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Projecting effects of intensified biomass extraction with alternative modelling approaches

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Abstract

The effect of intensified biomass extraction on forest ecosystems is a timely question since harvest residues are increasingly utilised to produce energy and the impacts of the changed management practises are not always well understood. We compared two different modelling approaches, the MOTTI-YASSO and the EFIMOD-ROMUL model combinations, with respect to the simulated impacts of the biomass extraction in final felling on subsequent biomass and soil carbon stocks. Simulations following the latest silvicultural recommendations over a rotation were made for six Finnish forest sites varying in fertility, tree species and latitude. Model-projected effect of the intensified biomass extraction was larger with EFIMOD-ROMUL than with MOTTI-YASSO. The soil model ROMUL projected slower decomposition of organic matter than YASSO at all studied sites, which made the effect of biomass extraction on soil larger with EFIMOD. The process-based model EFIMOD-ROMUL includes feedback from soil nutrient status to productivity. With EFIMOD-ROMUL, the intensified biomass extraction decreased slightly the simulated growth of the forests and thereby the biomass carbon stock and litter input to the soil. With the empirical MOTTI model, the intensity of the simulated biomass extraction did not affect forest growth. Our results underline the importance of the selection of the modelling approach when projecting the potential effects of forest management practises on forest carbon balance.

Keywords: Biomass extraction; Carbon balance; Forest management; Harvest residues; Model comparison; Slash removal

1. Introduction

Possibilities to alleviate the human induced increase of greenhouse gases in the atmosphere have introduced carbon management as one of the multiple objectives of forest management (Brown et al., 1996). Carbon in forests is bound to vegetation and soil, which are stocks of different dynamic properties. Globally, forest soil is a remarkable carbon stock (Jobbágy and Jackson, 2000), and its share of the total forest carbon stock in the boreal zone is particularly significant (e.g. Liski et al., 2002).

The effects of different forest management regimes on forest carbon stocks are often studied with simulation models (Rolff and Ågren, 1999; Karjalainen et al., 2002; Peng et al., 2002; Masera et al., 2003; Mikhailov et al., 2004; Thürig et al., 2005). Models are seen especially valuable for the estimation of soil carbon stock changes, since the direct measurements of that stock are hindered by the large spatial variability commensurate with the relatively slow changes in stock (Conen et al., 2004). Differences in selected time and spatial scales where models operate, as well as differences in model assumptions, naturally affect model results and thereby how models respond to different forest management actions. Model validation, including different forest management actions, is difficult since relevant long-term data, especially soil data, are rare. Model comparisons, both qualitative reviews (e.g. Mäkelä et al., 2000; Landsberg, 2003; Peltoniemi et al., 2007) and

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quantitative comparisons of the model performance (e.g. Smith et al., 1997), bring useful information of the model properties by relating varying model results to differences in model assumptions. There are, however, only few model performance comparisons including the aspect of forest management (Matala et al., 2003; Schmid et al., 2006).

The effect of the intensified extraction of harvest residues on forest ecosystems is a timely question, since forest residues as well as stumps are seen as a potentially large renewable energy source (EEA (European Environment Agency), 2007). Intensive extraction of biomass in loggings has been noticed to affect, directly and indirectly, following development of both the carbon stocks of biomass (Jacobson et al., 2000; Nord-Larsen, 2002) and soil (Johnson and Curtis, 2001; Jandl et al., 2007). As a topic of model comparison this suits well, since the management itself can be implemented straightforward by varying the extracted amount of biomass by compartments. It can be expected that process level differences in the models may considerably affect simulated impacts on the carbon balance.

When determining greenhouse impact of forest residue energy from the life cycle perspective (e.g. Savolainen et al., 1994), the decomposition of harvest residues at a forest site is seen as an alternative emission source to the burning of the residues for energy. The estimate of the alternative release of carbon from the forest into the atmosphere is affected by the decomposition model in use. Following the decomposition dynamics of the residues is also one of the most straightforward ways to compare the decomposition models.

The intensity of forest residue utilisation in harvests and decomposition of harvest residues were selected to compare two modelling approaches on forest carbon balance and especially the soil carbon balance. The modelling approaches were: (1) the empirical stand simulator MOTTI (Hynynen et al., 2005) linked with the soil carbon model YASSO (Liski et al., 2005), a combination that has previously been tested in southern Finland stands (Peltoniemi et al., 2004), and (2) the individual-based process model EFIMOD (Komarov et al., 2003) with the sub-model of soil organic matter dynamics called ROMUL (Chertov et al., 2001). EFIMOD-ROMUL has been tested and applied in Finland (Chertov et al., 2003), Russia (Mikhailov et al., 2004), the Netherlands (Nadporozhskaya et al., 2006) and Canada (Shaw et al., 2006). The most relevant difference between the models, with regard to this study, is that EFIMOD-ROMUL includes the nitrogen dynamics omitted in MOTTI-YASSO.

