).

Effect of climate on decomposition

The climatic dependency of the YASSO model was tested in Study II along the wide climatic gradient in Canada. First, two sites with climatic conditions most similar to the reference conditions in Europe were selected to study the general level of the decomposition estimates predicted with the model. The model predicted a difference between the decomposition of litters in the two study sites, while the measured mass remaining values of these sites were rather similar (Figure 5). Summer drought affected the litter decomposition at these sites less than the model predicted. At the site with no summer drought and with conditions closer to those prevailing in the reference conditions, YASSO overestimated the rate of mass loss. The differences in the level of decomposition can be explained by differences in those conditions that the model did not cover, or differences between the Canadian and European litterbag experiments. According to these results, the current parameters of the model as such are not directly applicable to Canadian conditions, and the recalibration of the model with local data may have improved the accuracy of the model in Canada.
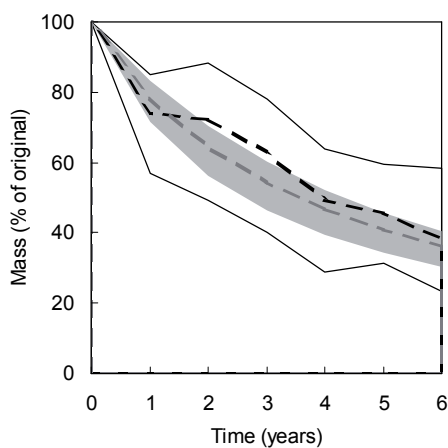
a) Topley   b) Kananaskis
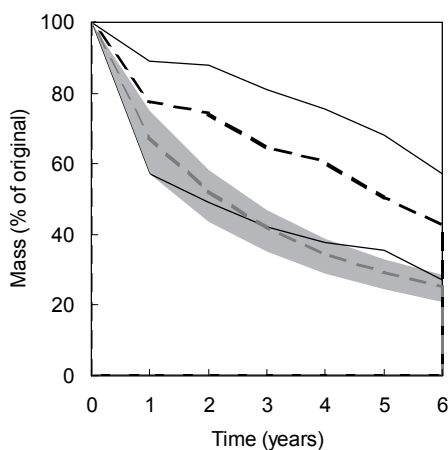
Figure 5. Leaf-litter mass remaining in a) Topley and b) Kananaskis study sites of the CIDET experiment. Means (dashed lines) and ranges (solid lines) of 10 leaf-litter types as predicted by the model (grey lines with grey area) and measured (black lines with white area).

The accuracy of the climate dependency of the YASSO model depended on the temperature variable used in the model. The model predictions with the effective temperature sum (DD0) were less biased, whereas the mean annual temperature (MAT) overestimated the differences between the sites (Figure 6). Decreasing the decomposition rates of the model would have decreased the bias of estimating the effect of climate. The model bias of the climate dependency of all litter types other than fescue litter (*Festuca hallii* (Vasey) Piper) followed the same pattern as that in Figure 6. The climate dependency of fescue decomposition was consistently overestimated. Fescue actually decomposed faster at all CIDET sites than YASSO predicted, and fescue was the only litter type for which the model constantly failed.

Climatic input given to the model for the above test was 30-year average climate data, similar to that used in calibrating the model for European conditions and in creating the climatic dependencies of the model. Inter-annual variations in climatic conditions were excluded from the model runs. Additional test runs made with annual climate data, however, failed to significantly change the results of the tests. In conclusion, the climate dependency covering both geographical and temporal effects of climate on decomposition should be developed further. The effect of selected stand characteristics (stand density, basal area and their combination), assuming they affected the microclimate at the sites, was tested, but they failed to explain the differences between the model-predicted and measured mass remaining values.

Effect of litter quality on decomposition

The Canadian litterbag test showed that the model correctly predicted differences in decomposition rates among litter types in the early years of decomposition, but underestimated them in later years (Table 3 in Study II). This can partly be explained by the different development of variability over time between the litter types in the measured and model-predicted mass remaining values.

The model's performance was particularly incorrect for two litter types. For the fescue, the model underestimated the decomposition, and for the tamarack (*Larix laricina* (Du Roi) K. Kock), the model overestimated it. The underestimation of the tamarack decomposition could mostly be attributed to our decision to use for tamarack the same decomposition rate for extractives as for other coniferous species rather than the rate used for deciduous species. This explained, on average, 70% of the overestimation of the tamarack decomposition. The reason for the underestimation of the fescue decomposition remains unclear.

DD0 and D:
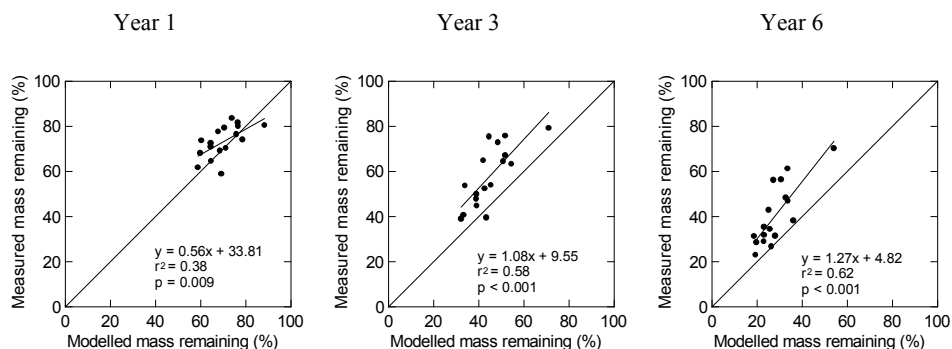
MAT and D:
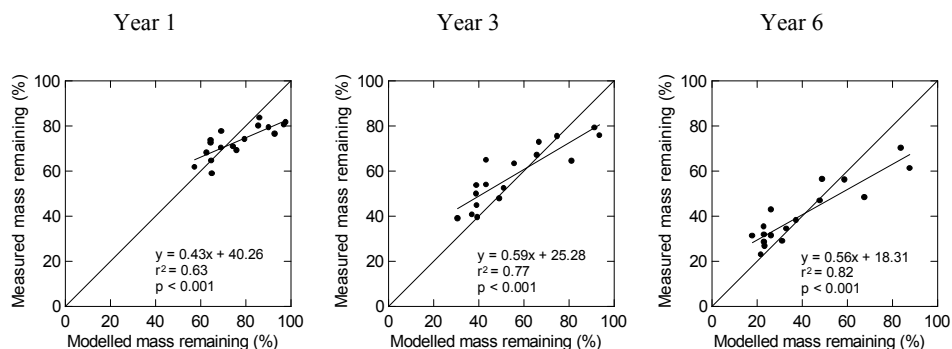
Figure 6. Measured over model-predicted litter mass remaining (mean of 10 litter types) at 17 study sites of the CIDET experiment. Incubation time of figures are 1, 3 and 6 years and effective temperature sum with 0°C threshold (DD0, °C days) and mean annual temperature (MAT, °C) are used as temperature variables in the model.

