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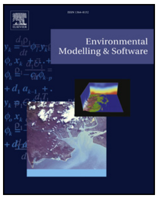

A climate-sensitive forest model for assessing impacts of forest management in Europe

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ABSTRACT

FORMIT-M is a widely applicable, open-access, simple and flexible, climate-sensitive forest management simulator requiring only standard forest inventory data as input. It combines a process-based carbon balance approach with a strong inventory-based empirical component. The model has been linked to the global forest sector model EFI-GTM to secure consistency between timber cutting and demand, although prescribed harvest scenarios can also be used. Here we introduce the structure of the model and demonstrate its use with example simulations until the end of the 21st century in Europe, comparing different management scenarios in different regions under climate change. The model was consistent with country-level statistics of growing stock volumes (R^2 = 0.938) and its projections of climate impact on growth agreed with other studies. The management changes had a greater impact on growing stocks, harvest potential and carbon balance than projected climate change, at least in the absence of increased disturbance rates.

1. Introduction

Europe is aiming at a transition to a low-carbon economy by 2050, in order to mitigate climate change by reducing carbon emissions from fuel consumption and industrial production chains (European Parliament and Council, 2013). Replacing fossil-based products by renewable sources, for instance energy from coal and gas with bioenergy, has been suggested as a key component of this strategy (Lundmark et al., 2014; Williamson, 2016). For example in Finland, the governmental climate and energy strategy aims to increase the annual cutting level from the current, about 66 million $m^3\ yr^{-1}$ to 80 million $m^3\ yr^{-1}$ by 2030, simultaneously increasing the usage of harvest residues for biofuel from 8 million $m^3\ yr^{-1}$ to 14–18 million $m^3\ yr^{-1}$ (Ministry of Agriculture and Forestry, 2015). On the other hand, increasing cuttings have raised concerns about biodiversity and carbon sequestration capacity of forests, and it has been proposed that increasing the carbon

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Software availability

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Year first available 2018
Hardware required PC
Software required R (https://www.r-project.org)
Program language R
Program size 2 MB
The FORMIT-M program code and input data will be made freely available through Mendeley Data at https://doi.org/10.17632/344n6ts3tg.1

storage in ecosystems would lead to more effective climate change mitigation than increasing the use of forest biomass (Holtsmark, 2012; Vanhala et al., 2013). These alternatives are largely mutually exclusive at least within a confined region, and depending on how storage and harvesting will be combined at the local, regional and national scale, forest management may need to be adjusted.

Analysing the implications of such alternative strategies requires a forest model that is responsive to both management actions and climate change, returning as output the time development of ecosystem carbon stocks and fluxes but also the main forest product assortments. The impacts of climate change on forest ecosystems has usually been described with process-based, physiological models (Thornton et al., 2002; Jin et al., 2016), whereas management impacts and economically relevant model outputs have mainly been produced with tree- or stand-based empirical models (Huber et al., 2013; Thurnher et al., 2017). While the physiological models provide good plot-scale predictions in the short term, their larger-scale application is often restricted by intensive input and parametrisation requirements and changes in stand composition not incorporated in the models (Pietsch et al., 2005; Jin et al., 2016). The empirical models, on the other hand, often do not include an appropriate representation of climate change impacts. So-called hybrid ecosystem models propose to overcome these problems by merging empirical functions with simplified descriptions of physiological processes, leading to physiologically driven, empirically constrained forest ecosystem models (Seidl et al., 2005; Mäkelä et al., 2016). A recent study showed that hybrid models outperformed complex physiological models when applied at regional spatial and decadal temporal scale, suggesting that at this scale, forest composition and structure may be more influential than physiological detail (Jin et al., 2016).

In large-scale continental or global models key challenges involve accurate scaling of the model outputs and representation of the large spatial variability, yet keeping the calculations feasible both as regards computation time and input requirements (Seidl et al., 2013). Perhaps the most common method of spatial up-scaling is to do the calculations in grid cells of specified size, homogenising inputs and outputs within each cell (pixel). This approach provides a wall-to-wall description of model outputs but may require a huge computational effort as the ideal

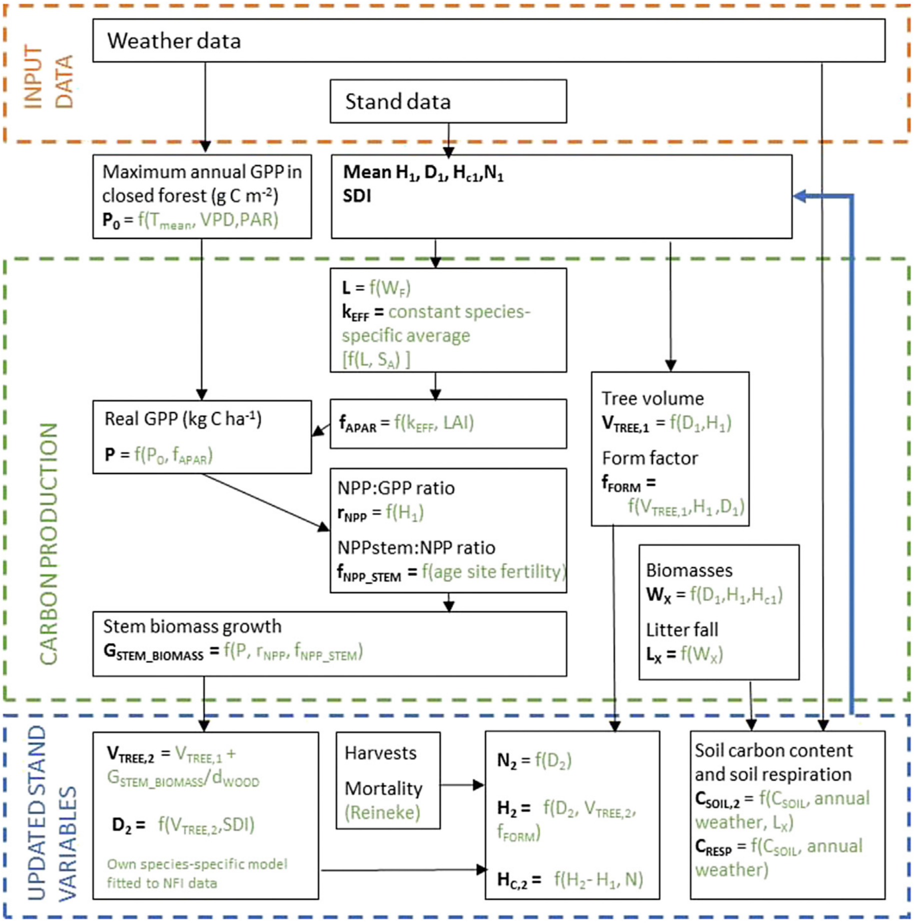

Fig. 1. Structure of FORMIT-M.

grid cell size should be based on internally homogeneous pixels with regard to input and output variables. Some models consider potential forest structure as a response to long-term climatic patterns, leading to relatively large pixel size determined by mean climatic variability. Examples of this are landscape level succession models (e.g. Seidl et al., 2012, Huang et al., 2017) and dynamic global vegetation models (e.g. Cramer et al., 2001; Friend et al., 2014; Naudts et al., 2015).

To model effects of forest management realistically, it is important that the forward predictions are initialised on the basis of the measured state of forests. Model outputs must be informative about the distribution of product assortments. Because the spatial variability of species, age and soil type is, in general, high, large-scale inventory and projection in forestry is usually not based on gridded, wall-to-wall mapping but systematic sampling is used by most national forest inventories (NFI). The samples are used as representations of frequencies of measured variables in larger regions such as countries or provinces rather than spatially explicit maps. Most large-scale modelling methods utilising NFI data are based on direct manipulation of country-level distributions on the basis of empirical relationships (Schelhaas et al., 2007; Sirkiä, 2012; Mubareka et al., 2014; Schelhaas et al., 2015). However, the NFI network could also provide a good basis for driving stand-level models (Wang et al., 2014). Initialising the simulations by NFI sample plot data, the aggregated country-scale results would be representative of the sampling network, provided that the model is reliable.