The aim of this study was to assess the effects of intensified extraction of biomass in final felling on carbon stocks of stand biomass and soil by using two alternative modelling approaches. We were particularly interested in the importance of the effect of nitrogen feedback from soil to vegetation and the differences in decomposition dynamics between the soil models. The comparison was made with stand information from six Finnish upland forest sites and by following the latest silvicultural recommendations of the Finnish Forestry Development Centre Tapio (Anonymous, 2006).

2. Material and methods

2.1. Study sites

Six typical Finnish forest sites with mineral soils, two in southern, two in central and two in northern Finland were selected for the comparison. Table 1 shows the geographical information and the stand composition of the studied forest sites. Three were dominated by Scots pine (*Pinus sylvestris* L.) and three by Norway spruce (*Picea abies* (L.) *Karst.*). According to the Finnish classification of forest sites (Cajander, 1926), the pine sites were subxeric *Vaccinium* type (VT) and mesic *Myrtillus* type (MT) and the spruce sites were moist and highly productive *Oxalis-Myrtillus* type (OMT) and mesic *Myrtillus* type.

The study sites were established by the Finnish National Forest Inventory (NFI) for permanent monitoring. Stand data were measured in 1985, and soil data from the same sites were measured between 1986 and 1989 (Tamminen, 2003). 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).

2.2. Stand models

Input information and runtime assumptions of the studied models are given in Table 2.

Table 1
Site information

Study site	Site type	Dominant tree species	Geographical co-ordinates [N–E]		Climate information	
			Latitude	Longitude	DD5 (°C days)[a]	Prec[b] (mm)
VT Pine south	Subxeric	*Scots pine*	60°40′	27°54′	1363	628
MT Pine central	Mesic	*Scots pine*	63°07′	28°17′	1168	600
VT Pine north	Subxeric	*Scots pine*	66°50′	28°11′	780	531
OMT Spruce south	Most productive	*Norway spruce*	61°38′	23°06′	1210	593
MT Spruce central	Mesic	*Norway spruce*	62°41′	26°05′	1147	624
MT Spruce north	Mesic	*Norway spruce*	64°23′	29°21′	960	591

[a] Effective temperature sum with 5 °C threshold calculated from mean monthly temperatures.
[b] Annual precipitation.

Table 2
Comparison of the model input and runtime assumptions used in this study

	EFIMOD	MOTTI	ROMUL	YASSO
Climatic information	Mean monthly air temperature (°C) and monthly precipitation (mm)	Annual temperature sum with 5 °C threshold (degree days)	Mean monthly soil temperature (°C) and moisture (mass %) in organic layer and in mineral layer[a]	Annual temperature sum with 0 °C threshold (degree days) and monthly precipitation (mm)
Other site specific information	Forest site type with Russian classification (Remezov and Pogrebnyak, 1965)	Forest site type with Finnish classification (Cajander, 1926), index describing the nearness of sea or lakes, stoniness[b], and degree of peat formation[b]	Nitrogen deposition ($\mathrm{kg\ m^{-2}\ a^{-1}}$), soil texture (rank)	–
Initialisation information	Tree species composition, age, mean height, dbh, basal area and number of trees per hectare for each tree cohort, deadwood ($\mathrm{kg\ m^{-2}}$)[c]	Tree species, no. of trees, dbh and mean height of the tree classes[d]	Total carbon and nitrogen stocks in organic horizon and mineral soil taken from measurements or from literature[c]	Initial carbon stocks for model compartments are calculated with spin-up runs using litter input of the standard scenario
Forest management actions	Timing[e] and removal percentages for fellings and planting instructions, i.e. number of seedlings, year of sowing	Timing[e] and the removal percentage for fellings	–	–
Litter quality	–	–	Nitrogen and ash contents	Division of biomass compartments to extractives, celluloses and lignin-like compounds (Hakkila, 1989)
Time step	Annual	5 years	Monthly	Annual
Simulated soil depth	–	–	1 m	1 m

[a] In this study the soil climate generator SCLISS (Bykhovets and Komarov, 2002) was used to generate the soil temperatures and moistures. SCLISS requires monthly air temperature (°C), precipitations (mm) and soil hydrology characteristics, i.e. wilting point, full capacity and field capacity (mm).

[b] Study sites of the current study did not have peat cover or substantial quantities of stones.

[c] For this study the EFIMOD-ROMUL model was initialised for each study site with the measured data from sites of different ages. Model was then run until the end of that rotation to reach the start of the studied rotation.

[d] MOTTI was initialised with the stand description of EFIMOD (output) just after the first thinning. The stand age of this first thinning varied between 25 and 38 years among the studied sites.

[e] Timings for the fellings for both models were determined by the stand basal area (vs. dominant height) limits in silvicultural recommendations (Anonymous, 2006).

2.2.1. *MOTTI*

The stand simulator MOTTI (Hynynen et al., 2002, 2005; Matala et al., 2003; Salminen et al., 2005) is developed for assessing the effects of different forest management practises on stand development, the profitability of forest management, carbon sequestration and biodiversity. MOTTI is based on extensive empirical data from Finnish forests; more than 68,000 trees on 4400 sample plots with a wide geographical coverage in Finland have been used to develop this model. It is able to simulate the stand development of all major tree species in Finland. MOTTI operates with a stand description where trees are classified into tree classes describing the tree species, the number of trees in the class, diameter at breast height (dbh), height and the crown ratio. The tree classes are updated every 5 years: growth is estimated with a distance independent single tree growth model; mortality is predicted with a single tree survival model and a stand-level self-thinning criteria (Hynynen and Ojansuu, 2003).