To test whether the accuracy of the model could be improved by adding litter chemistry variables, model residuals (model-predicted values minus measured mass remaining values) were compared to the chemistry variables not used in YASSO. According to these tests, incorporating the initial nitrogen concentration of litter would be effective only if used together with the initial lignin content (Figure 7a,b). Accounting for *O*-alkyl and phenolic compounds, however, could improve the accuracy of the model (Figure 7c,d).

a)   Nitrogen (N)
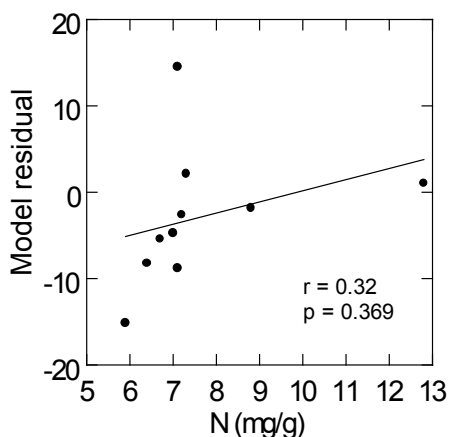
c) Phenolic carbon (PHEN)
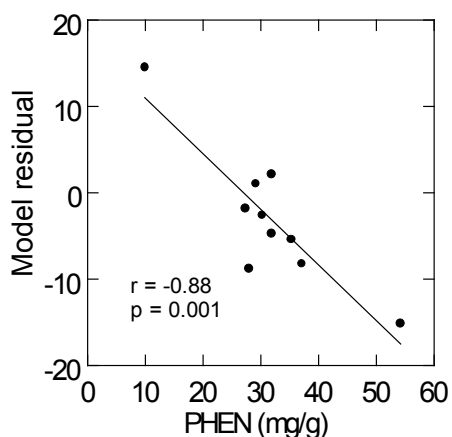
b) Lignin to nitrogen ratio (KLIG/N)
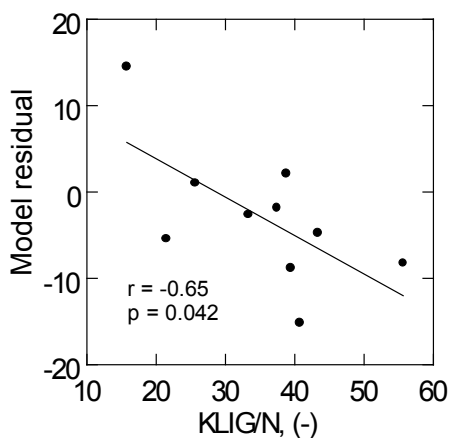
d) O-alkyl carbon (O-ALKYL)
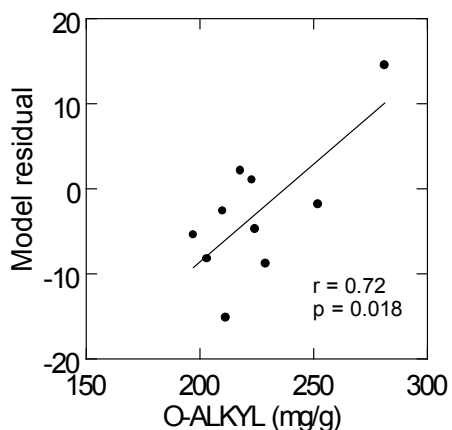
Figure 7. Model residuals (modelled – measured) plotted against initial chemical characteristics of litter; a) nitrogen, b) lignin-to-nitrogen ratio, c) phenolic carbon and d) O-Alkyl carbon. Each dot represents mean of mass remaining values of one of the 10 litter types.

Total soil carbon stock estimates

The results of the test in Study I suggested that model-calculated differences in soil carbon stocks due to the different litter production of the forest are plausible. The model-calculated estimates for the amount of soil carbon were, on average, 15% higher than the means of the measured values of different forest types and tree species, except for the least productive Scots pine stands, for which the model-predicted value was underestimated (Figure 6 in Study I). Excluding the low productivity forest type, the amount of soil carbon increased in a similar fashion with increasing site productivity, according to both the measurements and the model-calculations.

Comparison of decomposition models

The soil model ROMUL projected slower decomposition of harvest residues than did YASSO for all six Finnish forest sites studied (Figure 8). This means that the retention time of carbon in harvest residues as projected by ROMUL was longer than what YASSO projected. The decomposition in ROMUL was also more sensitive to the site conditions (e.g. climate) than was the decomposition YASSO projected (Figure 8).
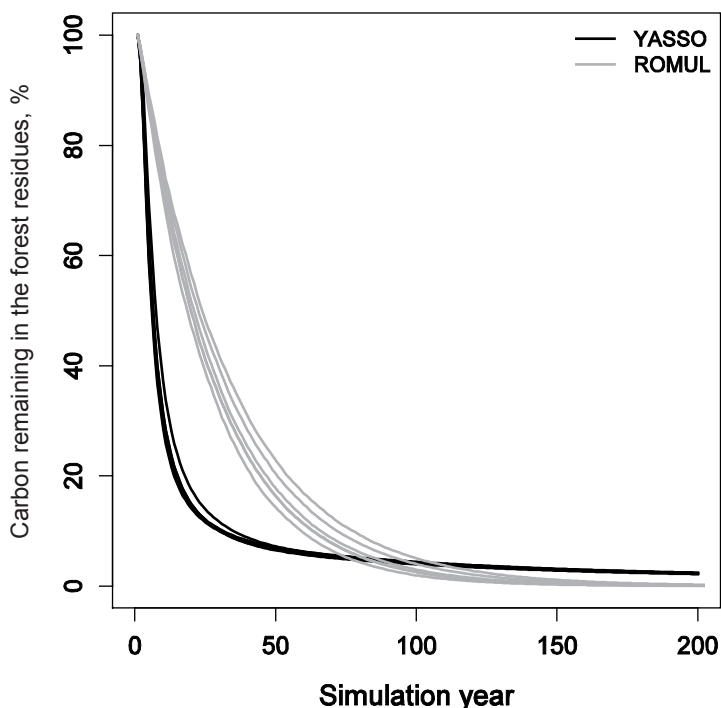
Figure 8. Decomposition dynamics of the same amount of similar harvest residues during 200 years predicted with the soil models YASSO and ROMUL. Each single line describes the development of (dry) mass/carbon remaining percentage (%) simulated in conditions of one study site.

3.2 Model applications

Effects of intensified biomass extraction on forest carbon balance

Study III focused on studying the effect of intensified biomass extraction on subsequent biomass and soil carbon stocks. The same silvicultural recommendations were followed in the implementation of the forest management actions in model simulations with MOTTI-YASSO and EFIMOD-ROMUL. Differences in simulated stand developments between the models, however, created differences in the modelled timing and intensity of the thinnings as well as in the timing of final felling (Figure 2 in Study III). Differences between the simulated rotation lengths, for example, were considerable. As intensified biomass extraction affected the simulated growth of EFIMOD, the rotations of EFIMOD were 0-26 years longer for the IBE scenario than for the STA scenario.

   The differences in soil carbon stocks between the two scenarios studied were rather small in comparison to the total carbon stock of both model approaches. Slower decomposition of harvest residues by ROMUL made the effect of biomass extraction on soil carbon stock larger with EFIMOD-ROMUL. With MOTTI-YASSO, the soil carbon stock of the IBE scenario nearly reached the level of the STA scenario at the end of the rotation. In EFIMOD-ROMUL, the differences in simulated soil carbon between the scenarios were more pronounced (Figure 3 in Study III).
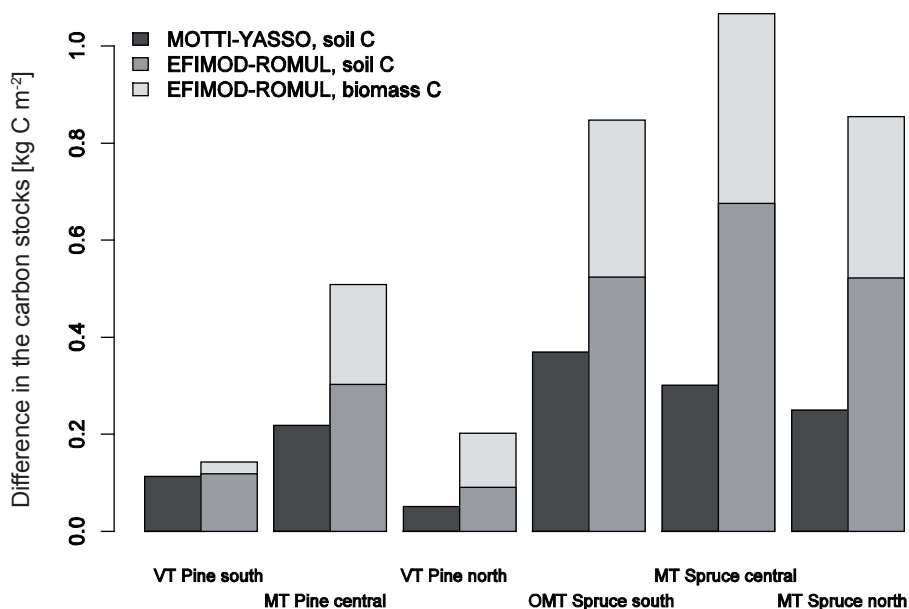
Figure 9. Differences between the carbon stocks of standard and intensive biomass extraction scenarios simulated with MOTTI-YASSO and EFIMOD-ROMUL. Differences are given as averages over rotation.

