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Modelling the impacts of intensifying forest management on carbon budget across a long latitudinal gradient in Europe

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Abstract

Global wood demand is projected to increase with accompanying intensification in forest management practices. There are concerns that intensive management practices such as whole-tree harvest (WTH) and shortened rotation lengths could risk the long-term productivity and carbon sink capacity of forest ecosystems. The historical (1915-2005) and future (2005-2095) development of five Scots pine (*Pinus sylvestris*) and five Norway spruce (*Picea abies*) stands were simulated across a long latitudinal gradient in Europe. The responses of above- and belowground carbon and nutrient cycles to changing forest management and climate were simulated using a biogeochemical ecosystem model and a dynamic litter and soil carbon model. The uncertainty deriving from the inter-annual climate variability was quantified by Monte Carlo simulations. The biogeochemical model estimated the historical stand development similarly to measurement-based estimates derived from growth and yield tables, supporting the validity of the modelling framework. Stand productivity increased drastically in 2005-2095 as a result of climate change. The litter and soil carbon and nitrogen stocks decreased as a result of WTH while its effect on the biomass carbon stock was positive. This indicates that the microbial controls of post-harvest on stand productivity require further research. Shortened rotation length reduced the carbon stock of biomass more than that of litter and soil. The response of the litter and soil carbon stock to forest management was very similar irrelevant of the model used demonstrating the pattern to be robust. Forest management dominated over the impacts of climate change in the short term.

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1 Introduction

Forest bioenergy and wood products have been proposed as an important strategy to mitigate the global climate change through substituting fossil fuels and construction materials. For example in the European Union, the growing demand for renewable energy is associated with intensifying forest management practices both domestically and in countries exporting roundwood to the EU (EC, 2009; Forsell et al., 2016; Pelkonen et al., 2014). Europe and North America have the highest supply potential of forest harvest residues while Russia is a major producer of fuelwood (IRENA, 2014). Concerns have been expressed that the intensive forest management practices such as whole-tree harvest and shortened rotation lengths might risk the long-term carbon sink capacity and productivity of forest ecosystems (Harmon et al., 1990; Hudiburg et al., 2011; Lamers et al., 2013).

In whole-tree harvest, residues such as tree tops and branches are removed from the site along with the stem. This reduces the litter and soil carbon stock and nutrient availability compared with conventional stem-only harvest (Thiffault et al., 2011). The use of forest bioenergy causes indirect CO_2 emissions to the atmosphere because the carbon stored in the harvest residues is emitted faster than when left on site to decompose (Repo et al., 2011). Some experimental studies have suggested that whole-tree harvest decreases the long-term productivity of forest, particularly when the nitrogen-rich fine woody debris and foliage are removed (Achat et al., 2015). Others have found a neutral or even a positive effect (Egnell et al., 2015). Short rotation lengths have been shown to be less effective in carbon sequestration than long ones because they reduce the biomass carbon stock and the litter input to soil (Peng et al., 2002; Pussinen et al., 2002). Changes in the rotation length also alter the supply of

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timber for long-lived wood products which in turn affects the substitution benefits from the use of harvested wood products.

Forests regulate climate both trough the biogeochemical cycles and the biophysical mechanisms such as evapotranspiration and surface albedo (Anderson-Teixeira et al., 2012; Naudts et al., 2016). The impacts of harvest system on the carbon and nutrient cycles of forest depend on environmental conditions such as climate, nitrogen deposition and soil type, as well as the ecophysiology of individual tree species (Thiffault et al., 2011). Climate change has been projected to enhance forest growth especially in the northern latitudes because of the fertilizing effect of the rising CO_2 concentration and the increasing mean temperature, under sufficient water supply. Its effects on the soil carbon stocks are more uncertain; increasing soil temperature may accelerate litter decomposition and cause higher greenhouse gas emissions from the soil to the atmosphere. The effects of alternative forest management scenarios, accounting for various site conditions and changing climate, can be best studied using process-based ecosystem models at the appropriate scaling. They enable the simulation of complicated feedbacks between the atmosphere, trees and soil.

Continuing climatic change has impacts on the biogeochemical cycles of ecosystems worldwide (Frank et al., 2015). At the same time, environmental management practices are changing due to economic and political pressures (Birdsey and Pan, 2015). Sustainable mitigation and adaptation policies require information on the joint impacts of climate- and human-induced drivers on greenhouse gas budgets (Lindner et al., 2010). The objective of this study was to simulate the potential responses of the forest carbon and nitrogen cycles to changing climate and forest management in boreal and temperate regions. A mechanistic

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biogeochemical model BGC-MAN was applied to simulate the development of Scots pine and Norway spruce stands across a long latitudinal gradient in Eastern Europe (Pietsch, 2014). These tree species were selected because they are the two major forest forming species and economically the most important ones over the study region. The modelling framework was evaluated by comparing the predicted stand biomass with measurement-based data. The robustness of the litter and soil carbon estimates was evaluated by comparing them to estimates produced with a dynamic soil carbon model, Yasso15 (Järvenpää et al., 2017). The complimentary use of two models aimed decreasing the uncertainty of the study results.

2 Materials and methods

2.1 Study area

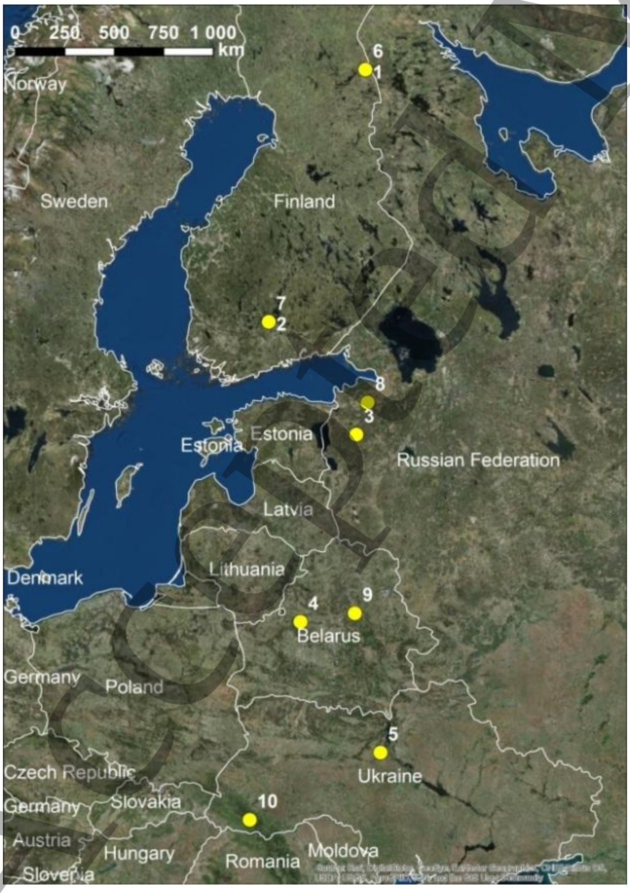

Figure 1. The location of the study sites (n=10) across a north-south gradient in eastern Europe. Numbers 1-5 denote Scots pine (*Pinus sylvestris* L.) and numbers 6-10 Norway spruce (*Picea abies* (L.) H. Karst) stands.