2.2.1.1. Conversion of stand volume to biomass. Biomass is estimated in MOTTI for each tree class separately, and for compartments of stem, branches, needles, roots (Marklund, 1988). Fine-root biomass (< 2 mm) is estimated with a relation $(0.1 + 0.0018 \times t) \times \mathrm{bf}$; where t is age of the tree and bf is foliage biomass (Vanninen and Mäkelä, 1999). These estimates were used for both standing and harvested trees.

2.2.1.2. Litter production estimates. Estimates of litter production were obtained by multiplying the biomasses with turnover rates (see Table 1 in Liski et al., 2006). Estimates of harvest residues were calculated for each removed tree with the biomass equations above.

2.2.2. *EFIMOD*

The EFIMOD model of the forest-soil system (Chertov et al., 1999; Komarov et al., 2003) describes population-level dynamics consisting of a set of individual trees that compete for light and soil nutrition with the nearest neighbour trees. The population of trees exhibits the realistic dynamics of averages. This approach makes it possible to trace population-based mechanisms of the development of forest stands and to assess the effect of various forestry practises (tree planting, cutting, etc.). Tree growth is calculated annually as a potential biomass increment determined by the foliage biomass and the climate (sum of daily temperatures >5 °C), the effect of which are further reduced according the Liebig's law of the minimum (von Liebig, 1840) as a function of available photosynthetic active radiation and available soil nitrogen. Tree mortality is estimated in the model with a threshold proportion of leaves to total biomass for a phase of intensive self-thinning and randomly for larger old trees.

2.2.2.1. Conversion of stand volume to biomass. Initial biomass in EFIMOD is estimated for each tree separately, and for compartments of stem, branches, needles and roots using Marklund's biomass equations with tree height and dbh as driving variables. Fine-root biomass (<2 mm) is assumed to be 10% of the coarse roots biomass (Kazimirov and Morozova, 1973; Kazimirov et al., 1977, 1978). During forest growth the total increment is distributed among tree's compartments in correspondence with some experimental coefficients (see Table 3 in Komarov et al., 2003).

2.2.2.2. Litter production estimates. Estimates of litter production were obtained by multiplying the biomass figures with coefficients depending on tree's age (Kazimirov and Morozova, 1973; Kazimirov et al., 1977). Harvest residues were estimated as a sum of corresponding compartments for each removed tree.

2.3. Soil models

2.3.1. YASSO

The carbon and decomposition model YASSO (Liski et al., 2005) describes the decomposition process of organic matter based on the litter quality and climatic information. Litter quality is taken into account by first dividing the input litter between non-woody (typically leaves/needles and fine roots), fine-woody (branches and roots) and coarse-woody litter (stems and stumps). The latter two input flows have also their own compartments in the model that describe the physical fractionation of woody litter. Woody litter in these compartments is transferred further based on its chemical quality to extractives, celluloses and lignin-like compounds. Non-woody litter is divided directly into these three compartments. This division is usually made on the basis of measured or literature values. Slowly decomposing compounds in soil are described with two humus compartments. The climatic dependency of the decomposition in the model is described with a rate modifier that multiplies the decomposition rates and physical fractionation rates in standard conditions. The rate modifier is calculated with a linear regression model developed based on the litterbag data across Europe (Liski et al., 2003). The basic parameter set described by Liski et al. (2005) was used in this study.

2.3.2. ROMUL

The ROMUL model uses a concept of 'humus types' in order to describe the mineralisation and humification of organic matter (Chertov et al., 2001). It calculates the processes of SOM mineralisation and humification separately for the organic and mineral layers.

Litter is divided according to its quality into different fractions. Each litter fraction decomposes through three stages. The first two stages or pools are separate for all the types of litter (undecomposed and partially decomposed litter) while the last humus compartment is common and indistinguishable for all litter fractions. The steps of litter decomposition through the model describe the mineralisation and humification processes by different communities of decomposers.

Soil temperature and soil moisture affect all the mineralisation and humification processes within the model. These processes are, however, different for different litter cohorts and they are affected by different factors such as soil and litter properties. These dependencies are described with a set of empirical regression models. The nitrogen and ash contents of the original litter influence the rates of litter transformation. The C/N ratio defines the decomposer community structure, which influences the rate of humification. Clay content of the mineral matrix affects the mineralisation of the humus compartment.

In ROMUL, nitrogen dynamics is linked with the carbon dynamics, but is more complex (Chertov et al., 2001). Nitrogen dynamics is affected by decomposer community structure, for example, by the presence or absence of earthworms. The model simulates the nitrogen pool available for plants, which is affected by the mineralisation and humification processes of SOM. Leaching and atmospheric deposition of nitrogen are accounted for in the full nitrogen balance in organic and mineral soil.