Depending on the study site and intensity of the extraction, collected harvest residues covered from 3% to 12% (range of EFIMOD and MOTTI estimates) of the total litter and harvest residues entering the soil during the rotations in the STA scenario. This change in the litter input would reduce the steady state soil carbon stocks, assuming the intensified biomass extraction would become a permanent regime for hundreds of years, from 2% (the smallest estimate of MOTTI-YASSO) to 14% (the largest estimate of EFIMOD-ROMUL).

The process-based model EFIMOD-ROMUL includes feedback from soil nutrient status to productivity. With EFIMOD-ROMUL, the intensified biomass extraction slightly reduced the growth of the forests, and thus the biomass carbon stock and litter input to the soil. Changes in stand development in EFIMOD due to the estimated decrease in growth were far smaller than the differences between the EFIMOD and MOTTI simulations (Figure 2 in Study III). Still, the decrease in growth affected the timing of the thinning interventions and final felling in simulations and contributed remarkably to the total differences between the scenarios (Figure 9). With the empirical MOTTI model, the intensity of the biomass extraction did not affect forest growth.

Net greenhouse gas emissions due to energy use of forest residues

In Study IV, the soil carbon deficit resulting from the harvest residue extraction was estimated by simulating the residue decomposition in forest with the YASSO model. Branches and needles were simulated to lose more than 90% of their initial carbon during the first 20 years, whereas stumps and roots were simulated to decompose more slowly (Figure 3 of Study IV). Within the 100-year rotation, the average carbon stock of branches and needles left in the forest as harvest residues was simulated to be 11% of the original amount of carbon they contained.

This remaining 11% of the carbon in forest residues during the following 100-year rotation was converted to an indirect CO_2 emission of the forest residues extraction, since the average stock describes the soil carbon deficit resulting from the biomass extraction. For a spruce stand that holds 15 Mg C ha^{-1} in harvest residues, 11% translates to a carbon emission of 1.7 Mg C ha^{-1}, or about 6.1 Mg CO_2 ha^{-1}. Assuming that the energy achieved is 135-150 MWH ha^{-1}, and a 100-year rotation length is applied, the indirect CO_2 emission from the decrease in soil carbon is 40-45 kg CO_2 MWh^{-1}.

For comparison, Finnish estimates (Wihersaari and Palosuo 2000, Wihersaari 2005) indicate that the CH_4 and N_2O emissions measured from the burning of forest residues are as small as 2 kg CO_2-eq MWH^{-1}. Emissions from collecting, chipping and transporting typically vary between 4.3 and 7.5 kg CO_2-eq MWH^{-1}. Granulation and recirculation of ash increase emissions only slightly, by about 0.2 kg CO_2-eq MWH^{-1}, and if fertilisation is used to compensate for nitrogen losses, the direct emissions from fertiliser production and the indirect emissions from forests would be about 7 kg CO_2-eq MWH^{-1}. These figures appear in Figure 10a.

The total greenhouse gas emissions from wood extraction would thus range from 45 to 63 kg CO_2-eq MWH^{-1}. For comparison, CO_2 emissions in Finland from burning coal are about 334 kg CO_2 MWH^{-1}, and from burning peat about 378 kg CO_2 MWH^{-1} (Wihersaari 2005) (Figure 10b). Taking into account the emissions from production, transportation and storage of these fuels, the emissions could be 4-11% higher (Wihersaari 2005). According to these figures, significant emission reductions could be achieved by replacing fossil fuels with energy from forest residues. Decreasing soil carbon storage substantially increased estimated emissions from forest residue production, but the amount of avoided emissions was nevertheless considerable.

Because Study IV was the very first application of the YASSO model, and since the model structure have been modified and more exact model parameterisation have been done after that, numerical results, if obtained now would differ slightly. With the parameterisation given in Study I, the decomposition was simulated to be slightly faster than in the version used in Study IV; using otherwise the same input information as in Study IV, the average carbon stock from residues in soils was simulated to be 9% of the original amount of carbon in harvest residues. This difference is, however, much smaller than the effect of the decomposing material for this subject. In Study III, the decomposed material also included coarse woody litter, stumps, which increased the average stock of remaining residues. With slightly varying shares of different litter compartments, different site conditions and different rotation lengths, the average stock remaining in the residues in the study sites of Study III varied from 12% to 19%. Because these estimates are calculated based on information from existing study sites, and by adhering to the current silvicultural recommendations for biomass extraction, the rough estimate of about 10% of carbon in residues to stay at the forest site after felling used in Study IV will likely lead to underestimated figures for indirect CO_2 emissions.

a) Net greenhouse gas emission sources of forest residues
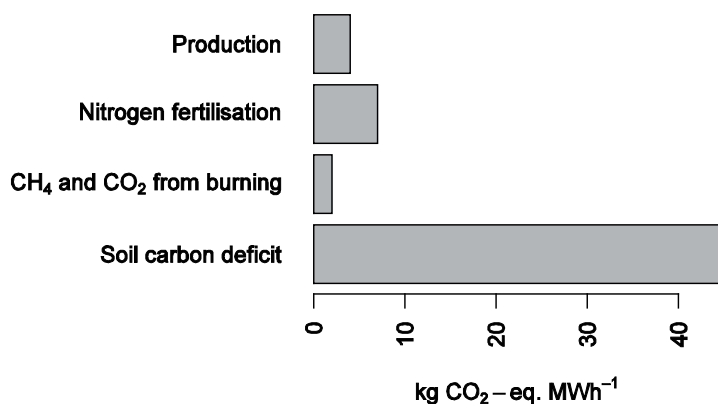
b) Net greenhouse gas emissions of forest residues compared with CO_2 emissions of coal and peat.
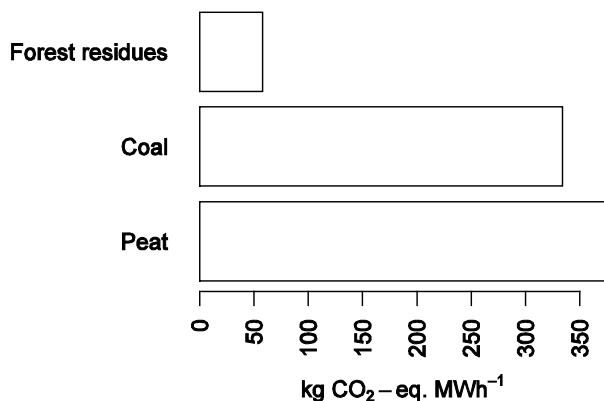
Figure 10. Greenhouse gas emissions from the energy utilisation of forest residues (a) compared with estimated CO_2 emissions of combustion of average coal fuel and peat (b).