Here we report the development of a new hybrid model that utilises NFI data from 10 European countries in order to reflect the actual forest resources and forest growth, and combines these with a process-based, meta model approach to climate impacts on net primary production (NPP) and stemwood growth (Valentine and Mäkelä, 2005; Härkönen et al., 2010). The model was developed in the EU FP7 project “FORest management strategies to enhance the MITigation potential of European forests” (2012–2016) (FORMIT). This new forest growth model “FORMIT-M“ produces estimates of carbon storage and fluxes at the forest site (above and below ground), as well as wood production available for harvests as roundwood accounting for forest product assortments and forest biomass, under selected climate scenarios. The simulation results can be used as inputs for life cycle analysis, economic analysis and finally, overall scenario analysis.

The objective of this paper is to (1) describe the model structure, parametrisation and testing, (2) demonstrate its applicability in three case studies in different parts of Europe, and (3) consider some initial overall results related to the impacts of management under climate change in Europe. The case studies focus on different relevant forest management questions including harvest intensities, rotation lengths and species selection. The analysis of results focuses on wood production and ecosystem carbon content.

2. Methods and materials

2.1. The model

2.1.1. Overview of model structure

The growth model is defined in terms of stand mean-tree variables and stand density, which together define stand level variables such as stem volume and component biomass. The actual state variables of the model comprise mean height (H, m), mean breast height diameter (D, cm), stand density (N) and depending on the region, mean height to the crown base (H_C, m). Empirical functions are applied on these to derive auxiliary variables, including mean tree volume (V_{TREE}, m^3) and form factor (f_{FORM}), component biomasses (W_x, kg), litterfall (L_x, kg yr^{-1}), and leaf area index (L) (Fig. 1).

The rate variables driving the dynamics in the growth model are derived from estimated Gross Primary Production (GPP) and its allocation to Net Primary Production (NPP) and further to stem growth. GPP is calculated using a semi-empirical, Light-Use Efficiency (LUE) based canopy level model (Mäkelä et al., 2008; Peltoniemi et al., 2015, Minunno et al., 2016), which uses daily weather data and LAI as inputs. An empirical model was derived using this GPP and NFI-based NPP (Neumann et al., 2016a, 2016b) for estimating the NPP:GPP ratio for different species and regions. Similarly, an empirical function for the ratio of stem growth to NPP was derived for species and European regions (Fig. 1, Table 1).

Stand level stemwood volume growth is obtained from the volume increment based on GPP and corresponding NPP allocation. This is divided by stand density to estimate mean tree growth, and empirically derived allometric functions are used to compute new values of H, D and H_c from new volume and stand density. The latter is updated on the basis of harvests and mortality, where mortality is assumed to occur if stand density exceeds the maximum density modelled according to Reineke's stand density index (SDI) (Reineke, 1933) (Fig. 1). The mean-tree approach was chosen to simplify the regional calculations, acknowledging that it may make the description of management systems with non-uniform structures more challenging.

Soil carbon dynamics are estimated using the Yasso07 model (Tuomi et al., 2009, 2011). Yasso07 takes tree litter fall and stand mean temperature and rainfall as input to estimate the development of soil carbon stocks. The initial soil carbon is estimated assuming the system is at steady state with respect to current litter input (Fig. 1).

2.1.2. Climate and site effects

FORMIT-M calculates annual GPP using PRELES (Mäkelä et al., 2008; Peltoniemi et al., 2015), a semi-empirical model of daily GPP designed for boreal and temperate coniferous forests but also parameterised for a Mediterranean *Pinus pinaster* stand (Mäkelä et al., 2008). The model uses the LUE approach, where the potential GPP is calculated as a function of Photosynthetically Active Radiation (PAR), which is subsequently modified by multiplicative factors depending on temperature, precipitation and vapour pressure deficit. Mathematically, PRELES is a multiplicative model of 4 driver functions:

$$P = \sum_k p_k = \sum_k \beta f_{APAR} \Phi_k f_L(\Phi_k) f_S(S_k) f_D(D_k) f_W(W_k) \tag{1}$$

where P is annual canopy GPP (g C m^{-2} yr^{-1}), p_k is canopy GPP on day k (g C m^{-2} d^{-1}), β is potential daily LUE (g C mol^{-1}), f_{APAR} is proportion of absorbed PAR (photosynthetically active radiation), Φ_k is PAR (mol m^{-2} d^{-1}), $f_L(\Phi_k)$ describes the saturation of GPP at high PAR, S_k is the state of acclimation to temperature, D_k is vapour pressure

Table 1

Country groups for estimation of FORMIT-M parameters. Countries with NFI data are written in italics. The species groups (SP) indicate the species groups (see Table 2) applicable to the European region.

European region	Countries	Species groups
Northern Europe	Denmark, *Estonia*, *Finland*, Latvia, Lithuania, *Norway*, *Sweden*	SP1, SP2, SP4
Central-West	*Austria*, Belgium, *France*, *Germany*, Ireland, Liechtenstein, Netherlands, Switzerland, UK, Andorra, Monaco	SP1, SP2, SP4, SP5, SP6
Central-East	*Czech R.,* Hungary, *Poland*, Romania, Slovakia	SP1, SP2, SP5, SP6
South-West	*Italy*, Portugal, *Spain*, San Marino, Vatican	SP1, SP2, SP3, SP4, SP5, SP6
South-East	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Greece, Malta, Montenegro, Serbia, Slovenia, The former Yugoslav Republic of Macedonia	SP1, SP2, SP3, SP4, SP5, SP6

deficit and W_k is the relative soil water availability. Another equation of PRELES calculates soil water balance and components of evapotransipiration, using daily rainfall as an additional input variable. The model has been previously parameterised using flux tower data for boreal and temperate coniferous sites (Mäkelä et al., 2008), and results from a recent study suggest that the parameters are largely independent of site at least within a selected vegetation type (Minunno et al., 2016).

On the basis of previous studies, PRELES can be regarded as comparatively reliable for predictions of GPP under stable atmospheric CO_2. Recently, CO_2 impacts have also been included in the model (Kalliokoski et al., 2018). However, in FORMIT-M we chose not to include an explicit CO_2 impact in our predictions under climate change. Although the direct CO_2 effect on potential GPP is comparable with the climate effect, there is mounting evidence that this effect is down-regulated due to other limiting factors (Comins and McMurtrie, 1993; Hyvönen et al., 2007, Smith et al., 2016). For example, in many FACE (Free Air Carbon Enrichment) experiments no long-term growth enhancement has been observed probably because of nutrient limitation (Norby and Zak, 2011; Reich and Hobbie, 2013). However, the postulated interaction between elevated CO_2 and stomatal conductance may be of significance at least at dry sites where it may counteract drought effects (Ainsworth and Rogers, 2007; Kalliokoski et al., 2018). As a result, our projections for the future climate are conservative rather than over-estimated, and remain to be evaluated critically from this perspective.

FORMIT-M computes forest growth on the basis of GPP and its allocation, first to respiration and NPP, then from NPP to stem volume growth. It is known from many studies that allocation of NPP to stem growth decreases with reducing site quality, while below-ground allocation increases at the same time (Litton et al., 2007; Valentine and Mäkelä, 2012). In order to provide site-dependent growth projections we therefore require information about site quality.

Site quality classifications differ between countries and are often not independent of forest growth measurements. In some countries, site quality assessment is based on indicator species of ground vegetation, and for example in Finland, this kind of site quality class is recorded at all NFI plots. Most commonly, site quality assessment is based on site index, which is derived assuming that dominant height growth is stable for a site type and thus determined as the height of dominant trees at a reference age (Skovsgaard and Vanclay, 2008). Site quality information is generally not available in NFI data, however.

In order to take the effects of site quality into account in carbon allocation, we devised a semi-empirical method of site quality assessment for those sites where site quality was not provided in the data. It is based on the well-established empirical observation that height growth within a confined geographical region reflects site quality. However, because our model potentially covers a wide geographical area, we also account for the impact of potential photosynthetic productivity on potential height growth. We defined a model for height growth as a function of site quality and photosynthetic productivity as follows:

$$H(a) = C(S_C)a^x P_0^z \tag{2}$$

where $H(a)$ is mean height (m) at age a (yr), $C(S_C)$ is a coefficient dependent on site quality, S_C, P_0 is potential annual GPP determined using Eqn (1) as GPP of a canopy absorbing all incoming PAR and without any water stress, and x and z are empirical parameters. We use this model to determine the mean height as a function of age and photosynthetic production, then classify sites into three site quality classes representing the mean as well as lower or higher quality compared to the mean (see section 2.1.3). The details of this model are provided in the Supplementary Information.