The ten study sites (Fig. 1) were located across a climatic gradient from northern Finland (66.29°N; 29.24°E) down to middle Ukraine (48.33°N; 24.20°E). The

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annual mean temperature ranged from -0.9°C in the north to 8.4°C in the south, and the annual mean precipitation from 619 to 811 mm, respectively, during 1971-2005. The vegetation zones comprised of boreal (middle and southern taiga) and temperate coniferous forest (zones of mixed forest, forest steppe and high-altitude spruce forest in Carpathian Mountains). The sites represented typical planted or semi-natural Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H. Karst) stands managed with regular thinning and clear-cutting.

In order to maximize the comparability of the results, the study sites were selected among the most represented zonal forest types, with a clear dominance (>90% by growing stock) of the studied species, growing in similar geomorphological conditions (gentle slopes from 1 to 5°), the same age (90 years in 2005) and similar elevation (65-150 m a.s.l.), and without visible consequences of natural disturbances (fire, insects and pathogens outbreaks). Site 10 is an exception because undisturbed stands dominated by Norway spruce are currently very rare in the plain territories of Northern Ukraine. This area is located in the mountain conditions of Carpathians, on a steep slope at 1280 m a.s.l. We also did not consider pine forests located in bioclimatic zones of southern forest steppe and steppe, because these territories belong to a xeric belt (an ecotone between the forest zone and southern forestless dry lands) where pine forests are forecasted as a tipping element due to the critical water stress there (Shvidenko et al., 2017).

Biometric and ecological characteristics on the study sites correspond to data from actual sample plots, of a size of 0.5 to 1 ha, established during recent decades. The characteristics of the selected study sites are as close as possible to data of regional yield tables of modal, i.e.

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most represented actual stands. More information and description of the diversity of sample plots can be found in national publications (e.g, Lakyda et al., 2016) and aggregated data bases (e.g. Schepaschenko et al., 2017).

2.1 Modelling framework

In this study, an application of the dynamic BioGeoChemistry Management model BGC-MAN (Pietsch, 2014) is presented. It is a mechanistic, species-specific ecosystem model developed based on Biome-BGC 4.2 (Thornton et al., 2002). BGC-MAN estimates the effects of management interventions on biomass productivity and carbon sequestration in terrestrial ecosystems at a daily time-step (Petritsch et al., 2007; Pietsch and Hasenauer, 2006). Previous tests of Biome-BGC 4.2 have shown that it is capable for estimating the long-term impacts of biomass removal (Merganicova et al., 2005) and thinning (Gautam et al., 2010) on forest carbon and nitrogen stocks at a regional scale in Central Europe. However, the validity of the current model at a wider climatic gradient remains to be tested.

The litter and soil carbon estimates of BGC-MAN were compared to those of Yasso15, which is a dynamic litter and soil carbon model for mineral soils (Järvenpää et al., 2017). It is based on a substantial number of litter decomposition and soil organic carbon measurements worldwide, and advanced statistical methods. The previous model version Yasso07 has been shown to predict the decomposition of litter correctly at the global scale (Tuomi et al., 2009). It has been applied in earth-system and global climate modelling (Goll et al., 2015; Thum et al., 2011) and national greenhouse gas reporting for UNFCCC. The model has also been applied to evaluate the climate impacts of alternative forest management practices, such as

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the removal of harvest residues for bioenergy production (Repo et al., 2015a; 2011; 2015b) and varying thinning regimes (Cao et al., 2010; Johnson et al., 2010; Pukkala, 2014).

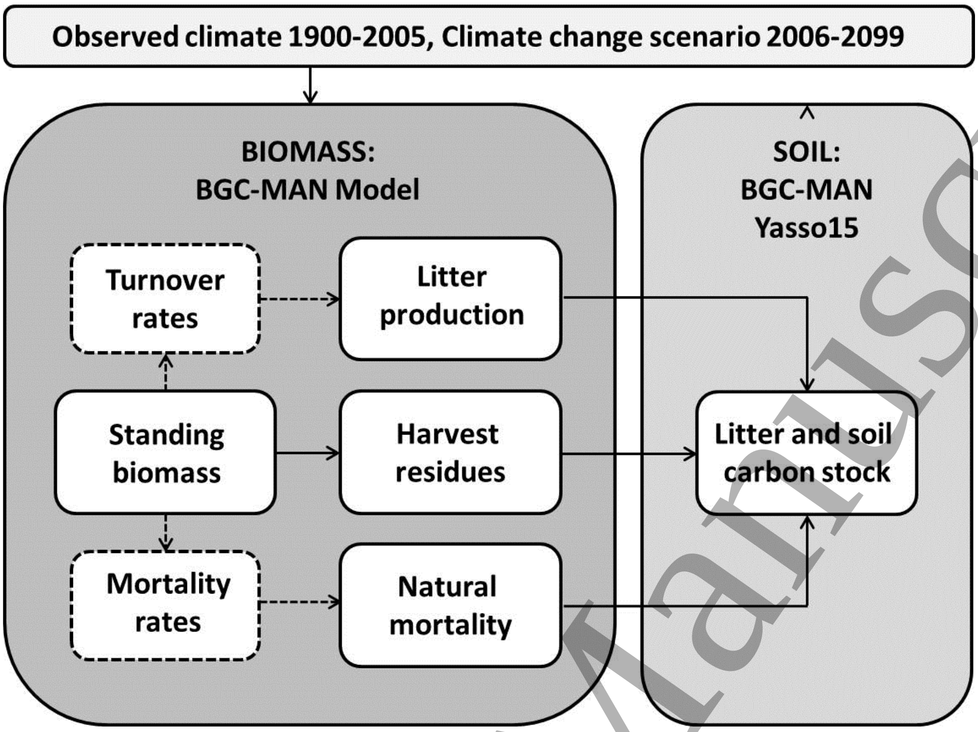

Figure 2. The calculation scheme for the estimation of carbon stocks in tree biomass, litter and soil using the BioGeoChemistry Management model BGC-MAN (Pietsch, 2014) and Yasso15 litter and soil carbon model (Järvenpää et al., 2017).