Carbon balance of Finland's forests

The carbon stock of biomass in Finland's forests increased by 50%, from 550 to 823 Tg, between 1922 and 2004 due to both the higher mean amount of carbon per forested area and expanded forest area (Figure 11a). At the same time, litter and soil carbon stock (Figure 11b) increased by 13%, from 848 Tg to 959 Tg, when transfers of carbon between the forests and other land-use types were accounted for. Excluding the transfers between land-use types increased the litter and soil carbon stock by 7%. The biomass of ground vegetation remained relatively stable during the 82-year study period, and any changes largely followed those of the net area of forests.
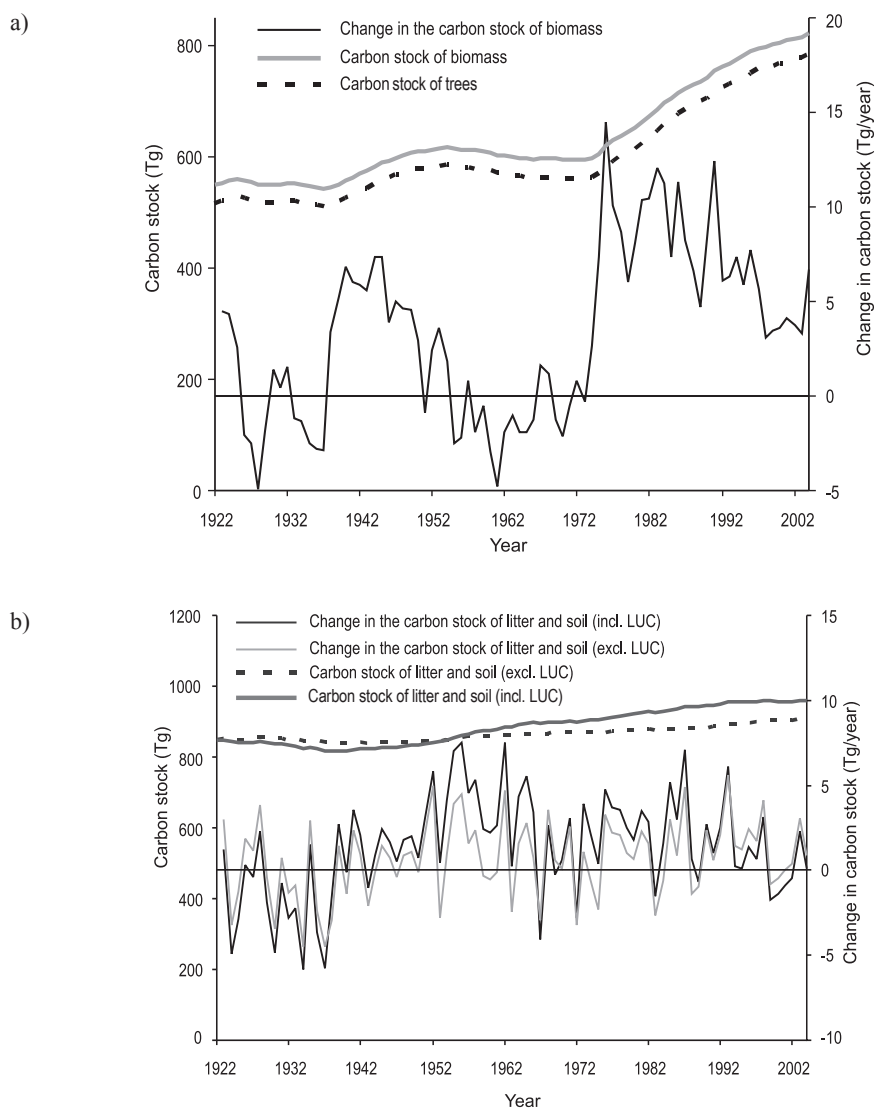
Figure 11. Carbon stocks of biomass and trees (a) and soil (b) in addition to annual carbon stock changes in Finland's forests between 1922 and 2004.

Annual changes in both the biomass (from -5.0 Tg to +14.5 Tg) and soil carbon stocks (from -5.8 to +7.5 Tg with the transfer of litter and soil between forests and other land uses, and from -2.9 to +5.3 without them) varied considerably (Figure 11a,b). Annual changes in the biomass carbon stock were driven mainly by the changes in tree growth and harvesting, whereas variation in soil carbon stocks resulted from the transfers of litter and soil carbon between the forests and other land uses, variable litter input and variable temperatures that affected the model-calculated decomposition. Varying amount of harvest residues affected most the annual changes in soil carbon stocks (Figure 12 and Figure 6 in Study V), whereas the effect of temperature on soil stock added about one fourth to the standard deviation and one third to the amplitude of variation. Harvest residues covered on average 22% of the carbon flow to soil in the 1990s, which was of about the same magnitude as that of litter production of ground vegetation (20%). The litter production of living trees covered the bulk (56%) of the carbon flow to soil, whereas natural mortality produced only a minor (2%) share (Figure 12).

Heterotrophic respiration covered about 70% (0.28 kg C m^{-2}) of the mean estimated NPP (0.38 kg C m^{-2}) of Finland's forests during the 1990s. The difference, 0.099 kg C m^{-2}, is the estimate for the NEP of these forests during this decade. More than half of the NEP was removed from the forests as harvested timber, while the rest that accumulated in the forests represented the estimated NBP. Nearly 72% of this NBP accumulated in the biomass of the forests, while the rest was accumulated in litter and soil.
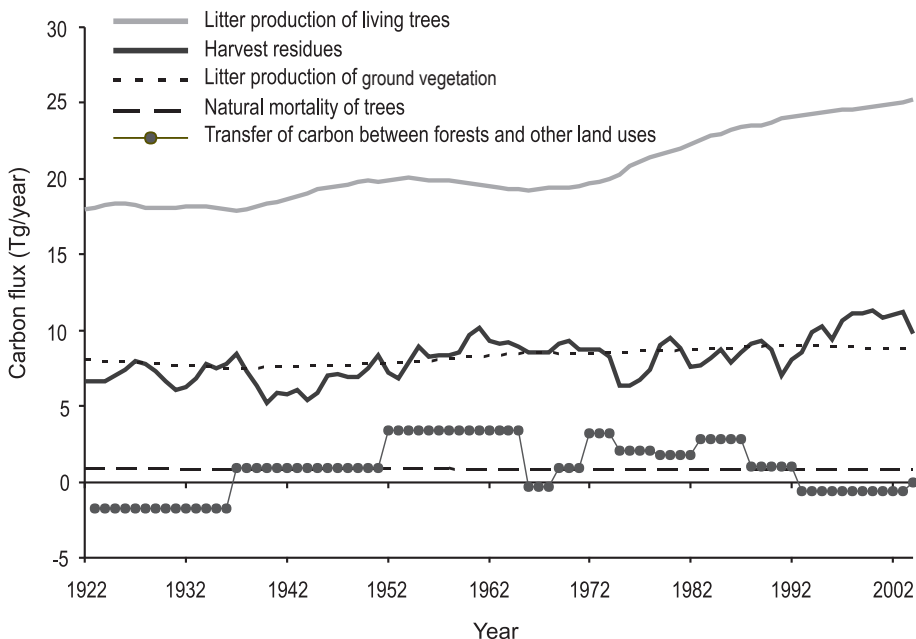
Figure 12. Sources of carbon input to the carbon stock of litter and soil by origin, and the transfers of carbon in litter and soil between forests and other land uses in Finland's forests between 1922 and 2004.