2.1.3. Model equations

The fraction of photosynthetically active radiation (**f_{APAR}**), which is actually absorbed by the forest depends on the forest structure approaching **f_{APAR}** $= 1$ with a fully closed canopy. In FORMIT-M the f_{APAR} is estimated based on **leaf area index** and an **effective extinction coefficient** as:

$$f_{APAR} = 1 - \exp\left(-\sum_i k_{eff,i} L_i\right) \tag{3}$$

where L_i denotes (all-sided) leaf area index of species i and $k_{eff,i}$ is effective extinction coefficient. L_i is calculated based on stand foliage biomass ($W_{F\ STAND,i}$, kg) and specific leaf area ($S_{LA,i}$ $m^2\ kg^{-1}$ DW) for the species as

$$L_i = W_{F\ STAND,i} S_{LA,i} \times 10^{-4} \tag{4}$$

Constant species-specific values for $k_{eff,i}$ were used, which were estimated for each species from tree-level structural data following Duursma and Mäkelä (2007):

$$k_{eff} = \frac{\varphi S_A}{L_A}\left(1 - e^{-(k_H L_A/\varphi S_A)}\right) \tag{5}$$

where S_A, (m^2) is crown surface area, L_A, (m^2) is leaf area and φ is an empirical parameter.

The actual stand-level GPP (P, kg C ha-1 year-1) is calculated as:

$$P = P_0 f_{APAR} \times 10 \tag{6}$$

where P_0 is potential canopy GPP, calculated from Eqn (1) with $f_{APAR} = 1$.

The ratio of net primary production (NPP) to GPP ($R_{NPP:GPP}$) is estimated as a function of mean stand height (m) (Mäkelä and Valentine, 2001; Härkönen et al., 2010):

$$R_{NPP:GPP} = f(H) \tag{7}$$

The fraction of NPP allocated to stem is estimated as function of stand age a and site quality class S_C:

$$f_{NPP\_STEM} = f(a, S_C) \tag{8}$$

Stand-level annual stem biomass growth (kg DW ha-1) can be expressed as:

$$G_{STEM\_BIOMASS} = 2PR_{NPP:GPP} f_{NPP\_STEM} \tag{9}$$

with 50% of dry weight biomass assumed to be carbon.

Biomass components (W_x, in kg DW) of the mean tree (foliage, branches, stem, bark, stump, coarse roots (≥ 2 mm)) are calculated using species-specific biomass functions (for details, see Neumann et al., 2016a):

$$W_x = f(D, H, H_C) \tag{10}$$

where x denotes the tree compartment (foliage, branches, stem, bark, coarse roots and stump). Regional biomass models may have different explanatory variables (see Chapter 2.2). Fine root (< 2 mm) biomass for mean tree (kg DW) is calculated as:

$$W_{FINE\_ROOTS} = r_{FR\_FOL} W_{FOLIAGE} \tag{11}$$

where r_{FR_FOL} depends on the tree species and site quality class. Stand-level biomasses (kg DW ha^{-1}) were obtained by multiplying the mean tree values by stand density per species (see below).

Stem volume for mean tree (m^3) is calculated using species-specific volume functions as:

$$V_{TREE,1} = f(H, D) \tag{12}$$

Stand-level stem volume ($m^3\ ha^{-1}$) in the beginning of the simulation year is calculated as:

$$V_{STAND,1} = N_1 V_{TREE,1} \tag{13}$$

Stand density index is calculated based on mean diameter and number of stems per hectare using Reineke (1933) rule as:

$$S_{DI} = N_1\left(\frac{D_1}{25}\right)^{1.605} \tag{14}$$

Stand-level stem volume after one year growth ($m^3\ ha^{-1}$) is calculated as:

$$V_{STAND,2} = V_{STAND,1} + G_{STEM\_BIOMASS}\rho_{wood}^{-1} \tag{15}$$

and **stem volume of the mean tree after one year growth ($m^3\ ha^{-1}$)** as:

$$V_{TREE,2} = \frac{V_{STAND,2}}{N_1} \tag{16}$$

where $V_{STAND,1}$ and $V_{STAND,2}$ are stand-level stem volumes ($m^3\ ha^{-1}$) in the beginning and end of the simulation year, respectively. $G_{STEM\_BIOMASS}$ is annual NPP allocated to stem growth (Eqn (9)) and ρ_{wood} is wood density (kg m^{-3}). $V_{TREE,2}$ is mean tree stem volume (m^3) in the end of the year and N_1 is the total number of trees per hectare in the beginning of the simulation year.

Stand mean diameter after one year growth (cm) is calculated using a model based on structural relationships of V, D and S_{DI} fitted with NFI data (FORMIT project's tree-level NFI data, first measuring round):

$$D_2 = f(V_{TREE,2}, S_{DI}) \tag{17}$$

where D_2 is mean tree's diameter (cm) and S_{DI} is stand density index (Eqn. (14)).

Stand mean height after one year growth (m) is calculated as:

$$H_2 = \frac{V_{TREE,2}}{f_{FORM}\,\pi\left(\frac{0.5D_2}{100}\right)^2} \tag{18}$$

where f_{FORM} is **form factor** calculated using mean height and mean diameter in the beginning of the simulation year as:

$$f_{FORM} = \frac{V_{TREE,1}}{H_1\pi\left(\frac{0.5D_1}{100}\right)^2} \tag{19}$$

Mean crown base height (m) is assumed to rise based on average spacing (or stand sparsity) of the trees in the stand, using the equations by Valentine et al. (1994) and Valentine and Mäkelä (2005) as:

$$H_{C,2} = \begin{cases} H_{C,1} + m_{CB}(H_2 - H_1), & H_1 > \beta_C X + H_{C,1} \\ H_{C,1} & H_1 \le \beta_C X + H_{C,1} \end{cases} \tag{20}$$

where m_{CB} is a parameter, β_C is the ratio of crown length to tree spacing after closure ($\beta_C = 2.0$, Valentine and Mäkelä, 2012) and $X = 100/\sqrt{N}$ denotes the average spacing of trees (m).

In case no thinnings occur in a simulation year, **the number of trees per hectare** is estimated according to Reineke (1933) rule as:

$$N_2 = \min\left\{N_1,\ e^{(a' - 1.605\ln(D_1))}\right\} \tag{21}$$

where a' is parameter.

Natural damages, e.g., caused by insects, storms or fire may lower the growth rates of stands considerably. Natural damages were included by annually assigning a prescribed share of plots as damaged, then selecting this share randomly from among all plots. We used the share of severely damaged forests as reported by forest statistics for 2010, and subsequently applied the shares predicted by Seidl et al. (2014). On the damaged plots the annual potential GPP was lowered by 50% in the first damage year, after which the full growth potential was regained linearly within 20 years.

If thinning takes place in the simulation year, **the number of trees in the end of the year** is:

$$N_2 = N_{AFTER\_THINNING} \tag{22}$$

where $N_{AFTER\_THINNING}$ is the number of trees per hectare left in the stand after thinning. Thinnings can also be expressed through basal area, as $B_A = N \times \pi \times \left(\frac{0.5D}{100}\right)^2$.

Soil carbon content is estimated using the Yasso07 soil carbon model Tuomi et al., 2009, 2011). Yasso07 estimates decomposition of non-woody (fine root and foliage) and woody litter (branches, stem, coarse roots). Modelling litterfall using turnover rates and biomass provide litterfall estimates that largely agree with observations, if regional species-specific parameters are used (Neumann et at. 2018). We used a similar approach and estimated **annual litterfall (kg DW ha^{-1})** based on published biomass turnover rates as:

$$L_x = f(W_x) \tag{23}$$

where L_x denotes the litterfall of biomass compartment x (Eqn. (10)).

The decomposition rates depend on mean annual temperature, temperature amplitude between the annual minimum and maximum of mean monthly temperatures, and annual precipitation. **Annual change in soil carbon, ΔC_S (g C $m^{-2}\ yr^{-1}$),** is estimated as:

$$\Delta C_S = C_{S,2} - C_{S,1} \tag{24}$$

where $C_{S,1}$ (g C $m^{-2}\ yr^{-1}$) is soil carbon at the beginning of the simulation year, and $C_{S,2}$ (g C $m^{-2}\ yr^{-1}$) is soil carbon at the beginning of the next simulation year. Net ecosystem exchange, **NEE (g C $m^{-2}\ yr^{-1}$),** denoted by E_{NET}, can be expressed based on net primary production ($P_N = R_{NPP:GPP} \times P$), litterfall, L_{TOT}, and annual soil carbon change, ΔC_S, as

$$E_{NET} = -(P_N - L_{TOT} + \Delta C_S) \tag{25}$$

Negative NEE indicates that the forest is a carbon sink and positive NEE indicates that it is a carbon source. Initial steady states were obtained from Yasso07 runs (Tuomi et al., 2011).