Yasso15 has five state variables representing the chemical compound groups of soil organic carbon: compounds 1) soluble in a non-polar solvent, ethanol or dichloromethane (denoted using E), 2) soluble in water (W), 3) hydrolysable in acid (A) and 3) neither soluble nor hydrolysable at all (N). The decomposition rate of these groups depends on temperature, precipitation and the diameter of woody litter (Tuomi et al., 2011) and results to formation of recalcitrant humus (H). Yasso15 operates on an annual time-step. The two models were

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coupled by running BGC-MAN first and using the litter production estimates as input to Yasso15 (Fig. 2).

2.2 Model input data

2.2.1 BGC-MAN

The model input data for the BGC-MAN simulations are shown in Table 1. The physical input data required by BGC-MAN include soil texture, effective soil depth, elevation, albedo and atmospheric deposition and biological fixation of nitrogen. Data on soil properties, i.e. the sand, silt and clay content were extracted from the European Soil Database (Hiederer, 2013a; 2013b; Panagos et al., 2012). The effective soil depth was assumed to be 1 meter at each study site because Yasso15 estimates the litter and soil carbon stock down to this depth. A constant value of albedo, 0.1, was used based on an estimate for boreal coniferous forests (Kuusinen et al., 2014). Values of the current dry and wet atmospheric deposition of nitrogen were extracted from the grid of annual averaged model results for 2010 (EMEP Status Report, 2015). The ecophysiological parameter values for Scots pine and Norway spruce were derived from a previous study (Pietsch et al., 2005).

The meteorological data required by BGC-MAN include daily minimum and maximum temperature, precipitation, vapor pressure deficit and solar radiation. Daily records of these variables were created for each study site based on interpolated observations (covering years 1951-2005) for the historical simulation period 1915-2005 and climate change scenarios for the future simulation period 2005-2095. The climate model applied in the simulations was MT-CLIM 4.3 (Thornton et al., 2000). It was run with IPCC's Representative Concentration

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Pathways (RCP) 4p5 which represents a moderate, less than 2 °C global warming by the late 21st century (van Vuuren et al., 2011). Historical climate data and the projections were provided by the Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP) (Hempel et al., 2013; Warszawski et al., 2014). Extrapolation to the specific sites was done with MT-CLIM 4.3 (Thornton and Running, 1999). Site elevation, slope and aspect required as additional input data by MT-CLIM 4.3 were extracted from Google Earth®.

2.2.2 Yasso15

The initial litter and soil carbon stock for the Yasso15 simulation was calculated from the coarse woody debris, litter and soil carbon pools of BGC-MAN. These pools were allocated to the EWANH fractions of Yasso15 as follows: For the initial litter carbon stock, fraction E of Yasso15 was assumed to equal 1/3 and fraction W 2/3 of the labile litter pool of BGC-MAN. Fraction A was assumed to equal the cellulose and fraction N the lignin pool of BGC-MAN. For the initial soil carbon stock, fraction E of Yasso15 was assumed to equal 1/3 and fraction W 2/3 of the combined fast and medium soil carbon pools of BGC-MAN. Fraction A was assumed to equal the slow soil carbon pool, and fractions N and H each 1/2 of the recalcitrant soil carbon pool of BGC-MAN.

The litter input to Yasso15 consisted of the litter production of living trees, harvest residues and natural mortality derived from the annual output of BGC-MAN (Fig.2). The biomass estimates of foliage, fine roots and coarse woody debris were multiplied with the litter turnover and mortality rates specified in the species-specific ecophysiological parameters of BGC-MAN (Pietsch et al., 2005). A diameter of 2 cm was used for coarse roots and 15 cm for coarse woody debris (branches, stem residues and stumps) in this study. The annual

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estimates of the litter carbon pools of BGC-MAN were converted to the EWANH fractions of Yasso15 as described above.

Table 1. Physical and meteorological input data used in the BGC-MAN and Yasso15 model simulations. Sites 1-5 represent simulated Scots pine and sites 6-10 simulated Norway spruce stands across the study area.

Site characteristics	1	2	3	4	5	6	7	8	9	10
Country	FIN	FIN	RUS	BLR	UKR	FIN	FIN	RUS	BLR	UKR
Tree species	Pine	Pine	Pine	Pine	Pine	Spruce	Spruce	Spruce	Spruce	Spruce
Stand age in 2005	90	90	90	90	90	90	90	90	90	90
Latitude (°)	66.3	61.2	58.7	54.0	50.3	66.3	61.2	59.4	54.2	48.3
Longitude (°)	29.4	25.1	29.0	26.5	30.1	29.4	25.1	29.5	29.0	24.2
Elevation (m a.s.l.)	219	130	65	160	160	210	130	130	160	1280
Slope (%)	3.5	3.0	1.0	1.0	5.0	3.5	3.0	0.0	2.5	42.0
Aspect	SE	NW	-	-	W	SE	NW	-	-	N
Sand (%)	41	85	37	37	23	41	85	76	35	42
Silt (%)	29	10	46	46	50	29	10	16	54	38
Clay (%)	30	5	17	17	27	30	5	8	11	20
Soil depth (m)	1	1	1	1	1	1	1	1	1	1
T_{max} (°C)	3.3	7.6	8.5	10.5	12.4	3.3	7.6	8.0	10.2	8.8
T_{min} (°C)	-5.4	-0.3	0.7	2.4	4.4	-5.4	-0.3	0.7	2.2	-0.4
T_{mean} (°C)	-1.1	3.7	4.6	6.4	8.4	-1.1	3.7	4.3	6.2	4.2
T amplitude (°C)	15.2	13.7	14.0	13.4	13.7	15.2	13.7	14.1	13.8	12.1
Prcp (mm $year^{-1}$)	619	648	714	675	659	619	648	655	718	812
VPD (Pa)	296	369	401	528	530	296	369	371	463	232
Srad (W m^{-2} s^{-1})	157	173	182	214	230	157	173	176	211	436
Ndep (g m^{-2} $year^{-1}$)	0.1	0.4	0.5	1.1	0.7	0.1	0.4	0.4	0.9	0.6
Nfix (g m^{-2} $year^{-1}$)	0.1	0.05	0.1	0.1	0.1	0.1	0.05	0.1	0.1	0.2