The rate constants and empirical regressions of the ROMUL model have been determined on the basis of laboratory experiments of litter and SOM decomposition in controlled conditions (Chertov et al., 2001).

2.4. Forest management

The latest silvicultural recommendations in Finland (Anonymous, 2006) were followed in all model runs, and forest management decisions were made independently for both of the models. The timing and intensity of the management actions depended on each of the models' projections on stand development (basal area and dominant height) and silvicultural recommendations.

2.4.1. Stand establishment

Stand establishment assumptions relate only to EFIMOD, since MOTTI was run only starting from the state of the stand after first thinning (as simulated by EFIMOD). In EFIMOD the stand establishment after the final felling was done by planting 2080 two-year-old seedlings on a regular grid in the same year as the final felling happened. No soil preparation was assumed to be applied.

2.4.2. Thinning interventions

Silvicultural recommendations in Finland connect both timing and intensity of the thinning interventions by thinning rules that are based on stand basal area (versus dominant height) (Fig. 1). As the thinning rules are tree species, forest type, and location (north, central, south) specific, different limits were applied for all the six study sites. For spruce we applied the lowest thinning limits for timing and the average of

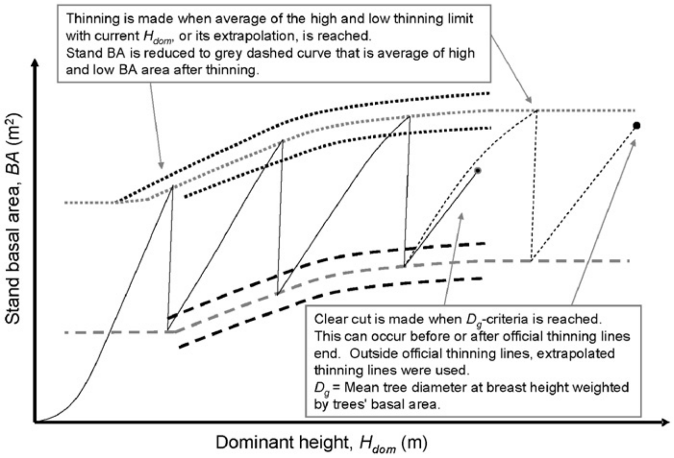

Fig. 1. Illustration of the concept used for determining the timing and intensity of thinning interventions and timing of the final felling.

recommended thinning limits for the remaining basal area. For pine the average of recommended thinning lines were applied for both timing and remaining basal area.

2.4.3. *Final felling*

Timing for the final felling was determined based on the recommended maximum limit for mean tree diameter (at breast height, weighted with trees' basal area). The maximum diameters ranged from 22 to 32 cm.

2.5. *Scenarios of harvesting intensity*

Two scenarios of the intensity of the biomass extraction were applied. In the standard scenario (STA), only stems (95% of the stem biomass) were assumed to be removed from the study sites after thinning interventions and in final felling. In the scenario of intensified biomass extraction (IBE), the harvest residues (i.e. needles, branches, and tree tops) and tree stumps in addition to stems were assumed to be extracted from the final fellings. The recommendations of the harvest residue extraction given in the silvicultural recommendations in Finland (Anonymous, 2006) were followed in this scenario. Thus, residues and stumps were only extracted from the final fellings, since it is not recommended to extract them from the same site both in final fellings and in thinnings. Furthermore, extraction of needles, branches or tree tops was not assumed to happen during the harvests of the nutrient poor VT sites. However, extraction of stumps was assumed to happen on all sites. In reality, not all harvest residues can be extracted. Moreover, the recommendations state that part of the nutrients in the residues should be left in the forest. It was assumed that 60% of the biomass of the harvest residues and stumps can be extracted, and that 50% of the coarse root biomass follows the stump when it is lifted up.

2.6. *Initialisation of the models*

2.6.1. *MOTTI-YASSO*

The stand simulator MOTTI was initialised with the stand information from EFIMOD after the first thinning. This was done because the description of the development of the young stands in MOTTI is currently under development and was not applicable in this study. For the soil model YASSO, the litter input during the early years of rotation was taken from EFIMOD.

The initial soil carbon stocks of the soil model YASSO were determined by calculating the steady state using spin-up runs (like e.g. in Liski et al., 2005) with the input of the standard scenario (STA) and given climate information at each site. The steady state assumption is commonly used with YASSO, since all of the model compartments as such are not directly comparable with measured soil data.

2.6.2. *EFIMOD-ROMUL*

EFIMOD-ROMUL was initialised with both stand and soil measurements from the study sites. Since the ages of the measured stands varied, the model was first initialised and then run until the end of the rotation according to the STA scenario. This pre-run period varied from 1 year in MT Spruce north site to 70 years in MT Spruce central site.

2.7. *Model runs*

EFIMOD-ROMUL was run for each of the six forest stands applying the two forest management scenarios. As tree growth in the current version of the MOTTI model is not affected by the whole-tree harvest and subsequent nitrogen loss, the stand projections in the scenarios are equal. The scenarios of intensified biomass extraction with MOTTI-YASSO thus include only the differences in soil. Climate of the sites was assumed to be stable during the simulations meaning that the same values of the climatic variables were applied for each year. For simplicity, ground vegetation was excluded from our analysis, so it was not taken into account neither in biomass carbon stocks or litter flows from biomass to soil.