4 DISCUSSION

4.1 Soil carbon model YASSO as a tool for carbon assessment

A simple and functional tool for carbon assessment

Because YASSO was developed for practical applications, it had to be simple. The purpose was to develop an easy-to-use model with limited requirements for input data and provides transparency throughout the modelling process. All this was necessary to ensure the practical applicability, or usability, of the model. Only models that are easy to calibrate, test and apply can also be of use outside the group of model developers. In the case of YASSO, the practical applicability of the model was clearly attained, which have different groups of people confirmed with their applications of the model. For example, the model has served as a part of Finnish greenhouse gas inventories (Statistics Finland 2005) and has been included as a soil module in some wider modelling systems (Karjalainen et al. 2002, Masera et al. 2003, Hynynen et al. 2005). When comparing soil models available for estimating short-term changes in the soil carbon of forests over large areas, Peltoniemi et al. (2007a) noticed that YASSO presented the one with the fewest input requirements as well as the fewest factors affecting decomposition. Among the models compared, Peltoniemi et al. assumed that the more detailed models (CENTURY, ROMUL, Forest-DNDC, SOILN) would be more accurate due to the greater level of detail present in their structure. In practise, however, those models with fewer requirements with respect to input data (YASSO, RothC) may be the only option for many countries struggling with reporting requirements.

YASSO describes the decomposition of organic matter taking into account litter quality and climatic conditions, both of which are important determinants of decomposition (Meentemeyer 1978, Edmonds 1987, Gholz et al. 2000, Preston et al. 2000, Trofymow et al. 2002). Litter quality is of particularly importance in forests, where several litter types exist. According to one test, YASSO managed sufficiently to describe the effects of both the variable litter and climatic conditions on decomposition (Study II). When combined with stand models or other systems providing litter information, the dynamic approach of the model has proved powerful for estimating changes in soil carbon stocks at the regional or national level (Study V, Peltoniemi et al. 2004, Thürig et al. 2005, de Wit et al. 2006, Peltoniemi et al. 2006, Schmid et al. 2006). The model has been tested widely, which has provided us with knowledge of the properties and limitations of the model.

Model applicability

Because YASSO was developed for forestry purposes, its applicability to other land-use remains untested. For example, the effect of management and differences in vegetation make agricultural soils very different from forest soils. When other soil models have been used for both forest and agricultural soils, their structure (Li et al. 2000, Chertov et al. 2001) or parameterisation (Peng et al. 1998, Falloon and Smith 2002) has been modified for both land-use types.

With regard to soil type, the applicability of the model is clearly limited to upland mineral soils only, because YASSO has no limitation mechanisms for decomposition or peat formation in wet conditions.

In Study II, the model was tested with ten different leaf-litter types, of which YASSO plausibly estimated the decomposition of most. The model, however, consistently underestimated the decomposition of fescue litter (the grass). Because this type of litter is more typical in other land-use types than in forests, it is important to develop the model further in order to describe the decomposition of grasses more accurately, thus rendering the model more widely applicable.

Due to the nature of the data used for the parameterisation of the model, YASSO is most suitable for large scale applications. The geographical boundaries for the applicability of the model are due mainly to the coverage of the data used for determining the climatic dependencies and model tests. Studies have shown the model to work rather well in both boreal and temperate forests, whereas its applicability in tropical forests is limited due to the annual time step, which is too long for rapid decomposition in those conditions.

Aspects in model structure affecting the reliability of the model results

The intentional simplicity of the model structure brings some inevitable limitations to the accuracy of YASSO's results as well as to its meaningful application. The following section discusses some properties of the model, omitted processes, assumptions and their implementations.

Inflexibility of the decomposition estimates

The selected model structure was noted to provide inflexible estimates of decomposition in comparison to measured data (Figure 5, Table 3 in Study II) or to the other decomposition model (Figure 8). This means that the current model structure may allow insufficient variation driven by different litter properties or climatic conditions. Inflexibility may result from the model structure that inevitably cascades the material from the faster to slower decomposing compartments and includes only a few factors affecting the decomposition process. In Study II, we tested additional litter chemistry variables available for the initial litter material against the model residuals of the first year of decomposition. Statistically significant correlations were identified between the residuals and phenolic and O-alkyl carbon (Figure 7c,d). These types of signals with different carbon compounds raise the question of whether the division of the model compartments is sufficient and whether additional litter quality factors would improve the accuracy of the model results. Adding model compartments or factors affecting the decomposition would, however, increase the amount of input information needed and would reduce the practical usability of the model.

Climatic dependency

The applicability of the model to different geographical areas has been an important aim throughout the model development process. The basic parameter set was determined based on Scandinavian data (Study I), but the data used to generate the climatic dependencies of the model already covered conditions from the Arctic tundra to tropical rainforests (Liski et al. 2003). According to the model test with Canadian litterbag data (Study II) and two tests for the decomposition rates of YASSO with litterbag data in different parts of Europe, southeast Norway (de Wit et al. 2006) and two regions of Switzerland (Thürig et al. 2005), the model provided plausible projections of decomposition in these areas, which were characterised by climate conditions different from those of the model calibration in Sweden and Finland. These types of tests build confidence in the approach of the climatic dependency in the model.

The data behind the regression models describing the climatic dependency of YASSO are long-term averages for different geographical locations. The regressions therefore describe differences in decomposition due to the varying average climatic conditions along the geographical gradient. Applying the same regressions to describe differences in decomposition within the same locations due to annual climatic variability (like in Study V) is based on the implicit assumption that the short-term acclimation of the decomposer communities to changing environmental conditions is similar to differences measured among the different communities that are genetically adapted to the range of conditions typical of the site where they are located. Annual climate variables applied in the model also omit the intra-annual variation in climatic conditions that is important for decomposer communities.

Research has shown the summer drought variable used in the model to be problematic. Even though it together with temperature was identified as an effective variable when creating the regression models for the climatic dependency applied in YASSO (Liski et al. 2003), for example in Canada the effect of drought on decomposition was not as strong (Liski et al. 2003, Study II). On a practical level, the implementation of the drought effect on decomposition in YASSO has been considered problematic in many applications, due to the fixed season determined for summer. Drought also requires the calculation of potential evapotranspiration, which is not an explicit variable (i.e. different calculation methods of PET yield different values (Xu and Singh 2002)). Also, the threshold set (i.e. only negative values of the drought variable are applied) creates a turning point to a linear climate dependence. The preferable option for models such as YASSO would be to utilise climatic dependencies based on the most generally available climatic variables, such as mean annual temperature and precipitation only. This modification has recently been implemented in the next version (Tuomi, M. et al. manuscript in preparation, www.environment.fi/syke/yasso) of YASSO.

The accuracy of the description of climatic dependency is important for many soil carbon model applications. The sensitivity of the decomposition of organic matter to temperature, however, remains an open question with different hypotheses (Davidson and Janssens 2006). The description of the climatic dependency of the model has therefore received a central role in the further development of the YASSO model.