FIN denotes Finland, RUS Russia, BLR Belarus and UKR Ukraine. T_{min} and T_{max} are the average daily minimum and maximum temperature, T_{mean} the average annual temperature, Prcp the annual precipitation sum, VPD the vapor pressure deficit, Srad the solar radiation, Ndep the deposition of nitrogen in 2010 and Nfix the average fixation of nitrogen. T amplitude, required as input by Yasso15, is the difference between the average temperatures of the warmest and the coldest month.

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2.3 Simulation procedure

2.3.1 Self initialization

The initial values of the carbon and nitrogen pools of soil and vegetation were determined by running the model to a steady state with constant model input data and the available climate records from 1951-2005. The model steady state is defined as the long-term equilibrium of soil organic matter (Thornton et al., 2002). All spin-up simulations were conducted using pre-industrial carbon dioxide concentrations and nitrogen deposition levels (0.1 g m^{-2} $year^{-1}$). A linear mortality pattern was applied for pine and a dynamic mortality pattern for spruce, respectively (Pietsch and Hasenauer, 2006). The spin-up times varied between 4 800 and 40 800 years depending on the site.

2.3.2 Management history

The result of the spin up run represents equilibrium without any human interference. It was therefore corrected for possible degradation of soil nutrient status due to forest management. All ten forest stands were assumed to have been established in the early 19th century in 1815 by clear-cutting and planting and developed for hundred years until the early 20th century, to 1915, which was the starting point of the historical simulation period. Clear-cutting was simulated by removing all above-ground woody biomass and assigning the foliage, fine and coarse roots to the litter and coarse-woody debris pools.

2.3.3 Current stands

During the historical simulation period 1915-2005, the forest stands were assumed to develop according to standard, even-aged forest management with planting, regular thinning and

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clear-cutting. Appendix 1 summarizes the initial values of the BGC-MAN carbon and nitrogen pools of litter and soil at the time of planting the stands in 1915. The stands were thinned twice during the rotation period and clear-cut at the age of 90 years. The stands were renewed by planting in the beginning of the year 2005. The rotation length was in line with country-specific regulations and recommendations (e.g. CMU, 2007; MPR RF, 2017; Tapio, 2006). Thinning and clear-cutting were simulated by cutting 30% and 100% of the above-ground stem biomass, respectively. The fraction of merchantable timber (70% for pine and 85% for spruce as in Pietsch et al. (2005)) was removed and the remaining harvest residue was assigned to the coarse woody debris pool. Foliage, fine and coarse roots were reduced with the same proportion and assigned to the litter and coarse-woody debris pools.

During the future simulation period 2005-2095, different harvest scenarios were applied. They were conventional stem-only harvest (SOH) with long rotation length, stem-only harvest with shortened rotation length, whole-tree harvest (WTH) with long rotation length, and whole-tree harvest with shortened rotation length. In SOH and normal rotation length scenario, the forest stands were harvested similarly to the historical simulation period. In the WTH scenarios, all above-ground harvest residues including the foliage were removed. In both SOH and WTH scenarios with shortened rotation length, the rotation length was 45 years.

2.4 Model evaluation

To test the validity of the modelling framework, the simulated stem volume in the historical simulation period 1915-2005 was compared with measurement-based estimates representing

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average forest stands in the study area. The measurement-based estimates were derived from empirical growth and yield tables of Scots pine and Norway spruce stands (Koivisto, 1959; Shvidenko et al., 2008). The simulated estimates of stem carbon stock were converted to merchantable timber volume to make them comparable with the measurement-based estimates derived from the growth and yield tables. The fractions of merchantable timber, carbon in dry matter, dry matter in fresh weight and timber density values applied by Pietsch et al. (2005) for pine and spruce were used. To evaluate the robustness of the modelling framework regarding the prediction of the litter and soil carbon stock, an inter-model comparison was performed. The output of BGC-MAN was compared with that of Yasso15 for each study site for the historical and future simulation periods.

The uncertainty caused by inter-annual weather variation was quantified by making Monte Carlo simulations for each site. The starting point of the weather records was let to vary randomly between 1815 and 2005. This period included the simulated management history of 100 years and the historical simulation period 1915-2005. Hundred model runs were conducted for each site. A standard deviation of the mean over the rotation period was used as a measure of uncertainty.

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3 Results

3.1 Model evaluation across the study area

Stand volume increased across the latitudinal gradient studied (Fig. 3). The simulated mean stand volume was 85-254 m^3 ha^{-1} over the simulation period 1915-2005 depending on the study site. The simulated estimates were generally higher than the measurement-based estimates derived from the growth and yield tables; the mean difference was 14%, the range being 2-26%. The discrepancies were the largest during the late phases of stand development (Fig. 3). The litter and soil carbon stock did not show a clear trend across the latitudinal gradient studied (Fig. 4). It was 3.9-9.8 kg m^{-2} depending on the study site. The northernmost pine stand (site 1) and the high-altitude spruce stand (site 10) had distinctively high estimates. The Yasso15 litter and soil carbon model produced generally lower estimates than BGC-MAN. The mean difference between the two model outputs over the simulation period was 8%, the range being 3-16% (Appendix 2). The largest discrepancy between the two models was found in the northernmost pine stand (site 1). Based on the Monte Carlo simulations, inter-annual climate variability caused little variation to the simulated estimates.