2.2. Model formulation and parameter estimation

The quantification of the model was based on regions and species groups. Due to insufficient data in the south-eastern region we combined the southern countries to one Mediterranean region. The country groups were selected to provide an approximate representation of biomes and climates: boreal (northern), temperate continental (east-

Table 2
Species groups in FORMIT-M.

Species group	Code	Species
Light demanding conifers	SP 1	*Pinus sylvestris, Larix* spp., *Pinus nigra, Pinus cembra, Pinus heldreichii, Pinus leucodermis, Pinus radiata, Pinus uncinata, Pinus mugo, Pinus contorta, Pinus strobus, Cedrus* spp., *Juniperus* spp.
Shade tolerant conifers	SP 2	*Picea abies, Abies* spp., *Pseudotsuga menziesii, Thuja* spp., *Taxus baccata, Tsuga* spp., *Chamaecyparis* spp.
Mediterranean conifers	SP 3	*Pinus pinaster, Pinus halepensis, Pinus pinea, Pinus canariensis, Cupressus* spp., *Pinus brutia*
Fast growing deciduous	SP 4	*Betula* spp., *Populus* spp., *Alnus* spp., *Salix* spp., *Robinia pseudoacacia, Eucalyptus* spp.
Slow growing light demanding deciduous	SP 5	*Quercus robur, Q. petraea, Q. cerris, Q. pubescens, Q. faginea, Q. frainetto, Q. macrolepis, Q. pyrenaica, Q. rubra, Q. trojana, Q. hartwissiana, Q. vulcanica, Q. macranthera, Q. libani, Q. brantii, Q. ithaburensis, Q. pontica, Fraxinus* spp., *Castanea sativa, Rosaceae (Malus, Pyrus, Prunus, Sorbus, Crataegus, etc.), Juglans* spp., *Cercis siliquastrum*
Slow growing shade tolerant deciduous	SP 6	*Fagus* spp., *Carpinus* spp., *Tilia* spp., *Ulmus* spp., *Buxus sempervirens, Acer* spp. *Ilex aquifolium*
Mediterranean evergreen trees	SP 7	*Quercus suber, Quercus ilex, Q. coccifera, Q. lusitanica, Q. rotundifolia, Q. infectoria, Q. aucheri, Tamarix* spp. *Arbutus* spp., *Olea europea, Ceratonia siliqua, Erica* spp. *Laurus* spp., *Myrtus communis, Phillyrea* spp. *Pistacia* spp. *Rhamnus* spp. *(R. oleoides, R. alaternus), Ilex canariensis, Myrica faya,*

Table 3

Summary of FORMIT-M equations and methods of parameterisation.

RESPONSE VARIABLE	GENERAL MODEL	REGIONAL APPLICATION IN FORMIT PROJECT	EXAMPLE: FINNISH SIMULATOR	Eqn
Annual maximum GPP	LUE model (Mäkelä et al., 2008) $P_0 = f$ (T, VPD, global radiation)	Regional model parameters from Mäkelä et al., (2008)	Parameters for Hyytiälä from Mäkelä et al., (2008) are used	1
Annual real GPP	Lambert-Beer law $P = f$ (P_0, f_{APAR}, k_{EFF})	Species-specific averages of k_{EFF}	Averages of k_{EFF} estimated for Scots pine, Norway spruce and birch sites are taken from earlier study (Härkönen et al., 2010)	5
NPP:GPP ratio & NPP to stem (%)	NPP_GPP_ratio = f (stand mean H) & NPPstem% = f (site quality, stand age)	Models parameterised based on measured NPP and simulated GPP values or parameters from earlier studies	Parameterised based on PipeQual simulations (Härkönen et al., 2010)	7,8
Biomasses (foliage, stem etc)	–	Neumann et al. (2016a)	Repola (2008, 2009) biomass models: $W_i = f$ (H_{TREE}, D_{TREE}, $H_{C,TREE}$)	10,11
Stem volume	–	Neumann et al. (2016a)	Laasasenaho volume model (1982), $V_{TREE} = f$ (H_{TREE},D_{TREE})	12
Annual growth of stem volume, height and diameter	–	Own regional models fitted (NFI data) to describe relationship of mean diameter, stem volume and stand density index. The model is applied for defining new mean diameter, once the new stem volume is estimated based on annual NPP.	Fitting new model $D_2 = f$ (V_2,SDI) → $H_2 = f$ (form factor, D_2, V_2)	17
Annual crown base rise	Valentine et al. (1994), Valentine and Mäkelä (2005) $\Delta H_C = f$ (N, ΔH), species-specific parameters	Used only in Finnish biomass models		20
Stand density	Reineke's rule (Reineke, 1933, Pretzsch and Bieber, 2005) $N_2 = f$ (D_2), species-specific parameters			21
Litterfall	–	Turnover rates for biomass compartments based on literature	Annual turnover rates by Liski et al. (2005), $L_x = f$ (W_x)	23
NEE	Yasso07 model (Tuomi et al., 2009) NEE = f (NPP, litterfall, weather)	Regional parameter sets	Parameters used in Finnish Greenhouse Gas Inventory (listed e.g in Härkönen et al., 2011)	25

central), temperate maritime (west-continental) and Mediterranean. NFI data was available for a subgroup of countries in the regions (Table 1).

Silvicultural management as well as growth and carbon storage properties are largely species-specific. As the number of species is large, we reduced the number of cases to cover by grouping the species on the basis of their ecology (Table 2).

The regional functions and parameters were based on data from the countries with NFI data using the NFI data and previously published results (Table 3). The models were parameterised for species groups relevant for each country group (Table 1) using the most common representative of the species group as a basis. A more detailed description of the parameterisation is provided in Supplementary Information.

2.3. Description of forest management

2.3.1. Silvicultural systems

The description of forest management was based on seven silvicultural systems (Table 4) that were defined as management chains with values of control variables described with submodels for each combination of species, silvicultural system and country group, termed *Forest Management Unit* (FMU) (for definitions see Supplementary Information). The following control variables were defined for each FMU:

- planting density
- harvest frequency
- rotation length
- harvested yield fractions (timber, pulp, waste, retained trees and coarse woody debris).

Forest management scenarios were defined on the basis of these silvicultural systems. A *Business As Usual* (BAU) scenario was defined as reference, to represent the current management practices in the country groups. While the scenarios, by definition, determined the timing and intensity of harvests for each FMU, a fraction of these scenario-based harvests was omitted if the overall harvest level, determined by the roundwood demand, was lower than the supply based on forest growth and the applied harvest rules (see below). The rules for thinning and final cut were generally based on the mean diameter and height of the standing stock, with variation caused by site quality. Regeneration in the BAU management was done with the same species as currently occurring. The details of the rules were defined on the basis of expert opinion among the participants in the FORMIT project and are provided in the Supplementary information.

The impact of alternative forest management options on forest development and carbon stocks was analysed by defining *alternative management scenarios* where changes relative to the BAU scenario were specified. The alternative management scenarios considered here are defined separately for each case study (see Section 2.5).

2.3.2. Cutting levels

The timber cuttings were decided in three different ways, labelled respectively demand-limited, supply limited and constant harvests. In the *demand-limited* cuttings, the level of total cuttings per country for the coming years was decided using the economic equilibrium market model EFI-GTM (Kallio and Solberg, 2018; Moiseyev et al., 2014) to secure consistency between roundwood harvests and demand for each year and country, including considerations of import and export. The boundary conditions in EFI-GTM depended on the management scenario but not on the RCP scenario. The equilibrium was found by repeated iterations between FORMIT-M and the EFI-GTM, in order to obtain a situation where, for each country, the harvests and forest growing stock in EFI-GTM equalled (within satisfactorily limits) the harvests and growing stock in FORMIT-M for the respective forest management scenario analysed. In the initial iteration, FORMIT-M gave the first estimate of the harvest supply by country and assortment, based on the state of the stand and the management rules, and EFI-GTM calculated the demand of different species by country corresponding to the pre-specified global demand for forest industry products. In the next iteration, the FORMIT-M cuttings were modified to satisfy the former EFI-GTM harvest (but not exceeding the cuttings possible by the specified harvest rules, see Tables 2.1–2.4 in Supplementary Information), and the growing stock estimates from FORMIT-M were used in EFI-GTM's growing stock sub-module. Such iterations were continued until the two models were in balance. The actual harvest operations were applied to a (new) random set of plots each year, such that the annual total harvest corresponded to the demand in the country. The demand included a split between conifers and hardwood, as well as a specification of assortments (timber, pulp, biomass). The plots to be managed were selected among the plots in silvicultural systems 2–7 that were mature for cutting according to the defined harvest rules.