2.8. *Model comparison*

Model outputs, i.e. estimates of the carbon in biomass by MOTTI and EFIMOD, estimates of the total carbon in soil by YASSO and ROMUL as well as the sum of both forming the total forest carbon, were compared for the studied rotation. The differences between the two scenarios within the modelling approaches were calculated. Decomposition dynamics of the harvest residues was modelled with both soil models and compared at each site.

3. Results

3.1. *Simulated forest management*

The timing and intensity of the thinnings as well as the timing of the final felling (i.e. rotation lengths) varied between the models (Fig. 2). Both models, however, simulated two thinning interventions in all cases. With the STA scenario, EFIMOD rotations were longer than MOTTI rotations in the study sites of southern and central Finland. The largest difference (23 years) was in the most fertile OMT Spruce south

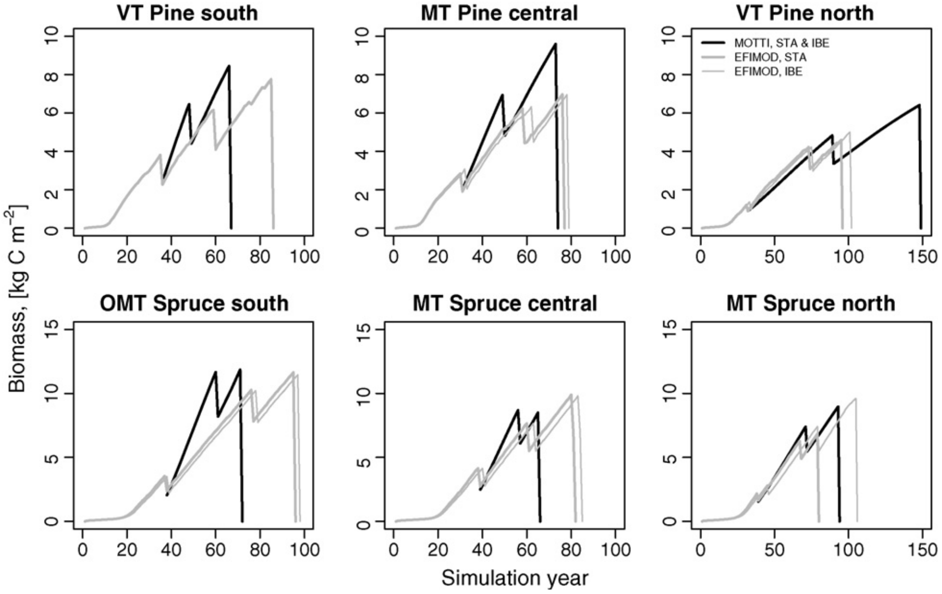

Fig. 2. The development of the biomass carbon stock of the studied forest stands over rotation with EFIMOD and MOTTI models. For EFIMOD the runs are done with standard (STA) and intensified biomass extraction (IBE) scenarios separately and for MOTTI the scenarios are equal. With VT Pine south site the difference between the EFIMOD projections for STA and IBE scenarios is not notable.

site. In the northern study sites MOTTI projected longer rotations in the least fertile study site VT Pine north, the difference being 54 years. The intensified biomass extraction (IBE) scenario elongated EFIMOD rotations with 0–26 years, depending on the site, in comparison to the standard scenario.

3.2. Biomass carbon stock

MOTTI projected faster accumulation of biomass carbon (forest growth) than EFIMOD in sites of southern and central Finland (Fig. 2). In northern Finland, the biomass accumulation rates were similar with both models. EFIMOD projected that the growth of forest stands decreased with the intensified extraction of biomass (in contrast to the empirical model MOTTI where feedbacks from soil are not included). Differences between the models were constantly larger than the differences between the two scenarios in EFIMOD.

3.3. Soil carbon stocks

The general level of soil carbon (including the litter) was quite similar with both models at four sites out of six (Fig. 3).