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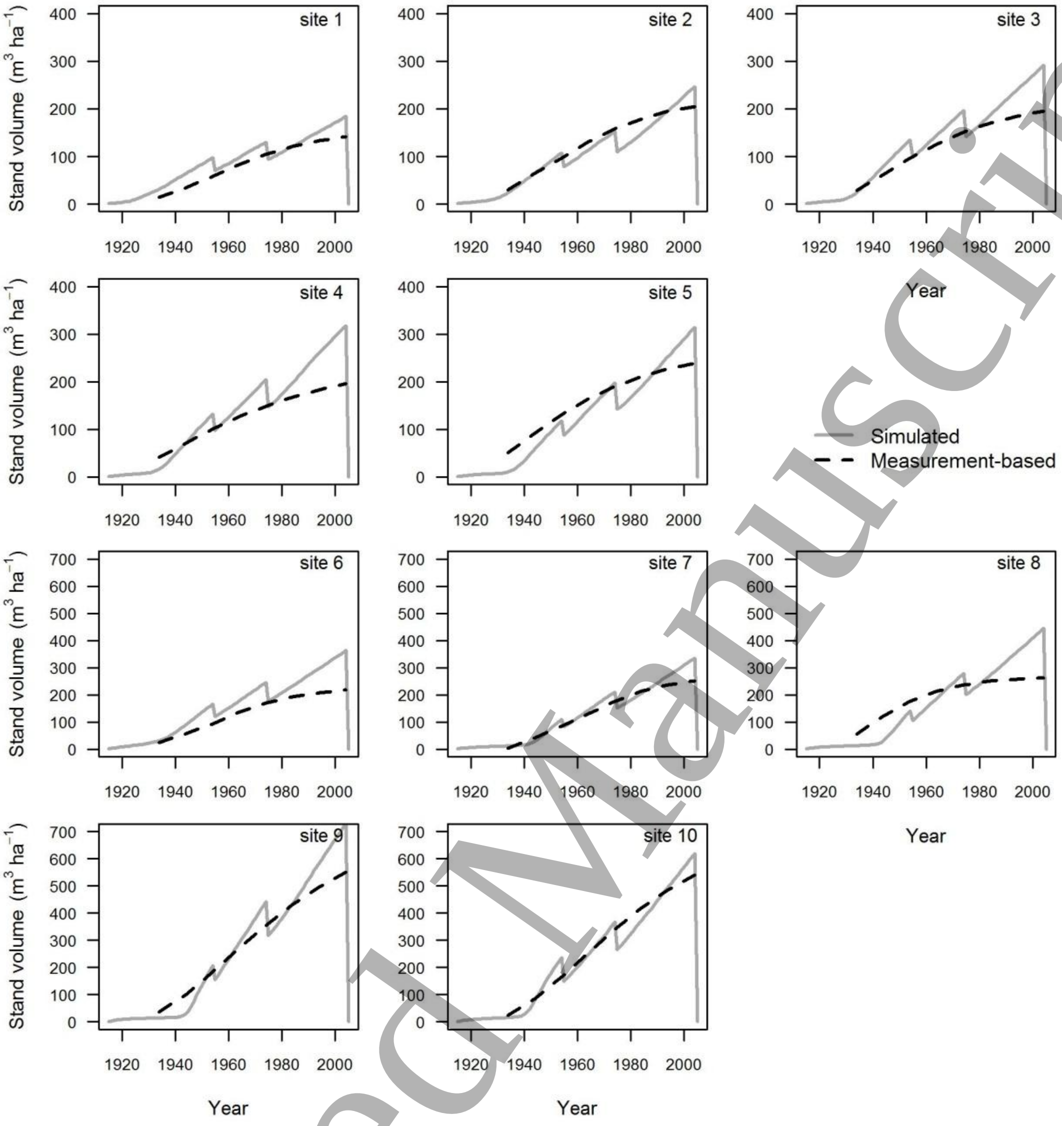

Figure 3. The simulated (denoted with solid line) and measurement-based stand volume (dashed line) (m3 ha-1) in the study sites over the historical simulation period 1915-2005. The descents of simulated stand volume result from thinning in 1955 and 1975, and a clear-cut in 2005. Sites 1-5 represent Scots pine and sites 6-10 Norway spruce stands in a latitudinal gradient from north to south.

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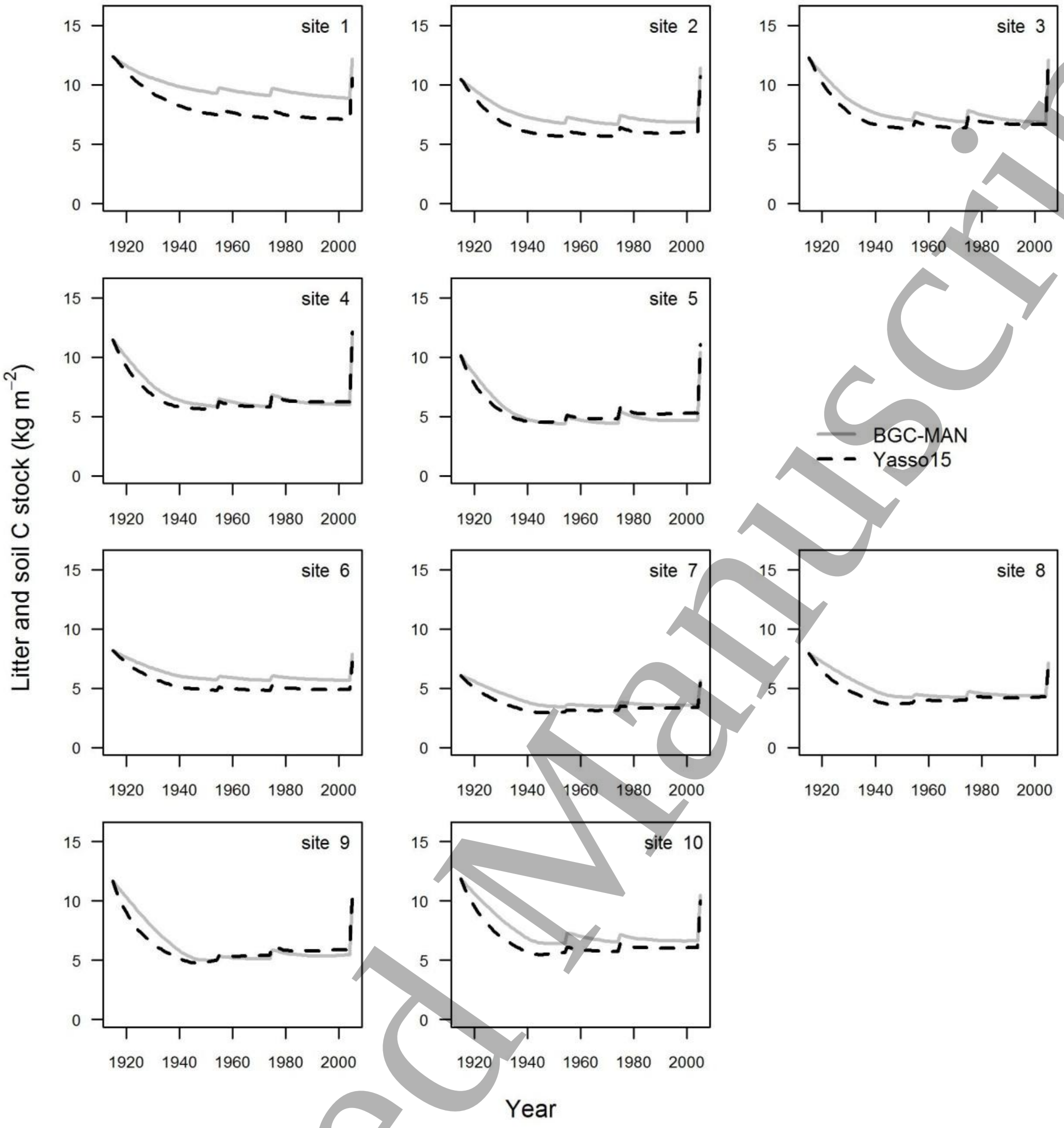