Effects of nitrogen on decomposition and soil carbon

Nitrogen was omitted from the model in order to limit the input data requirements of the YASSO model. In many other decomposition models, such as CENTURY, ROMUL and Forest-DNDC, carbon dynamics are coupled with nitrogen dynamics. This means that they require quite detailed nitrogen input data, such as atmospheric nitrogen deposition and nitrogen additions in fertilisers (Peltoniemi et al. 2007a). The production of temperate and boreal forests is generally limited by the shortage of nitrogen. In addition, low nitrogen concentrations can regulate decomposition in early phases (Berg 2000). With higher nitrogen levels, however, forest growth benefits more than does decomposition from the increasing nitrogen amounts, and nitrogen deposition has been shown to enhance the NEP (Magnani et al. 2007). This is because within the decomposition process, nitrogen also yields opposing, retarding effects, particularly in the later phases of decomposition. According to Berg (2000), low-molecular nitrogen compounds repress the formation of lignolytic enzymes in white-rot fungi, and products of lignin degradation may react with ammonia or amino acids to form recalcitrant complexes. In Study II, residuals between YASSO's estimates and the measured values of the first year of decomposition were not correlated with nitrogen (Figure 7a). This result is reasonable since more significant retarding effects of nitrogen on decomposition may appear only in later phases of decomposition. Study III showed that YASSO omits one possibly important aspect, as it provides no information on changes in the soil nutrient status. When studying the effects of different forest management actions, and especially different biomass extraction intensities, the feedback from soil to productivity of the stand is important.

Soil texture as a determinant of the soil carbon

Research has shown that associations formed between soil minerals and organic materials or by aggregate formation that encapsulates or shields organic matter from microbial and enzymatic attack (Krull et al. 2003) affect the biological stability of soil organic matter. The YASSO model omits the relationship between soil structure and decomposition. This omission was based on the fact that the texture data for forest soils is seldom easily available. The soil texture is also less relevant in forest soils where the formation of the separate organic layer above the mineral soil is typical and where that layer holds a remarkable share of the dynamic carbon in soils. The validation test for soil carbon in Study I supported the view that the model can predict differences in soil carbon stocks in Finnish forests driven by differences in the productivity of the forest. Moreover, the simulated stocks and stock changes along the forest chronosequence (Peltoniemi et al. 2004) were similar to the measured values. However, the model-estimated total soil carbon in Norway was clearly underestimated (de Wit et al. 2006). Interestingly, the same underestimation occurred in Southern Alps, whereas in other regions of Switzerland the model-predicted soil carbon stocks were similar to the measured values (Thürig et al. 2005). Possible explanations for these findings are high precipitation in Norway and strong rain events in the Southern Alps, which increase the downward transport of dissolved organic matter to the subsoil, where it is stabilised in organo-mineral complexes (Eusterhues et al. 2003). The calibration conditions of YASSO in Finland did not cover a high range of precipitation, and the model structure itself incorporates no differential decomposition rates in soil horizons. In some other soil models, such as ROMUL, RothC and CENTURY, the texture affects decomposition both by affecting soil moisture through the soil's water-holding capacity and by affecting the stabilisation of soil organic matter at higher clay contents. In the further development of the model, connecting the stabilised organo-mineral complexes to the interpretation of the slowly decomposing compartments may prove fruitful.

Model input and parameterisation affecting the reliability of the model results

The uncertainty analysis conducted for YASSO provides information on the model's precision, which is affected by the uncertainty in model inputs and parameters. Uncertainty analysis thus does not cover possible inaccuracies inherent in the insufficient model description. According to the results of the uncertainty and sensitivity analyses in Study I, YASSO's estimates for the soil carbon stocks are uncertain, because those parameters that most strongly affect these estimates (rates of formation and decomposition of humus) are poorly known. Carbon stock change estimates, on the contrary, are rather reliable, because the parameters determining these estimates are more thoroughly known. The uncertainty analysis that Peltoniemi et al. (2006) performed for the national scale forest carbon assessment presented in Study V also showed that the stock change estimates were more precise than the estimates of the stocks themselves. Key variables for the uncertainty in soil stock estimates were the parameters of YASSO, whereas the key factors for the uncertainty in soil stock change estimates were the initialisation of the soil model and temperature. Peltoniemi et al. (2006) also noted that on a national scale, annual drain determining the amount of harvest residues ending up in the soil significantly affects the uncertainty of the annual soil carbon stock change estimates.

Litter input

To provide reliable estimates of soil carbon stocks and their changes, YASSO requires reliable and complete estimates of the litter input. The capacity of the system providing the litter input affect the reliability of the model results as well as the questions that can be meaningfully studied with the model. The reliability of the estimates of the amount of litter input in forestry applications varies between the litter cohorts. Particularly challenging is to estimate the litter from underground biomass and ground vegetation. The biomass of fine roots is difficult to assess, and fine roots have also been estimated to have a wide range of turnover rates (Matamala et al. 2003), which makes them a considerable source of uncertainty in the litter production estimation approach used in this dissertation. The share of ground vegetation in the total litter production of forests is also a subject that has seen little study. Even though the share of ground vegetation biomass in the total biomass of forests is negligible, due to its high turnover in comparison to that of tree biomass, the effect of ground vegetation on soil carbon at the national level is important (Study V). Ground vegetation represented 16% of NPP and 28% of the litter production of living vegetation in Finland's forests during the 1990s.

Another type of data regarding the litter YASSO requires is information on litter quality, which is typically taken from the chemical analysis of different biomass compartments (e.g. Berg et al. 1982, Ryan et al. 1990, Preston et al. 1997). Variations among the analysis methods bring variation to the results of the analysis. The chemical composition of the litters also varies greatly. Both these aspects affect the precision of the litter information, and thus the modelled soil carbon estimates as well.

Model initialisation

In many applications the YASSO model has been initialised by assuming that the model compartments are in steady-state with a litter input estimate. The accuracy of the equilibrium assumption depends on the application, and easily leads to underestimated soil carbon stock change estimates in such applications where the true soil carbon stock is far from equilibrium.

Assuming an equilibrium state in model calibrations with soils that are not in equilibrium may also lead to the overestimation of the decomposition rates of the slowest pools and to the overestimation of the stocks of recently disturbed sites (Wutzler and Reichstein 2006).

Studies have shown that model estimates of soil carbon changes during the first simulation years are quite sensitive to this initialisation (de Wit et al. 2006, Peltoniemi et al. 2006). However, this uncertainty can be avoided rather effectively by running the model for some years. These pre-run periods require information about the history of the studied area. Creating models with measurable soil carbon pools would also help with this question, since then the measured values could serve as initialisation values for the model. For example, Zimmermann et al. (2007) found promising results when they tested fractions received with a fractionation procedure against model compartments used in the RothC model.

Parameterisation

Parameterisation of the models plays a central role in influencing the reliability of the model results. Although YASSO is considered a simple model, it incorporates quite a wide range of parameters: five decomposition rates, two fractionation rates, four parameters describing the proportion of decomposed mass transferred to a subsequent compartment, nine litter quality parameters, and four parameters related to climatic dependencies. Even though the litter quality parameters would be taken as litter input information and the climatic parameters taken as given, the model has eleven parameters that describe the decomposition process. Because most of these parameters cannot be measured directly, which is a feature very typical of soil carbon models, the model must be calibrated with measurements of the modelled system variables. With the large number of parameters incommensurate with measured data available, the parameter estimation is difficult, however, and necessarily leads to subjective decisions within the parameterisation process. These decisions render the uncertainty of the model results undeterminable. With YASSO, for example, anchoring the p-parameters that determine the share of material flowing within the model into the subsequent decomposition compartments is more or less a subjective decision, and the uncertainty behind these values is considerable.

Model identifiability is a concept used to describe whether the parameters of the model can be determined based on the measurement data. A priori global identifiability is studied theoretically, assuming noise-free observations and an error-free model structure (Bellman and Åström 1970, Walter 1982, Godfrey and DiStefano 1987). Practical identifiability, on the other hand, applies the actual data to determine whether the measured information is sufficient to determine the parameter values. It thus takes into account the noise and sparseness of data (Holmberg 1982). The a priori global identifiability of the YASSO model has been studied with a method based on concepts of differential algebra (Saccomani et al. 2003, Palosuo et al. 2006). According to the first results of this analysis, the YASSO model is unidentifiable as such with the currently available measurement data. However, after further development of the analysis tool to take into account the initial states of the model variable in the measurements, the model has proved to be identifiable. Although the practical identifiability of YASSO has not yet been studied, it will remain a topic of interest for a follow-up study to obtain further information on the requirements that are necessary for the data to successfully determine the model parameters.