The second simulated cutting method, labelled *supply-limited*, was carried out by considering only the prescribed forest management so that all stands where harvested whenever the management rules allowed for it. In other words it was assumed that the prescribed harvest quantities would be supplied independent of the timber prices. In the third option, *constant* harvest levels, a prescribed harvest level was specified and followed throughout the simulation.

2.4. Simulation setup

The simulation setup of FORMIT-M was based on NFI data points. The model was initialised and simulated at all NFI points available. Initialisation was done by updating all the NFI plots from the year of

Table 4
Silvicultural systems applied in the study.

System	Definition
1. Unmanaged forests	No management
2. Continuous cover forest management	Continuous cover forest management ● Selection cuttings based on diameter
3. Even-aged forest management with shelterwood	Even-aged (2-layer) forest management ● Regeneration: natural ● Thinnings ● Shelterwood cut after certain mean diameter (or age) has been reached
4. Even-aged forest management: Uniform clear-cut system	Uniform forest management ● Regeneration: planting or natural ● Thinnings ● Clear-cut after certain mean diameter (or age) has been reached
5. Coppice	Woodland which has been regenerated from shoots formed at the stumps of the previous crop trees, root suckers, or both, i.e., by vegetative means.
6. Coppice with standards	Coppice system under low density uneven-aged high forest
7. Short rotation	Plantation forestry including exotic species.

measurement to the year 2010 by running FORMIT-M with RCP 4.5 climate data (average for 2000–2010 period, 2010 cutting levels and BAU forest management). (Note that historical climate is characterised with the same statistics in all RCPs.) The results for all scenarios were aggregated to the FMU level on the basis of country, silvicultural system and species group. All output variables were presented in these aggregated units. The individual NFI plot simulations were not used for the results as they cannot be regarded representative on their own.

The initial shares of each silvicultural system in each country were determined on the basis of a questionnaire sent to forestry professionals in each country as part of the FORMIT project (Cardellini et al., 2018). Where-ever possible, the replies were derived from forestry statistics, but as official statistics do not necessarily record the silvicultural systems and FMUs used in this study, the shares were partly based on expert opinion.

For initialising the simulation, the country-level information about the shares of silvicultural systems was disaggregated to each NFI point in the calculation using a prescribed random selection procedure, except for the unmanaged plots, which were selected based on their location (Natura 2000 map of protected areas in Europe (European Environment Agency, 2011)). However, in many areas in Europe forest management may occur in protected areas to support the aims of protection, and unmanaged forests may occur outside of protected areas. On one hand, if the mapped protected area was smaller than unmanaged area reported in the statistics, a random selection of the remaining NFI plots was excluded from all management. On the other hand, if less unmanaged area was reported than the share of mapped protected area, the shares of the rest of the silvicultural systems were scaled up accordingly. The NFI plots to represent the rest of the silvicultural systems were selected randomly from the remaining plots, such that the total shares of each silvicultural system corresponded with those reported in the statistics, yet the location of the plots does not necessarily correspond to the real locations. The NFI plots were then simulated according to the management-scenario-specific definitions for each silvicultural system.

As noted above, utilizable NFI data was only available for 11 European countries (Table 1). In order to obtain European-wide estimates, we extended the simulated results to those European countries where no NFI data was available to the project (henceforth called “non-NFI countries”), by multiplying their FMU areas by the nearest NFI-country's simulated average result in the corresponding FMU (Supplementary Information). The initial area of FMUs in each non-NFI country was obtained from a spatial analysis, where the FMU areas were calculated based on the Natura 2000 protected area map (European Environment Agency, 2011), species map and age class map produced using a k-NN algorithm (Moreno et al., 2017). The development of the age class distribution was calculated by transferring 1/20 of the age class area (age classes are defined in 20 year periods) to the next age class each year. Species and management class distributions were kept as they were initially. Further, the share of clear-cut plots in the simulations was used for determining which share of area is annually moved to the first age class in the non-NFI countries.

As described above, daily weather data was required for aggregating the annual level maximum potential gross primary production to be used as input for the model. The weather data was generated by the MPI-M-MPI-ESM-LR model version CCLM4-8-17, which was run by the “EU-consortium" (CLMcom CLM Community with contributions by BTU, DWD, ETHZ, UCD,WEGC) and provided by the knot of the German climate calculating centre (carbon.dkrz.de) (http://www.mpimet.mpg.de/en/science/models/mpi-esm/james-special-issue.html). We used three scenarios defined as RCP2.6, RCP4.5 and RCP8.5 (Representative Concentration Pathways). The climate scenarios were run for 100 years from 2000 to 2100. For scenarios with current climate we repeated the scenario data from 2006 to 2010.

The simulator is available at Mendeley Data (FORMIT-M simulator, https://doi.org/10.17632/344n6ts3tg.1).

2.5. *Case studies*

In order to demonstrate the applicability of FORMIT-M, we present three case studies where we analyse impacts of different management and climate scenarios in different regions in Europe. The case studies include (1) a comparison of the BAU scenario with an intensive bioenergy management scenario with a range of total cutting levels (demands) in the Nordic countries, (2) a comparison of the BAU scenario with a scenario to increase biodiversity with a range of total cutting levels in selected Central European countries, and (3) a comparison of climate scenarios using BAU management in selected south European countries.

2.5.1. *Increased harvests for bioenergy in the Nordic countries*

In Sweden, Finland and Norway forests cover about 2/3 of the land area, and forestry-based bioeconomy has widely been regarded as a potential means of climate change mitigation. Lundmark et al. (2014) suggested that if forest management was intensified in Sweden, a considerable additional biomass production could be obtained that could be used to substitute fossil fuels and energy-intensive materials and thus increase the contribution of forestry to climate change mitigation. However, several other Nordic country-level studies have concluded that using forests for bioenergy is not an efficient management strategy for climate change mitigation (Repo et al., 2011; Holtsmark, 2012; Kallio et al., 2013).

Here we consider the development of Nordic forests using six different forest management scenarios, where BAU management is compared with intensified management for increased bioenergy production. Both BAU and management for bioenergy are considered under three different cutting levels: current cutting level, 30% increase to the current level, and supply-limited cuttings. The bioenergy scenario is defined thus:

- 66% of the harvest residues are removed from the forest for bioenergy use
- Spruce stumps are harvested from fertile site quality classes
- No thinning takes place
- Clear cut is made in the year of the stand's maximum mean average increment (MAI) of stem, branches and coarse root biomass
- Birch or Norway spruce are planted on semi-fertile and fertile site classes (2–3) after clear cut, Scots pine on dry sites (class 1)

2.5.2. *Increased biodiversity in Central Europe*

Biodiversity and tree species selection has received a lot of attention in the recent discussions of forest management strategies in Central Europe (e.g. Kraus and Krumm, 2013). For example in Germany, only 30% of the forest area is covered by native species which is considered as a key indicator of biodiversity, if spruce in lowlands is considered as a non-native species. One of the concerns is that the non-native species may be more susceptible to climate change induced damages compared to natural vegetation (Netherer and Schopf, 2010).