Figure 4. The BGC-MAN (denoted with solid line) and Yasso15 (dashed line) output of the litter and soil carbon stock (kg C m-2) in the study sites over the historical simulation period 1915-2005 across the latitudinal gradient studied. The ascents of the litter and soil carbon stock result from thinning in 1955 and 1975, and a clear-cut in 2005. Sites 1-5 represent Scots pine and sites 6-10 Norway spruce stands.

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3.2 Climate change and forest management impacts

With the climate change scenario, the biomass carbon stock increased in each site during 2005-2095 compared with the historical simulation period 1915-2005 (Fig. 5a, b; Appendix 2). At a stand age of 90 before final felling, the simulated estimates of the biomass carbon stock were 18-62% higher than in the end of the historical rotation period. With SOH and a normal rotation length, the mean biomass carbon stock over the simulation period 2005-2095 was 5.4-11.0 kg m^{-2} depending on the study site. WTH further enhanced the accumulation of the biomass carbon stock by 14-40%. Stand net primary productivity had a similar pattern (Appendix 3 a, b). The increase was the largest during the first decades of stand development (Fig. 5a, b). The shortened rotation length decreased the biomass carbon stock by 24-39% compared with the normal rotation length. WTH partly compensated the effect of the shortened rotation length (Appendix 2).

The responses of the litter and soil carbon stock to changing climate were less clear than those of the biomass carbon stock (Fig. 5b, c; Appendix 2). At a stand age of 90, the simulated estimates of the litter and soil carbon stock were 9-29% higher compared with the end of the historical rotation period. In the northernmost pine and spruce stands (sites 1 and 6), the difference was only 0 and 2%, respectively. With SOH and a normal rotation length, the mean litter and soil carbon stock was 4.1-9.3 kg m^{-2} over the simulation period 2005-2095 depending on the study site. WTH decreased it by 7-13% and the shortened rotation length boosted the effect. The response of the litter and soil carbon stock to the WTH scenario was very similar independent of the model used (Appendix 2).

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The litter and soil nitrogen stock increased during 2005-2095 compared with the historical simulation period 1915-2005 in 8 study sites out of 10 (Fig. 5c, d; Appendix 2). In those sites, the simulated estimates of the litter and soil nitrogen stock were 3-23% higher at a stand age of 90 compared with the end of the historical rotation period. The increase was the largest in the southernmost sites. In sites 1 and 6, the litter and soil nitrogen stock decreased by -5 and -3%, respectively. With SOH and a normal rotation length, the mean litter and soil nitrogen stock was 0.31-0.76 kg m^{-2} over the simulation period 2005-2095 depending on the study site. WTH decreased it by 3-6% whereas the shortened rotation length had no effect (Appendix 2). The loss of nitrogen through leaching and trace-gas volatilization was very small compared with the nitrogen loss through harvests (Appendix 4 a, b). SOH increased the microbial uptake of nitrogen temporarily, associated with a decrease of the plant uptake (Appendix 4 c, d).

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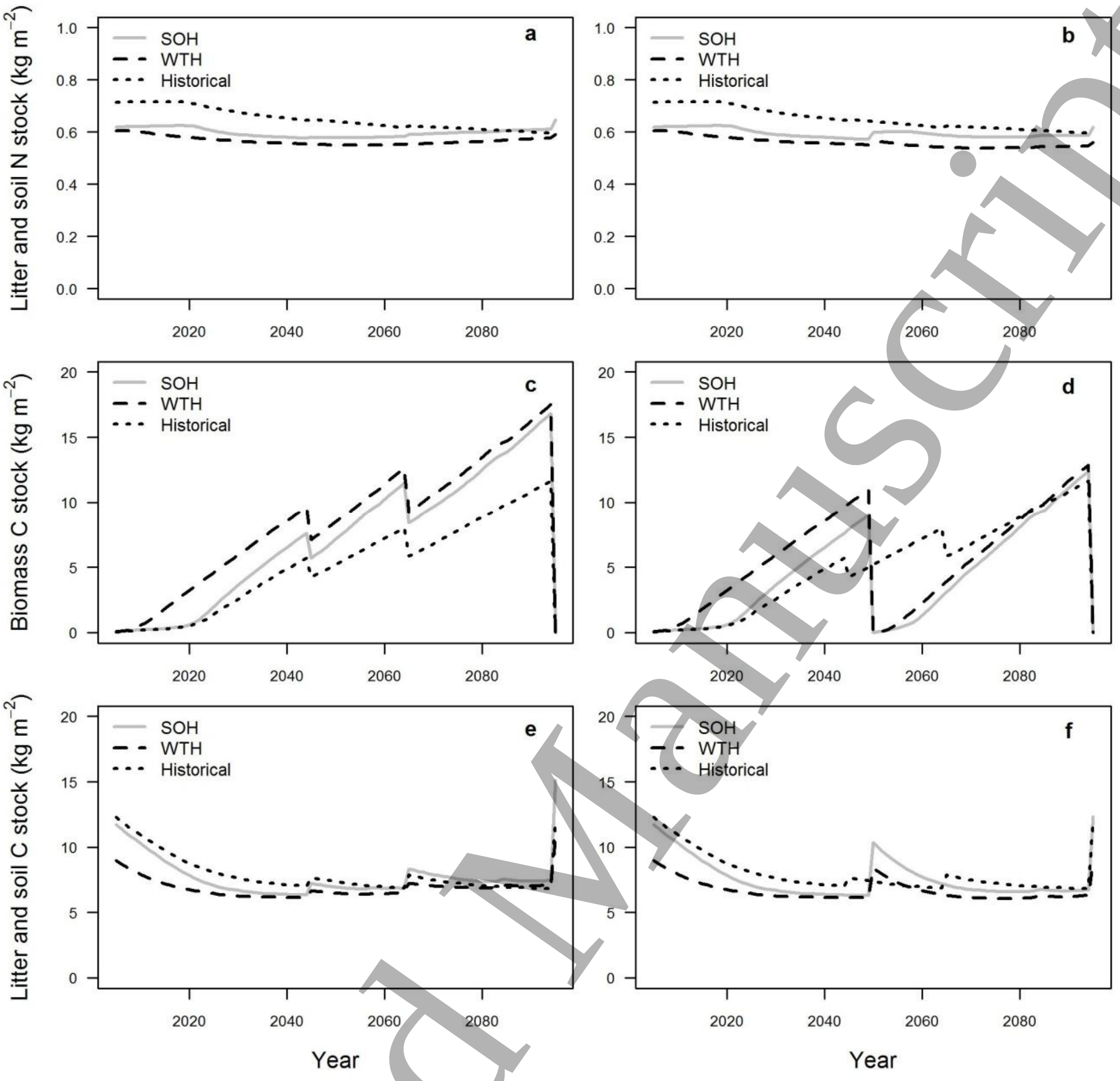