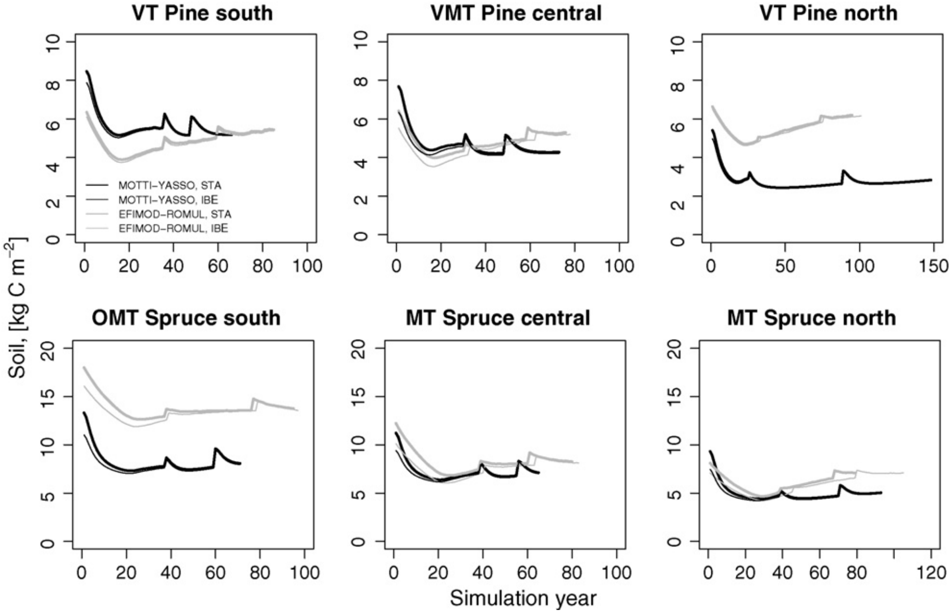

Fig. 3. Soil carbon stocks of the studied stands over rotation projected with the MOTTI-YASSO and EFIMOD-ROMUL models. Simulations start from the final harvest with harvest residues counted in soil carbon. For these simulations natural litter produced by EFIMOD was given to YASSO during the first years of rotation.

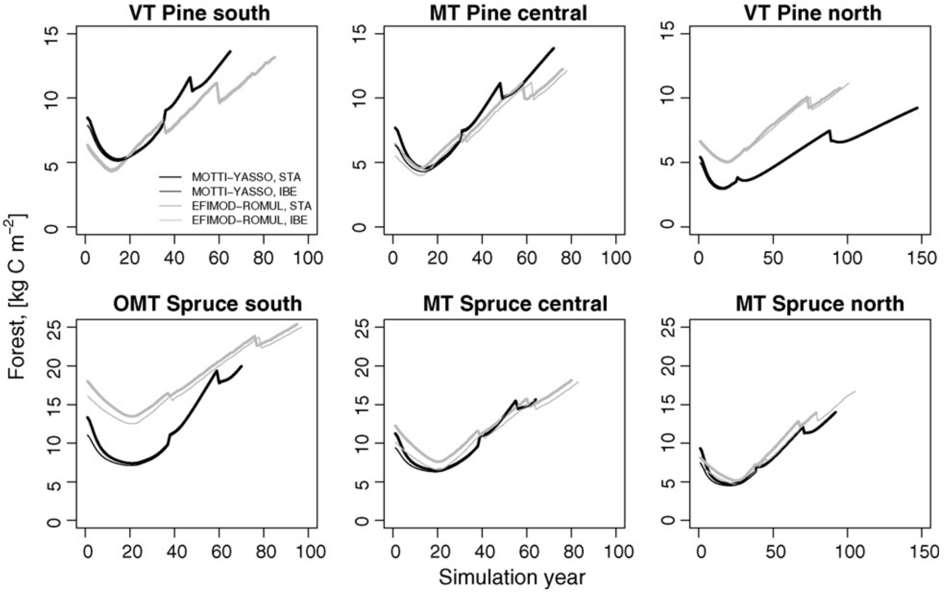

Fig. 4. Total forest (biomass + soil) carbon stock development of the studied forest stands over rotation.

Soil carbon stocks of the least (VT Pine north) and the most (OMT spruce south) fertile sites were predicted to be larger with EFIMOD-ROMUL than with MOTTI-YASSO.

Soil carbon dynamics of the models differed so that EFIMOD-ROMUL gained carbon, whereas with MOTTI-YASSO the soil carbon stocks remained quite stable after the decomposition of the harvest residues from the final felling.

The differences in soil carbon stocks between the two scenarios were rather small with both model approaches. With MOTTI-YASSO, the carbon stock of IBE scenario nearly reached the level of the STA scenario at the end of rotation. In EFIMOD-ROMUL the differences in soil carbon between the scenarios were more pronounced and did not completely disappear until the end of the rotation.

3.4. Forest carbon stocks

The total forest carbon stocks (biomass + soil) and their development during the rotation were similar for both model approaches at four sites out of six (Fig. 4). At the least (VT Pine north) and the most (OMT Spruce south) fertile sites EFIMOD projected larger total forest carbon stocks as a consequence of larger soil carbon stocks (Fig. 3).

The differences in total forest carbon stocks between the two scenarios with MOTTI-YASSO are small and only caused by the differences in soil carbon stocks. With EFIMOD-ROMUL the differences in total forest carbon stock between the scenarios are larger.

The differences in the average soil carbon stock over rotation between the two scenarios in all the study sites were larger in EFIMOD-ROMUL than in MOTTI-YASSO (Fig. 5). The effect of decreasing biomass growth contributes remarkably to the total differences between the scenarios simulated with EFIMOD-ROMUL. The share of EFIMOD biomass varied remarkably within the pine sites (from 17 to 55%) but was rather constant within the spruce sites (from 37 to 39%). The size of the differences depended on the intensity of biomass extraction, and consequently, the differences in the spruce sites were larger than in the pine sites and the smallest differences were in the two VT sites (where only stumps were assumed to be extracted).