Here we compare the development of forests in selected Central European countries (Germany, Austria, Poland and the Czech Republic) under BAU management and alternatively under a management strategy aimed for increasing biodiversity and conservation. A general outline of management strategies that countries have adopted to achieve these goals can be found in the criteria and indicators of sustainable forest management by FOREST EUROPE (2011). The Biodiversity and Conservation (BDC) strategy differs from BAU in the following aspects:

- 20% of the plots are left unmanaged (the plots located on protected areas + randomly selected plots)
- regeneration is done with species groups representing the “Potential natural vegetation of Europe”
- 20% of the harvested stems are left as dead wood

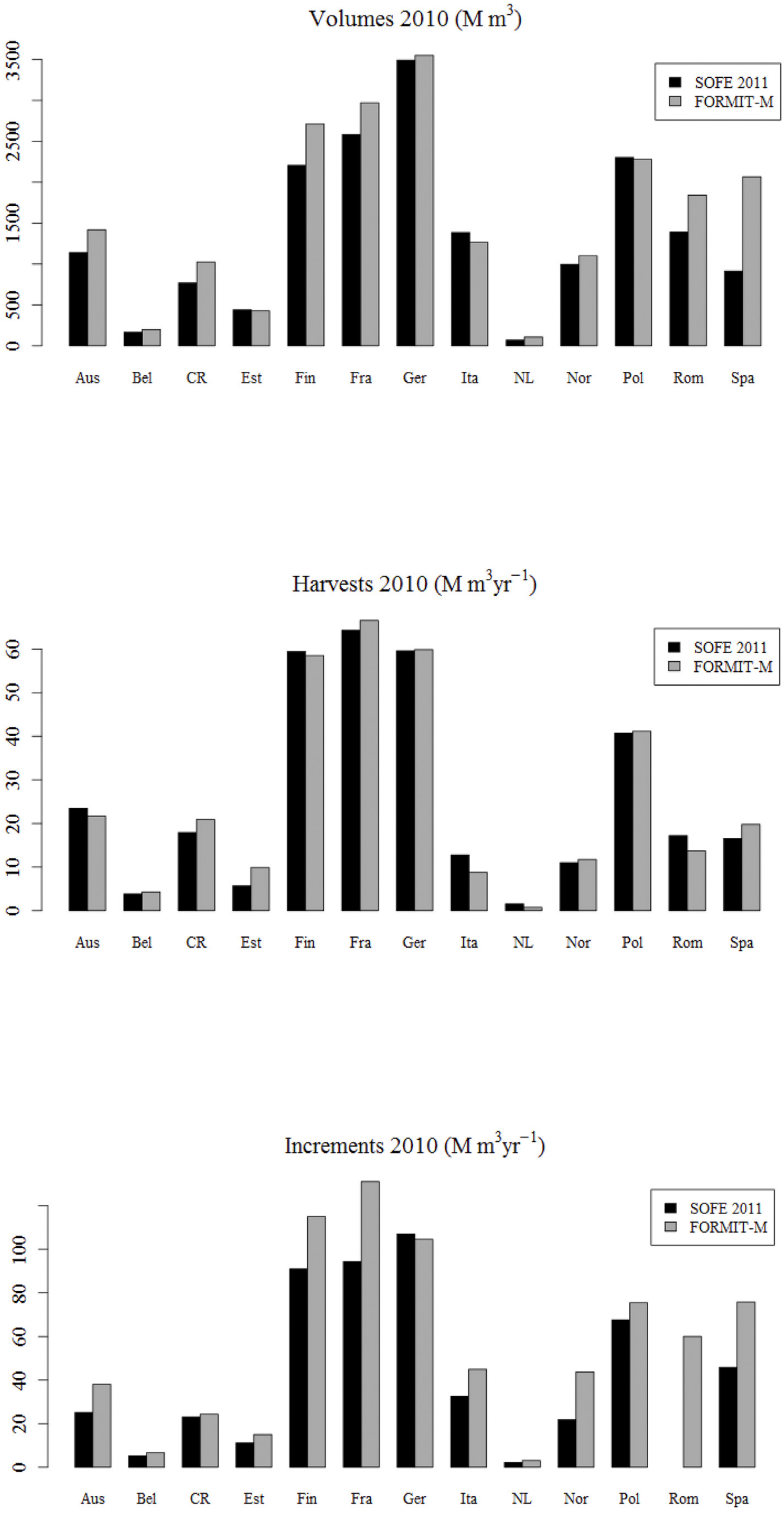

Fig. 2. Comparison of FORMIT-M outputs in 2010 with European statistics (SOFE 2011) (Forest Europe 2011). a) Volume, b) harvests, c) volume increment.

- Final cut is postponed (25% longer rotation time)
- Harvest residues are left in the forest (not used as bioenergy) [no difference to BAU]

2.5.3. Impacts of climate change in Southern Europe

Mediterranean forests are expected to be the most severely affected by climate change in Europe, as the climate is projected to become significantly dryer, especially during the summer months, and drought is already a key limiting factor to growth in southern Europe (Seppälä et al., 2009). Here, we compare the effect of the different climate scenarios (RCP2.6, RCP4.5 and RCP8.5) on the forest carbon budget in Southern Europe (Italy, Spain and Portugal) using the demand-limited BAU scenario. The combined scenarios are termed BAU26, BAU45 and BAU85.

3. Results

3.1. Comparison with data on growing stock, increment and harvests

The growing stock corresponded quite well with the estimates presented by European forest statistics for 2010 (FOREST EUROPE 2011) ($R^2 = 0.938$), with an average overestimation of 15% in all countries and 11% in the countries for which we had data available. The largest over-estimations were found in Spain and in Romania (Fig. 2a). The harvest levels coincided well with statistics, with only about 1% overestimation both in the entire data set and in the NFI data (Fig. 2b). However, volume increment was about 20% overestimated both in the entire data set and in the NFI data (Fig. 2c) compared with the respective statistics in Forest Europe 2011).

3.2. BAU in all Europe

The climate change impact in FORMIT-M operates through the maximum potential annual GPP, showing an increasing trend in northern Europe and a decreasing trend in southern Europe, except under RCP2.6 where no marked change was detected in southern Europe (Fig. 3). The average impact in BAU (i.e. under RCP 4.5) had an increasing trend with increasing latitude (Fig. 4.1 in Supplementary Information).

In the BAU scenarios with cuttings at the level predicted by the EFI-GTM model, a common trend in Europe was that growing stocks kept increasing because the demand of wood and forest biomass was predicted to be less than its supply (Table 5). This resulted in an increasing trend in both tree stand and soil carbon stocks (Fig. 4a). At the same time, the harvests increased modestly in pace with the increasing demand, but gross increment was predicted to saturate towards the end of the century (Fig. 4b). The development of the growing stocks and harvests was rather insensitive to the climate change scenario under the demand-driven management scenarios.

Table 5
Development of growing stock (Mm^3) in European countries according to BAU managemet scenario with RCP4.5 climate during 2010–2100, with a comparison with FAO statistics (Forest Europe; UNECE; Forest Europe UNECE FAO, 2011) for 2010.

Country	FAO	FORMIT-M			
	2010	2010	2040	2070	2100
Albania	75	83	180	252	317
Austria	1140	1420	1545	1664	1764
Belgium	168	199	304	355	376
Bosnia and Herzegovina	358	241	552	784	999
Bulgaria	656	1130	1616	1918	2218
Croatia	410	208	414	565	709
Czech Republic	769	1024	976	1040	1154
Denmark	113	151	224	260	258
Estonia	441	427	536	595	627
Finland	2207	2712	3614	4509	4968
France	2584	2971	5002	6319	7128
Germany	3492	3551	4018	4124	4275
Greece	185	422	992	1358	1630
Hungary	356	586	911	1220	1403
Ireland	74	199	294	331	319
Italy	1384	1264	2030	2642	3113
Latvia	633	606	1066	1289	1502
Lithuania	479	405	715	866	1011
Luxembourg	26	25	39	46	48
Montenegro	73	47	107	152	194
Netherlands	70	108	153	176	201
Norway	997	1100	1745	2323	2741
Poland	2304	2279	2903	3200	3342
Portugal	186	327	766	1129	1380
Romania	1390	1843	2904	3487	4037
Serbia	415	308	564	760	950
Slovenia	416	377	575	680	795
Slovakia	514	602	899	1075	1238
Spain	914	2066	3601	4747	5541
Sweden	3243	4195	5124	6354	7062
Switzerland	429	440	587	675	755
United Kingdom	379	763	1166	1364	1449