Figure 5. The simulated litter and soil N stock (a, b), biomass C stock (c, d) and litter and soil C stock (e, f) in site 3 in 2006-2095 with different harvest systems and the climate change scenario RCP4p5. SOH stands for stem-only harvest and WTH for whole-tree harvest. Simulations with the normal rotation length (90 years) are shown on the left and those with the shortened rotation length (45 years) on the right hand side.

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4 Discussion

4.1 Climate change impacts

The results of this study suggest that forest growth will be enhanced as climate change continues, throughout the environmental gradient studied. Therefore the conditions for wood production will likely improve, creating opportunities for wood industries in the study area. Several studies have predicted that the growth of Scots pine and Norway spruce will increase by climate change due to improved climatic conditions and accelerated nutrient cycling, particularly in the boreal and temperate regions where a water stress is not expected (Hlasny et al., 2011; Lindner et al., 2010). The risk for severe drought periods is, however, projected to increase especially in the southernmost areas of the distribution of these tree species, out of the study area (Babst et al., 2013; Shvidenko et al., 2017; Zang et al., 2014), adding uncertainty to the predictions. Increased drought may also increase the risk of fires and insect outbreaks as these stands get more stressed. Based on the simulations, the water availability was sufficient across the study region with the climate change scenario applied.

The impacts of climate change on the litter and soil carbon stock are more difficult to estimate. Its changes depend on the litter input, affected by stand productivity, and on the decomposition rate, regulated by litter quality and climatic conditions. According to this study, the litter and soil carbon stock increased in most of the sites because of increased litter production due to enhanced stand growth. In some sites, accelerated decomposition offset this effect leading to litter and soil carbon loss compared with the historical simulation period (see Appendix 4 for the respiration estimates). This is supported by other studies that report a decline in the soil carbon stock as a result of climate change (Karhu et al., 2010; Mäkipää et

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al., 2014). The total below- and aboveground carbon stock increased by 24-76% in 2005-2095 depending on the study site indicating a positive feedback of climate change on the forest carbon sink. Also the litter and soil nitrogen stock increased in most of the sites during the future simulation period 2005-2095 as a result of increased litter production.

4.2 Forest management impacts

The stand net primary production and biomass carbon stock increased as a result of WTH in spite of increased nutrient extraction from the site compared with SOH. This may relate to the nonlinear feedbacks in the partitioning of nutrients among decomposers and plants (Kuzyakov and Xu, 2013). In BGC-MAN, soil microbes take up more mineral nitrogen than trees immediately after harvesting which slowed down tree growth temporarily after SOH. The higher amount of feed left for decomposers in SOH increases their biomass resulting in higher microbial nitrogen immobilization. The high C/N ratio of the coarse woody debris left in the forest changes the overall C/N ratio of the feed of decomposers, providing another explanation for reduced nitrogen availability for the re-growing trees. A recent study showed that regeneration was the lowest in the sites with the highest wind damage impact in terms of seedling numbers, indicating that large amounts of coarse woody debris may hinder forest regeneration (Dobrowolska, 2015).

WTH caused lower microbial immobilization of mineral nitrogen together with higher plant uptake than SOH because of smaller input of dead organic matter to the soil (see Appendix 4). Merganicova et al. (2005) noticed that the effect lasted for 8-10 years after thinning. According to our results, the growth enhancement related to WTH was even stronger and

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more long-lasting after the final felling which calls for improvement in the description of nitrogen cycle in the model. Merganicova et al. (2005) suggested adding processes such as nitrogen leaching from the litter, and mycorrhizal symbiosis between tree roots and fungi to the model structure. However, more site- and species-specific experimental data on the nitrogen cycle is needed to perform these model adaptations correctly.

Decline of stand productivity and biomass carbon stock after WTH has been observed previously in studies applying different process-based models in boreal conditions (Mäkipää et al., 2014; Palosuo et al., 2008). Based on experimental studies, WTH causes nutrient losses compared with SOH, associated with reductions in site productivity. Based on a comprehensive meta-analysis of experimental studies covering boreal and temperate regions worldwide, tree growth was reduced by 3-7 % up to about 30 years after WTH (Achat et al., 2015). Also several Nordic experiments indicate that short- and medium-term growth reductions occur after thinning on both Norway spruce and Scots pine sites, and moderate reductions on Norway spruce sites after final felling (Egnell, 2017). The positive feedback of WTH to stand productivity found in this study is thus highly uncertain and requires further research on the microbial controls of post-harvest stand growth. Intensified thinning regime through shorter rotation length caused a decrease in the biomass carbon stock because of more frequent interventions in the forest ecosystems functioning, which is consistent with the patterns found in other modelling studies (Zanchi et al., 2014).