Over-parameterised models are very typical in soil modelling where, the weak measurability of the selected model compartments (Elliot et al. 1996) easily leads to an unidentifiable model structure with respect to the measurements. These models are not fully resolvable from the measurement data, and their successful parameter estimation with classical system identification methodology requires additional constraints. Bayesian inference provides a useful, alternative approach for parameter estimation (Bernando and Smith 1994, Reichert and Omlin 1997, Van Oijen et al. 2005). This approach requires statistical characterisation of the prior probability distributions of the model parameter values and updates these distributions with the information from the measurements. This method does not require global identifiability of the parameters, and can be used to study the uncertainties of the parameters and model predictions as well as the correlations between the parameter values. On the other hand, it requires prior information on the parameters and is computationally more demanding than classical estimation techniques.

Data used for model calibration naturally affect the reliability of the model parameters and thus the model results. YASSO was calibrated with litterbag and soil carbon measurement data. Bradford et al. (2002) have claimed that artefacts brought by the mesh that inhibits the normal change of microbes, temperature and moisture with the surrounding environment affect litterbag studies. Still, litterbag experiments are a commonly applied method in the study of decomposition. Litterbag experiments mainly describe the decomposition in the top most soil layer, whereas the majority of soil carbon is located in the deeper layers under different conditions. In forests, however, the majority of the decomposition occurs in the humus layer above the mineral soil, which is why information from the decomposition in that layer is so relevant. The decomposition dynamics of woody logs is a very slow process that can last for several decades. For the decomposition estimate, one would need information on the current and the original mass of the logs as well as on the time period since the death of the tree, all of which are difficult to determine when studying the logs decomposing in forests (Laiho and Prescott 2004). These methodological difficulties partly explain why woody litter decomposition rates in all data gathered on the subject vary so widely. Also soil carbon stock measurements are affected by several sources of uncertainty brought by field sampling and laboratory measurements (Sollins et al. 1999, Tamminen 2003).

When using several data for model parameter estimation, the choice of weightings between the data sets directly influences parameter estimates (Klepper 1997). In the parameterisation procedure of YASSO, no such weighting of the data occurred. However, as parameters determined from the litterbag data were anchored when using other data for further parameterisation, and the amount of litterbag data exceeded that of the soil carbon data, they assumed a primary position. This however, is, reasonable, as the litter decomposition data were more precise than the data available for soil carbon stocks. Intentional or unintentional weighting of the data sets is, however, one source of uncertainty for parameter estimation.

4.2 Model applications

Effects of intensified biomass extraction on forest carbon balance

In general, all forest management actions affect soil carbon either by changing the litter flow into the soil or by altering the conditions of decomposition in soils. The YASSO model has been successfully applied in different studies where the litter input to the soil has varied according to different management practises. For example, the model was applied to assess the effects of forest management and storm activity on soil carbon in Switzerland (Thürig et

al. 2005), as well as in another Swiss study to project the effects of alternative management regimes on future carbon stocks and fluxes (Schmid et al. 2006). Kaipainen et al. (2004) used YASSO within the CO2FIX model (Masera et al. 2003) to study the effect of changing rotation length on carbon sinks in European forests.

In Study III, YASSO was combined with the stand simulator MOTTI and both were used to study the effect of intensified biomass extraction on forest carbon stocks. These estimates were compared to estimates simulated with the process model EFIMOD and its soil module ROMUL. According to the model simulations with both model combinations, intensified biomass extraction affects carbon stocks of soil. Changes in the soil stocks compared to their total size during the first rotation were relatively small (Figure 4 in Study III), which means that detecting them by soil measurements would be difficult. However, the amount of dead biomass entering the soil decreased markedly, and long-term changes were simulated to be commensurate with the decrease in litter input to the soil (2%-14% depending on the study site and the intensity of the extraction).

YASSO or ROMUL did not cover changes in decomposition due to the management actions affecting the conditions of decomposition. In Study III, the relevant question is: What are the effects of stump extraction on the decomposition of soil carbon around the lifted stump? Because the stump removal typically exposes the mineral soil, it very likely also changes the soil properties and conditions for decomposition of the soil organic matter, as does soil preparation (Mallik and Hu 1997). If this is the case, then the effects on total soil carbon stock could be much greater than YASSO and ROMUL projected. Accounting for such effects on decomposition is a challenge for the future, and to model them would require more knowledge and measured information on the processes within the soil.

According to the EFIMOD simulations intensified biomass extraction affects forest productivity. Earlier results, both from modelling (Rolff and Ågren 1999, Peng et al. 2002) and empirical studies (Egnell and Valinger 2003) supports this conclusion. This feedback mechanism from soil nutrient status to forest growth, even though widely studied, still requires further analysis to provide a common understanding of the effects of biomass extraction on it.

All in all, Study III showed that when assessing the effects of the forest management on the forest carbon balance, special emphasis should be placed on model selection. The YASSO model can be applied for such purposes, but the reliability of its results depends also on the model or system used to provide the litter input for it. On the other hand, YASSO provides no information on the soil nutrient status to be applied by the stand model.

Net greenhouse gas emissions due to energy use of forest residues

The results of Study IV showed that taking into account the indirect CO_2 emission due to the decreased soil carbon markedly increases the emissions of forest residues (Figure 10). According to a simple example calculation, the net emissions of forest residues doubled or even increased tenfold depending on the emissions taken into account and the uncertainties in other emission sources. Still, when compared to the emissions of fossil fuels, the net effect of replacing fossil fuels with energy from forest residues is clearly positive. Emissions from the production chain of forest residues and indirect CO_2 emissions from decreased soil carbon together cover less than 20% of the CO_2 emissions from using coal or peat.

Decomposition models such as YASSO can be applied to such studies to estimate the alternative decomposition of residues in the forest. Such applications represent the strongest area of YASSO, since they omit problems with questions involving the total soil carbon and model initialisation, which are remarkable sources of uncertainty in, for example, regional

carbon assessment (Peltoniemi et al. 2006). The accuracy of the estimates of indirect CO_2 emissions with this approach depends on the model used to assess the retention of carbon in residues and the estimates of the composition of the residues. For example, the results of Study III show that using the ROMUL model instead of YASSO would have doubled the estimate of the indirect emissions. The similar average stocks with identical material at different study sites (Figure 8) varied between 13% and 15% for YASSO and between 25% and 31% for ROMUL. Because neither of these models have thus far been calibrated or tested particularly with forest residue material, it is difficult to say which is more reliable in this case. On the other hand, the assumed quality of the harvest residues may affect emission estimates even more than models. More slowly decomposing stumps have much higher calculatory emissions due to decreased soil carbon than do quickly decomposing needles.

In Study IV, the effects of nutrient losses on forest growth were omitted. On the other hand, emissions from compensatory nitrogen fertilisation were calculated and noted to be of a similar magnitude to that of emissions from the collecting, chipping and transportation of residues. If the decreased forest growth could be assessed similarly to Study III with EFIMOD-ROMUL, then this decreased biomass carbon stock could be counted as an indirect CO_2 emission similarly as was done in Study IV with decreased soil carbon stock. Figure 9 shows that including the emissions from decreased biomass stock would significantly increase emissions, and that the magnitude of this effect is almost the same as with the soil carbon deficit.