Despite this common trend, the simulated stocks and harvests

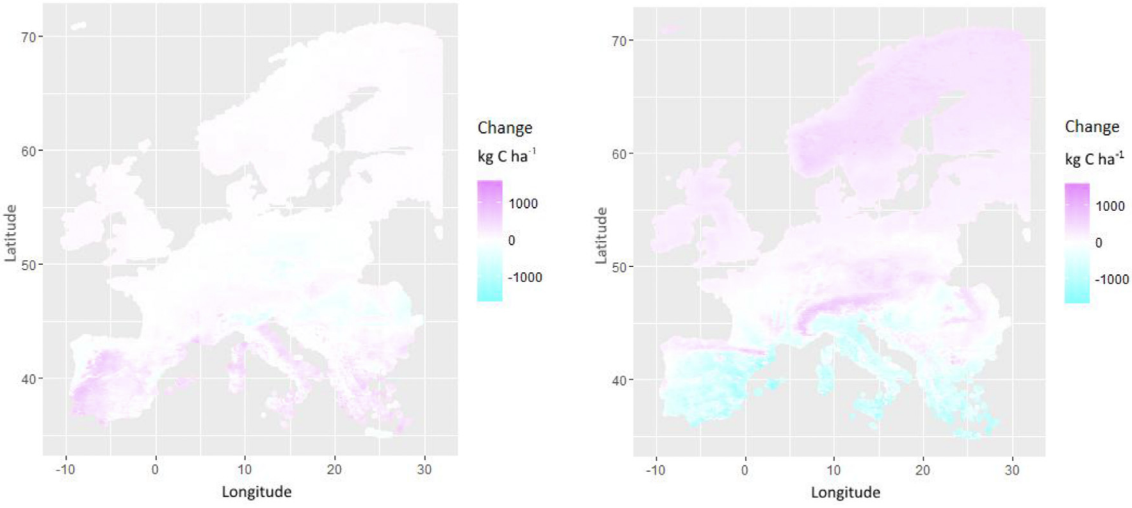

Fig. 3. Difference between annual maximum potential carbon production (calculated as P in Eqn (1) an 10 when $f_{APAR} = 1$) (kg C ha^{-1}) between 2010 and 2100 in Europe in RCP 2.6 and RCP 8.5.

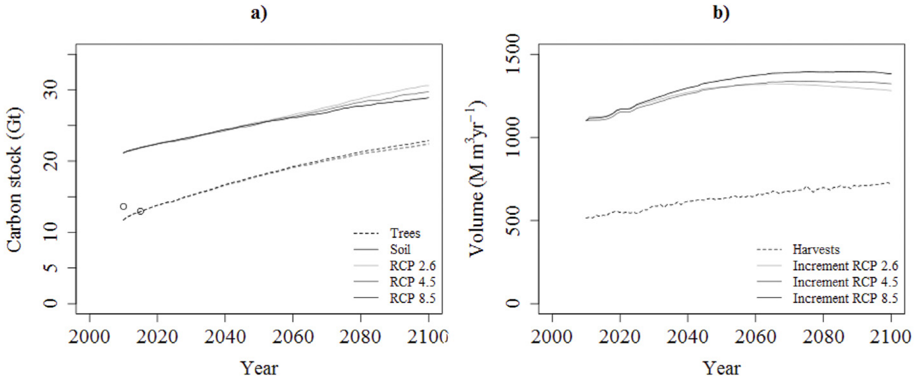

Fig. 4. a) Total forest stand and soil carbon, Europe, in BAU management with RCP2.6, RCP4.5 and RCP8.5 climate scenarios. The dots show statistics reported by FOREST EUROPE, 2015). b) Total EFI-GTM harvests and volume increment in BAU management with RCP2.6, RCP4.5 and RCP8.5.

behaved very differently in different countries, partly due to the current age structure and differences in raw material demand as predicted by the economic model (Table 5), but also due to the different species and assortment structures in different countries.

3.3. Nordic case study

The development of the growing stock volume varied among the scenarios (Fig. 5a). In the constant demand scenarios, the growing stock increased steadily during the simulation period, the increase being highest in the scenarios with the lowest (current) cutting level. In the supply-limited scenarios, there was a sudden decrease of growing stock at the beginning, reflecting the fact that a large.

Proportion of the growing stock was initially over-mature relative to the pre-specified cutting recommendations. After the initial dip, the standing growing stock started to increase again in both scenarios, reaching the initial level around 2040 in the BAU scenario but remaining lower in the bioenergy scenario.

Stemwood increment increased in all scenarios from 2010 to 2100, the pattern of increase being very similar between all the demand-limited scenarios with a slightly higher level in the bioenergy scenario compared with the respective BAU scenario (Fig. 5b). In the supply-limited BAU scenarios, there was also an increase of stem growth, but this generally remained lower and showed strong fluctuations.

The supply-limited bioenergy scenarios had the lowest average productivity, but the average growth of the supply-limited bioenergy scenario (scenario 6) periodically exceeded that of the other scenarios around 2030–2060.

The choice of forest management had a strong effect on the age distributions of stands (Fig. 6). In the demand-limited scenarios, distribution averages moved towards older forests. In the supply-limited scenarios the majority of forests at the end of the simulation period consisted of productive young or middle-aged forests.

3.4. Central European case study

The most distinct effect of the BDC45 scenario in comparison with the BAU45 scenario was that harvests were reduced by about a quarter from the beginning of the simulation, and the difference between the scenarios increased with time (Fig. 7a). The reduction of harvests caused the total increment to stabilize towards the end of the century, whereas in the BAU45 scenario the increment continued to increase. As a consequence of the reduced harvests, the age distribution shifted towards older stands in the BDC45 simulation compared with BAU45 (Fig. 4.2. in Supplementary Information). The BDC management scenario favoured regeneration with species belonging to the potential natural vegetation cover, and hence, the proportion of species groups 1 (pine and larch) and 2 (spruce) decreased and that of 5 (oak) and 6 (beech) increased towards the end of the simulation (Fig. 8).

The tree stand carbon pool increased more rapidly in the BDC45 than in the BAU45 scenario, especially towards the end of the simulation (Fig. 7b). However, the soil carbon pool slightly decreased in the BDC45 scenario (Fig. 7b). This was related (1) to a decrease in lying deadwood as a result of reduced frequency of harvests and therefore in harvest residues left to the sites (not shown) and (2) to the fact that deciduous litter was assumed to decompose faster than conifer litter. The total ecosystem carbon pool remained larger in the BDC45 than the BAU45 scenario throughout the simulation (Fig. 7b).

3.5. South-European case study

The harvests in the Mediterranean countries were predicted to almost double over the century in the BAU scenario with EFI-GTM demand (Fig. 9a), whereas the increment was predicted to increase only modestly under the RCP2.6 climate and decrease with RCP4.5 and RCP8.5. Because the increment nevertheless remained considerably above total harvests, the ecosystem carbon stock was predicted to increase both in the tree stand and soil. The accumulation of soil carbon was largest for RCP2.6 and smallest for RCP8.5 although there were hardly any differences in the tree stand carbon stock (Fig. 9b).

4. Discussion

Here we presented the structure and example results of a new semi-empirical (hybrid) climate-sensitive forest growth simulator, intended for predicting European forest development under different management and climate scenarios. The functioning of the simulator was demonstrated in three different case studies (Northern, Central Europe and Southern Europe) with region-specific management scenarios.

In addition to future socioeconomic development and political decisions, considerable uncertainty is related to climate change projections due to differences between climate models and their regional down-scaling, as well as to uncertainties about the impact mechanisms (Lang et al., 2017; Kalliokoski et al., 2018). Here, we used only one climate model (MPI-M-MPI-ESM-LR model version CCLM4-8-17), the projections of which are fairly conservative compared with many others but which, on the other hand, has been regarded as particularly applicable to Europe (Brands et al., 2013). We also treated the climate impacts on forest growth with a very simple approach, assuming that any direct CO_2 effects would be largely down-regulated by water and nutrient limitation (Hyvönen et al., 2007; Norby and Zak, 2011, Smith et al., 2016). However, despite our simple and straightforward approach, our results are consistent with the general understanding of impacts on productivity in the different vegetation zones in Europe (Seppälä et al., 2009, IPCC, 2014). The results are also in line with other forest model projections (Reyer et al. 2014; Gustafson et al., 2017). In