3.5. Decomposition of the harvest residues

The modelled decomposition of the harvest residues was clearly slower and more dependent on the site conditions (e.g. climate) in ROMUL than in YASSO (Fig. 6). The mass remaining values of ROMUL were higher during the first 75–110 years depending on the study site, but for the late stage of decomposition, YASSO projected more remaining residue carbon than ROMUL. In the northern study sites, ROMUL reached YASSO's mass remaining values later than in the southern study sites.

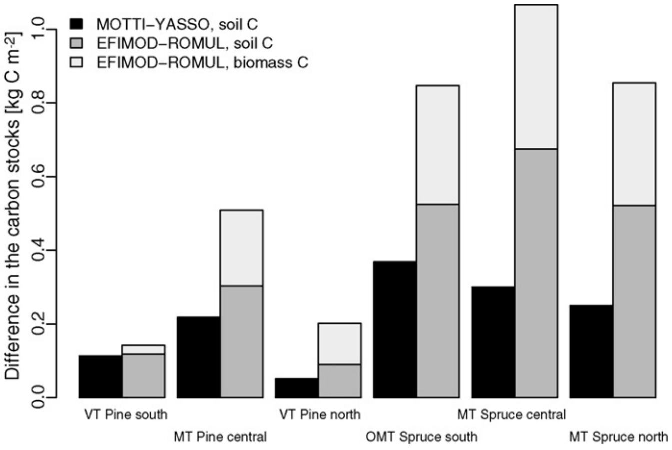

Fig. 5. Differences between the carbon stocks of standard and intensive biomass extraction scenarios simulated with MOTTI-YASSO and EFIMOD-ROMUL. Differences are given as averages over rotation.

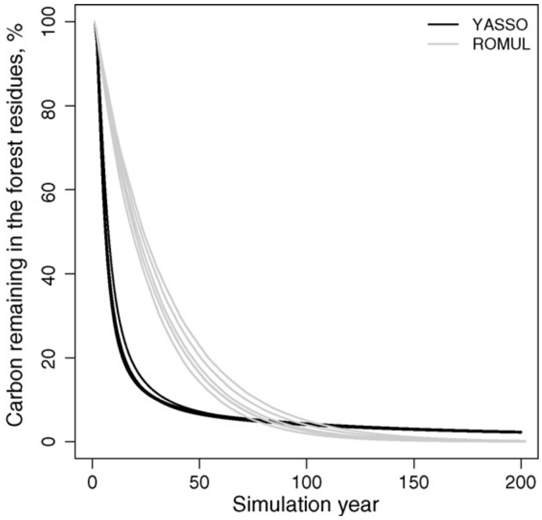

Fig. 6. Decomposition dynamics of the same amount of similar harvest residues during 200 years predicted with the soil models YASSO and ROMUL. Each single line describes the development of (dry)mass/carbon remaining percentage (%) simulated in conditions of one study site.

4. Discussion

Model comparisons, even though unable to validate the models, are useful tools helping us to understand the behaviour and possible limitations of the models with different theoretical approaches (Rastetter, 1996). They are particularly valuable when studying long-term processes in forests and forest soils from which the measured information is rare due to the long time series and intensive sampling with expensive analysis needed. They also highlight one of the most important sources of uncertainty, the uncertainty of model structure, which is often the largest source of error (Chatfield, 1995). In this study, we compared projections of an empirical stand simulator (MOTTI) linked with the soil carbon model (YASSO) and projections of an individual-based process model (EFIMOD) with the soil module (ROMUL) with respect to how intensified biomass extraction in final fellings affect the simulated carbon balance.

Carbon accumulation in tree biomass projected by EFIMOD was clearly slower in the sites of southern and central Finland than MOTTI's projection (Fig. 2). In northern Finland growth projections were similar for both models. As MOTTI is based on wide empirical data of the Finnish forests, its projections under regular forest management regimes are presumably reliable. EFIMOD thus underestimated the growth in southern and central Finland, which was due to the parameterisation used in the model. This underestimation, however, did not impede the comparison of the effect of altered forest management, because the systematic error affected both scenarios similarly.

Biomass development in EFIMOD-ROMUL was affected by the intensity of the residue extraction. While the changes in stand development in EFIMOD were far smaller than the differences between the EFIMOD and MOTTI simulations, they still covered a remarkable share of the total effect of the residue extraction on total forest carbon balance in the EFIMOD-ROMUL simulations (Fig. 5), and affected the timing of the thinning interventions and final felling in simulations (Fig. 2). Earlier results both from modelling (e.g. Rolff and Ågren, 1999; Peng et al., 2002), and empirical (e.g. Egnell and Valinger, 2003) studies support EFIMOD results that forest productivity is affected by intensified biomass extraction. Using models like the current version of MOTTI that are not sensitive to nutrient losses thus holds an implicit assumption that either nutrient losses do not affect growth or that the possible nutrient losses are compensated with fertilisation, which should then be taken into account as a source of greenhouse gas emissions. According to our results, omitting the growth effect would underestimate the effect of biomass extraction especially in spruce stands. This potentially important effect on growth should be incorporated in models that are used to assess the effects of forest management.