This dissertation concentrates only on the effects of forest residue extraction on carbon balance and greenhouse gas emissions. However, residue extraction may affect forest ecosystems in other ways. For example, intensified biomass extraction can severely affect the biodiversity and base cation balances of forests unless they are taken into account in the extraction planning (EEA 2007).

Carbon balance of Finland's forests

The carbon stocks of Finnish forests, both in vegetation and soil, have been increasing during the past few decades. This is due mainly to the expansion of forest area (Figure 1 in Study V), which accounted for most of the increase in litter and soil carbon stock. During the 82-year study period, biomass carbon density (expressed as the amount of carbon per area) increased by 29%. Carbon density in soils, on the other hand, increased by only 4%, because the accumulation of carbon in soil is slower than the responses of vegetation stocks to favourable conditions. It is particularly slow considering the huge flow of carbon from biomass through the soil carbon stock to the atmosphere. In the 1990s, for example, 70% of the NPP was decomposed and released from litter and soil as heterotrophic respiration. Estimated NPP, *Rh* and NEP values for Finnish forests were of the same magnitude as that measured from boreal regions by eddy covariance measurement sites (Luyssaert et al. 2007).

Interannual variation in changes of both the biomass and soil carbon stocks was high. They were driven mainly by interannual changes in climatic conditions and harvesting amounts. The effects of these factors were opposite those of biomass and soil carbon stocks. Increasing temperatures enhanced not only the growth of forests, but also decomposition in soils. On the other hand, harvests that decreased the biomass stock increased the soil stock due to the larger amount of harvest residues entering soils. These results demonstrate both the important effect of harvesting operations on the carbon balance on a national scale as well as the importance of covering all carbon stocks to obtain an overview of the whole balance. Intensive management of forests in Finland has kept the effects of natural disturbances, such as forest fires, smaller in Finnish forests than in those of many other countries.

With increasing stock amounts, the vegetation and litter and soil stocks of forests have mainly been sinks of carbon. However, the soil sink has been so small (average for the 1990s 1.5 Tg a^{-1}) that, when taking into account the uncertainties in calculations, the possibility of soil being a source instead of a sink will also be considerable for many years. Uncertainties in the inventory-based method developed in Study V have been estimated by Peltoniemi et al. (2006) and Monni et al. (2007) using a Monte Carlo method with uncertainty ranges determined for all the necessary input information and parameters. Uncertainties related to annual estimates were high and the method seemed to suit better the estimates of average stock changes for a period longer than one year (Peltoniemi et al. 2006). Soils dominated the uncertainties similarly to some other carbon assessment studies of forests (e.g. Kurz and Apps 1999, Heath and Smith 2000, Paul et al. 2003).

In this national-scale study, all harvest residues were assumed to be left in forests. The past few years have witnessed the rise of a strong increasing trend in utilising the forest residues for energy. For example, in heating and power plants, the energy produced from forest chips has trebled from 2000 to 2005 (Metla 2006). The total use of forest chips in 2005 was 3.0 million m^3, and the aim stated in the Future Review for the Forest Sector is to increase their use up 8 million m^3 by 2015 (Ministry of Agriculture and Forestry 2006). The draft for Finland's National Forest Programme 2015 indicates that the target is 10 million m^3 by 2015. What would these usage levels mean for the carbon balance of forests, and particularly of their soils? The target 10 million m^3 of forest chips corresponds to 2.2 Tg C. The amount of annual harvest residues calculated for the whole of Finland's forest area (i.e. also includes forests on peat soils) in the 1990s varied between 8 and 13 Tg C. Assuming that the general level of harvests and the litter production from living vegetation will remain at the same level as in the 1990s, utilising 10 million m^3 of harvest residues would decrease harvest residues entering the soils by about 20% and the total flow of carbon to soils by about 4%.

The effect of this diminishing carbon flow to soil stock on a national scale follows the patterns on a stand scale. The annual change in soil carbon stocks would be about 10-20% of the carbon in the collected residues (according the decomposition simulations in Studies III and IV), which, calculated from this 2.2 Tg C, is about 0.2-0.4 Tg C. Converting this carbon to CO_2, we obtain an indirect CO_2 emission of 0.8–1.6 Tg CO_2, which corresponds to 3–6% of the average carbon sink reported for Finnish forests during the years 1990–2005 (Statistics Finland 2007). If forest residue extraction and particularly stump extraction also indirectly affect decomposition processes by making the environmental conditions more favourable for decomposers, the decreases in carbon stocks could be greater. Taking into account the annual variability in the soil carbon stock change estimates (Figure 11b) and uncertainties related to the methodology (Peltoniemi et al. 2006), the additional decreasing trend caused by forest residue utilisation increases the risks of soils to be a source of carbon instead of a sink. That would have consequences on the reporting of forest sinks and their calculations to compensate for emission reductions.

5 CONCLUSIONS

YASSO and its development process is an opportune example of a model that aimed to be a practical tool from the very beginning, was based on the latest scientific information available, and has been applied to obtain information for the practical reporting needs and to assess the effects of forest management in several studies. Model development and tests have highlighted those processes that are important and those that are less important for soil carbon dynamics in mineral forest soils. Both the YASSO model and its application to a method for national forest carbon accounting have revealed those parts of the carbon balance of forests that still require further investigations. All this guides future studies and model development and helps to focus efforts on still unknown relevant topics. This is the major advantage of modelling as a tool in ecological and environmental studies. Unavoidable uncertainties related to the modelling of these complex systems obscure the interpretation of the model results in different applications, which is why model results should always be analysed and interpreted with caution.

Within this dissertation YASSO was applied to assess the effects of intensified biomass extraction on forest soil carbon stocks and to quantify indirect CO_2 emissions from utilising harvest residues as energy. According to these model-based assessments biomass extraction reduces soil carbon stocks slightly more than do conventional harvesting operations. Indirect CO_2 emissions calculated based on the soil carbon deficit are more considerable than other greenhouse gas emissions related to the production and burning of forest residues. Feedback from the soil nutrient status to forest productivity and the indirect effects of residue and stump extraction on the decomposition of soil carbon can potentially enlarge the effects on soil carbon stocks. Efforts should concentrate on improving understanding of these processes.

On a national level, soils play an important part in the forest carbon balance. Consequently, including them in the total assessment of forest carbon balance is important. The inventory-based method developed for the national scale assessment of the forest carbon balance including all biomass cohorts and litter and soil, has proved its applicability to large scale studies, and highlighted the importance of different carbon stocks and flows within forests.

Future interests related to soil carbon will certainly be related to climate change. Questions of interest focus on the sensitivity of soil carbon stocks to long-term changes in temperature and moisture conditions as well as on the effects of extreme events or large scale disturbances on soil carbon stocks. Also, different means for using soils of mitigation and adaptation to climate change will continue to be of interest. For all these questions, modelling can serve as, and in many cases is the only way to project possible future trends. Modelling as a tool for guiding the further study of soil carbon related questions will play an essential role in future as well, since our understanding of the relevant processes remains weak. In addition, the use of models to support empirical studies in planning soil sampling (Peltoniemi et al. 2007b), for example, is an option with high practical value.

Work around the YASSO model continues. A new version of the model is under development and such efforts are based on a wider range of data, and the Bayesian approach is being applied for the model parameterisation. The measurability of the model compartments to solve the problems with model initialisation in different applications has also been under discussion. Special emphasis has been placed on the development of the climatic dependencies of the model.

A question for the future is to develop this or other models to be applicable on peat soils also. This would be particularly important for Finnish carbon balance studies, but would also be relevant globally. Peat soils are an important source of other greenhouse gases, such as CH_4 and N_2O, which is why models should cover their dynamics in order to obtain a picture of the net effects of peat soils on climate change.

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