The litter and soil carbon stock decreased after WTH compared with SOH in each site because harvest residues were extracted for bioenergy production. Final felling caused greater litter and soil carbon loss than thinning due to a higher level of harvest residue removal. The

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carbon loss was the largest right after harvests and declined when the forest stands grew older. This was because also the harvest residues left on site in the SOH started to decompose. These findings were consistent with a previous study applying the predecessor of BGC-MAN in temperate forests (Merganicova et al., 2005) as well as other studies applying different process-based models in boreal forests (Mäkipää et al., 2014; Ortiz et al., 2014). According to experimental studies, the litter and soil carbon stock after WTH decreases 5-15% compared with SOH (Johnson and Curtis, 2001; Kaarakka et al., 2014). The estimate found in this study, 7-13%, is very similar to this variation.

According to the model simulations, the total above- and belowground carbon stock of forest ecosystems was 5-27% higher with WTH than with SOH over the simulation period 2006-2095, indicating that WTH would be beneficial for the carbon sequestration of forest. It is, however, noteworthy that the growth enhancing effect of WTH was very sensitive to the harvested stand volume depending on the rotation length. The combination of WTH and shortened rotation length produced namely a remarkably lower total carbon stock than SOH. With this scenario, the total carbon stock of forest was 19-50% lower than with SOH because the litter and soil carbon loss exceeded the carbon gain of biomass in 2050 (see Fig. 5d). The enhanced stand growth due to climate change was not sufficient to fully compensate these litter and soil carbon stock reductions. The result warrants that very intensive harvests exacerbate climate warming, similarly to previous studies (Harmon et al., 1990; Liski et al., 2001).

4.3 Evaluation of the modelling framework

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The reliability of the modelling framework is an important prerequisite for applying it for scenario analysis across various environmental conditions. Biome-BGC 4.2, the predecessor of BGC-MAN, has been previously applied in boreal and temperate conditions to estimate the effects of forest management and climate change on carbon cycling and productivity (Gautam et al., 2010; Merganicova et al., 2005; Petritsch et al., 2007). The unbiased and consistent simulation results in these studies support the use of BGC-MAN in the current study. The Monte Carlo simulations revealed that climate anomalies had little impact on the simulated estimates (Appendix 2).

The measurement-based estimates of stand volume were derived from growth and yield tables that represent typical, intensively managed Scots pine and Norway spruce stands across the study region. These tables were regionally validated using field measurement data, which recently were presented in the database containing about 11000 sample plots (Schepaschenko et al., 2017). The growth curves in the growth and yield tables are smooth because they have been compiled based on a large collection of forest stands of the same age class. The simulated volume curves, on the other hand, show discrete thinning responses because they represent single stands. The simulated estimates in the historical simulation period 1915-2005 were generally in line with the measurement-based estimates supporting the validity of the modelling framework.

There are rather numerous measurements of the litter and soil carbon stock of East European temperate and boreal forests. They are presented in the form of typical soil profiles and take into account soil types, bioclimatic zones, dominant species etc. The simulated estimates of the litter and soil carbon stock were satisfactory in comparison with measurement-based

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estimates from the study region (Lesiv et al., 2018; Schepaschenko et al., 2013). Both models likely overestimated the litter and soil carbon stock for the northern boreal pine stand (site 1). Yasso15 predicted very similar estimates than measured in Finland in an extensive soil monitoring project Biosoil while the estimates of BGC-MAN were somewhat overestimated (Lehtonen et al., 2016).

To assess the robustness of the predicted litter and soil carbon stocks the outputs of BGC-MAN and Yasso15 were compared. The two models produced very similar responses of the litter and soil carbon stock to forest management interventions and climate change, indicating a reliable representation of the litter and soil carbon cycle in the changing environment. According to previous studies, the previous version of the model, Yasso07, is suitable for predicting the effects of climate change (Goll et al., 2015; Thum et al., 2011; Tuomi et al., 2009), forest management (Ortiz et al., 2014; Sievänen et al., 2014) and the use of forest residue bioenergy (Repo et al., 2015a; 2011) on the litter and soil carbon stocks, which is supported by the current study.

The estimates of Yasso15 were, though, somewhat lower than those of BGC-MAN. The discrepancies between the two models may be related to differences in the temperature sensitivity of the soil organic carbon pools. Also the conversion of the litter and soil carbon pools of BGC-MAN to those of Yasso15 includes uncertainties, particularly about the composition of coarse woody debris. An example of the differences in model structure is that the size of woody litter controls its decomposition in Yasso15 (Tuomi et al., 2011) while BGC-MAN has a constant decomposition rate for coarse woody debris (Pietsch et al., 2005). Using species and site-specific size distributions of coarse woody debris in the Yasso15

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model simulations instead of constant values would improve the accuracy of the model predictions (Liski et al., 2013). On the other hand, lack of nutrient dynamics has been seen as a reason for underestimated litter and soil carbon stocks in Yasso07 (Ťupek et al., 2016).

Evidently, the demand and economic value of harvested timber depend also on its size and quality. However, the management regime used in this modelling exercise reflects a strategy aiming to provide the maximal productivity of industrial wood (commercial thinning at 30 and final felling at 90 years). According to forest management manuals, 90 years for pine and spruce is the age of technical maturity for timber of diameter at 24-28 cm. The short rotation harvest maximizes stem volumes and is mostly oriented for use of forest biomass for energy production.

5 Conclusions

The changes in carbon stocks and productivity as a result of management intensification were investigated across a long latitudinal gradient in Eastern Europe. The attractiveness of whole-tree harvest and shortened rotation length is likely going to increase to meet the increasing wood demand for energy and material purposes. According to the simulation results, whole-tree harvest caused litter and soil carbon losses especially when combined with shortened rotation periods. Contrary to some earlier studies, some of the simulation results indicated that WTH may have a positive impact on forest productivity in the long-term. Forest management dominated over the impacts of climate change in the short time perspective, indicating its crucial role in maintaining the carbon sequestration capacity of boreal and temperate forests. The modelling framework presented in this study accounts for the biogeochemical cycles in forest ecosystems under changing climate. In summary this study

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revealed that the microbial controls of post-harvest on stand productivity require further research.

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