Soil carbon stock levels and the dynamics of the stocks under the standard forest management differed between the models. ROMUL gained more carbon than YASSO during the rotation at all sites (Fig. 3). For the southern study sites after the age of 30 years, YASSO and ROMUL predicted soil carbon stock changes of on average +6 and +18 g m^{-2} a^{-1}, respectively. Recent studies by Häkkinen et al. (submitted for publication) (repeated measurements after 16–19 years) and Peltoniemi et al. (2004) (chronosequence, long-term averages) have reported soil carbon stock changes for the humus layer of managed forests in southern Finland of +23 and +5 g m^{-2} a^{-1}, respectively. Considering that these results are only for the humus layer and there are uncertainties related to chronosequence studies (Yanai et al., 2000), they give support to the larger changes by ROMUL. It is possible that the steady state assumption used for the initialisation of YASSO makes the predictions of changes too conservative (Wutzler and Reichstein, 2006; Ågren et al., 2007). The initialisation was done for both scenarios with the same values. This way the effect of initialisation remained similar in both scenarios, and there was no subsequent effect on the comparison of the scenarios.

EFIMOD-ROMUL estimated larger differences in soil carbon stocks between the management scenarios than YASSO (Figs. 3 and 5). This was due to slower decomposition of the harvest residues in ROMUL (Fig. 6) and due to decreases in litter input with decreasing forest productivity projected by EFIMOD. In the long-term (several rotations) both soil models simulate soil carbon stocks to gravitate towards new equilibriums, which are directly proportional to the reduced input from natural litter and harvest residues during the rotation. This would mean for YASSO a decrease in steady state soil carbon stocks from 2% on the VT Pine north site to 9% on the OMT Spruce south site when using the litter input from MOTTI. For EFIMOD-ROMUL, the decrease would be from 9% on the VT Pine south site to 14% on the MT Spruce north site. To reach these new equilibriums would, however, take several hundreds of years.

Slower decomposition predicted by ROMUL (Fig. 6) increases the retention time of carbon in harvest residues and makes them a longer lasting carbon stock than predicted by YASSO. The difference between the predicted mass remaining was remarkable during the first 50 years. The decomposition of soil organic matter predicted by ROMUL was also more sensitive to climate than the decomposition predicted by YASSO, as shown by the simulations on the climatic gradient consisting of the study sites (Fig. 6). The accuracy of the climate sensitivity of the modelling tools is essential for being able to assess the regional and temporal differences in using different forest management practises as a tool for mitigation and adaptation to climate change.

Both modelling approaches applied in this study include simplifying assumptions affecting the modelled results. For example, the side effect caused by the soil disturbance in stump extraction was not covered by either of the modelling approaches used in the study. As the stump removal typically exposes the mineral soil, it is very likely that it also changes the soil properties and conditions for the decomposition of the soil organic matter as does the soil preparation (Mallik and Hu, 1997) and taking it into account could increase the differences between the scenarios remarkably.

Similarly, the role of harvest residues and ground vegetation in nutrient dynamics after the harvests, affecting the possible leaching from the site (Palviainen et al., 2004, 2005), was omitted. Ground vegetation recovers from the final felling rapidly (Palviainen et al., 2005) and therefore it could slightly smooth the changes in biomass and soil carbon stocks after the final felling. The effect of the biomass extraction intensity on ground vegetation has been reported to be relatively small (Olsson and Staaf, 1995) indicating that the role of ground vegetation, in assessing the carbon balance of different biomass extraction intensities, may not be large either. Regeneration of the stands with EFIMOD was done similarly for both scenarios. The effects of intensified biomass extraction on the forest regeneration, i.e. survival and early development of seedlings, have been reported to be marginal and variable (Egnell and Leijon, 1999; Sikström, 2004; Carter et al., 2006).

The empirical stand simulator MOTTI applied in this study describes the stand development under standard forest management reliably, but the current version does not cover the effects of intensified biomass extraction in final felling on growth. A model version taking this into account is under development. The weakness of all empirical based models is that their applicability is restricted to the scope of the original data (Korzukhin et al., 1996). Process models, such as EFIMOD-ROMUL, are not dependent on the available empirical information but try to describe the underlying processes. The accuracy of these process-based model estimates is dependent on the accuracy of the process description in the models and the parameterisation of the models. They can potentially react on the simulated changes in environmental factors and are therefore stronger than the empirical models when applied in questions where there is not enough empirical information available. Combined use of these two modelling approaches could have considerable advantages. Empirical models could be used to calibrate process models and process-based models could provide information of the specific processes under changing environmental conditions that are not covered by the empirical models.

5. Conclusions

The aim of this study was to compare two alternative modelling approaches with respect to the effects of intensified extraction of biomass in final felling on the forest carbon balance. The results showed considerable differences in the effects of this changed forest management as projected by the empirical stand model with a decomposition model and the process-based model. This underlines that special emphasis should be put on model selection when studying the effects of forest management on forest carbons stocks. The feedback mechanism from soil to forest productivity is important and the approaches lacking this may underestimate the total effect of intensified biomass extraction. Concentrated efforts should be made to achieve measured information from the critical interactions in forest ecosystems. As shown in this study, models can be used to indicate those processes that have particular relevance.

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