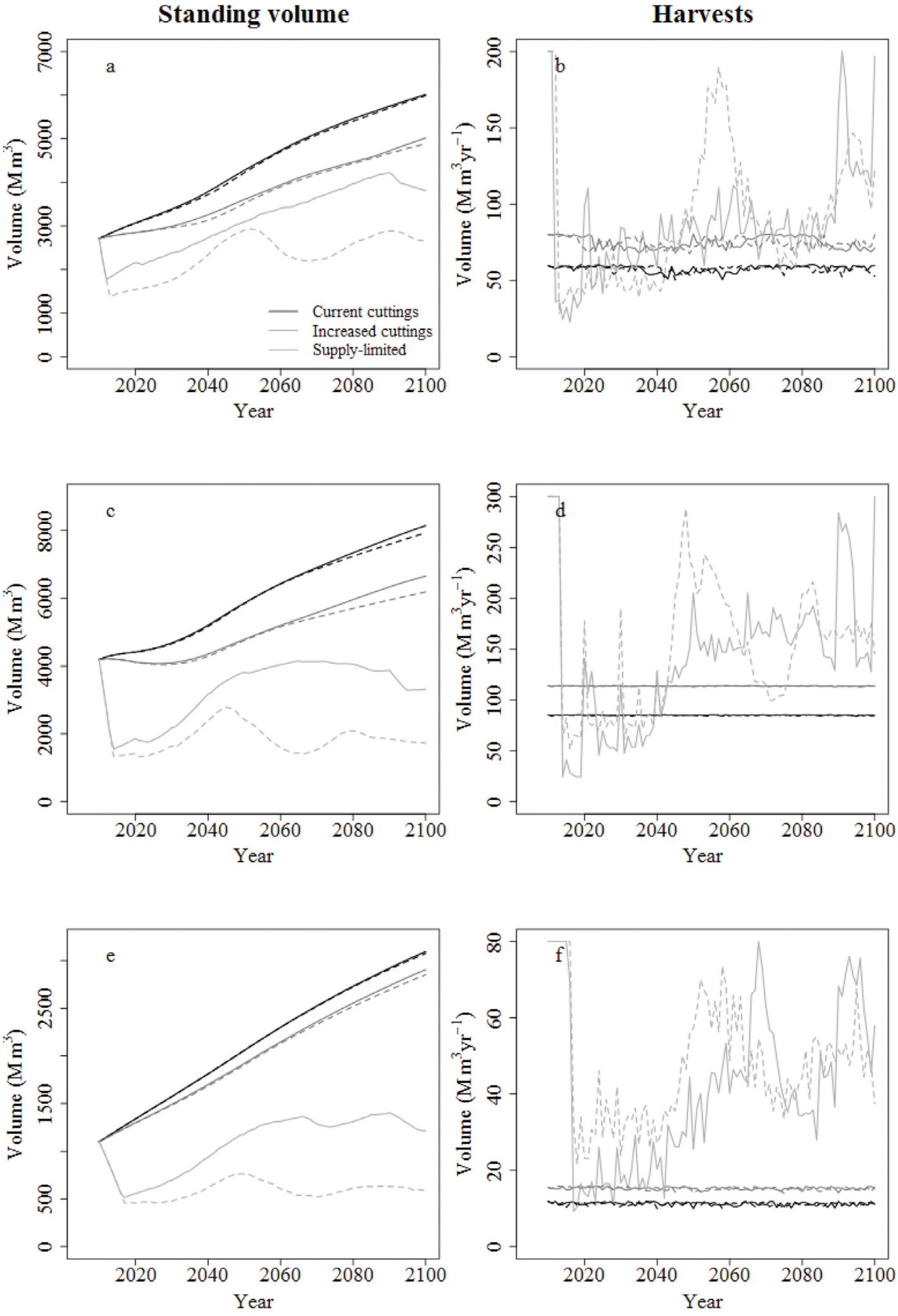

Fig. 5. Standing volume, growth and removals in Nordic countries under 3 different cutting levels (current, 30% increase and supply-limited) with RCP4.5 climate scenario. Solid lines: BAU scenarios, dashed lines: bioenergy scenarios. a & b: Finland, c & d: Sweden, e & f: Norway. The initial cutting levels in the supply-limited scenarios are outside the figure scale and one order of magnitude larger than the subsequent cuttings.

the north, productivity is expected to increase with increasing temperature as no considerable drought limitation is expected to take place. In contrast, higher temperatures are expected to be accompanied with severe drought effects in the Mediterranean countries, leading to clear reductions in productivity.

European forestry statistics are available for comparison in the early simulation years. FORMIT-M estimated the total growing stock in 2010 to be $34.0 \times 10^9\,m^3$ which was ~24% larger than the values ($27.4 \times 10^9\,m^3$) reported by FOREST EUROPE (2011). The total carbon stock in Europe in 2015 was estimated by FORMIT-M to be 12.9 Gt C in the tree stand, 21.5 Gt C in soils, 0.249 Gt C in deadwood and 0.520 Gt C in new litter. Here we should bear in mind that the model does not simulate carbon stocks in peatlands and will therefore underestimate the total C storage in soils. The vegetation pool reported by FOREST EUROPE (2015) was 12.5 Gt C/ha, which was about half of the soil pool, the other pools being considerably smaller. The litter pool was about 10-fold compared with that reported here, but here we only accounted for the most recent litter. An increasing trend in all pools was also reported by the statistics. As the simulations were started a few years earlier than 2010, the model result is a combination of initial state and simulation. However, the short simulations before 2010 were used only to produce a more consistent initial state and had little effect on the overall outcome of the model. This suggests that the NFI measurements show some difference in comparison with the statistics reported to FOREST EUROPE.

In accordance with other European (Schelhaas et al. 2015) and

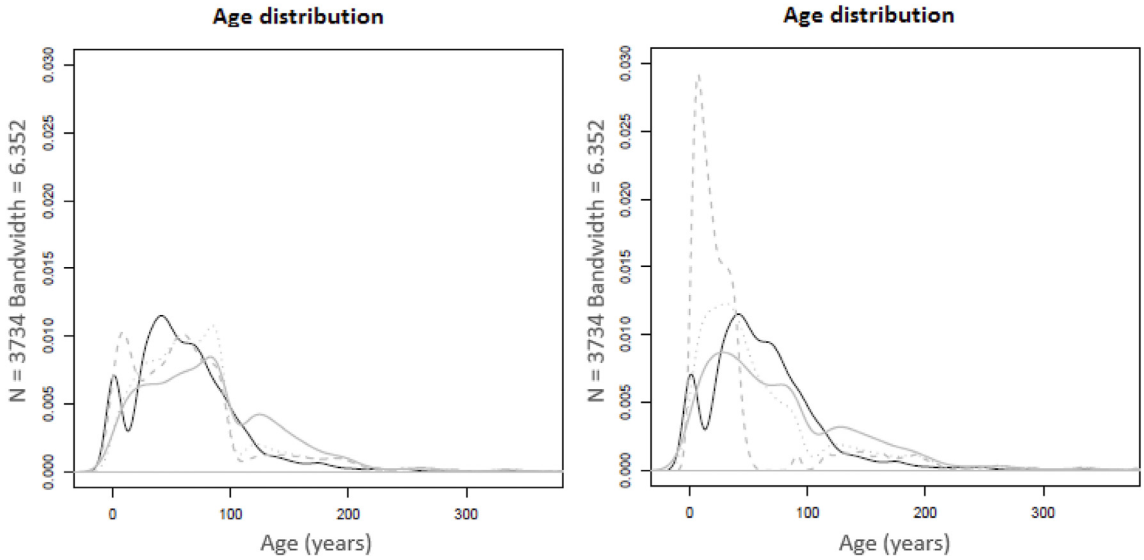

Fig. 6. Left. Age distributions in Finland. BAU with current cutting level in 2010 (black solid) and in 2100 (dotted), BAU with supply-limited cutting level in 2010 (grey solild) and in 2100 (dashed). Right: Age distributions in Finland. Bioenergy scenario with current cutting level in 2010 (black solid) and in 2100 (dotted), bioenergy scenario with supply-limited cutting level in 2010 (grey solild) and in 2100 (dashed).

country-level (e.g., Lundmark et al., 2014, Kalliokoski et al., 2018) studies, FORMIT-M projected an increase in the total growing stock and ecosystem carbon content in the BAU scenario. This is caused by harvests remaining below forest growth increment in the BAU demand scenario prescribed by EFI-GTM. The increasing potential productivity in the northern part of Europe had a minor additional impact on this trend. In the iterative simulation, keeping the cuttings at the level of the demand meant that forests were generally not harvested as intensively as could be acceptable according to forest management rules, and therefore a lot of potentially harvestable wood is accumulating in the European forests. According to good silvicultural practices (e.g. Smith et al., 1997) this situation has been considered undesirable, because postponing thinnings, particularly in young stands, reduces timber quality and increases the risk of damage due to wind and pests. Delaying final cuts increases the proportion of old stands that are considered less productive and susceptible to damage (Fig. 6).

Fig. 2c shows relatively high differences between modelled and actual forest increment in 2010. The over-estimation of increments is bigger in countries where the stocks have also been over-estimated, notably Finland, France and Spain (Fig. 2a). This could be related to discrepancies between forest areas used for scaling (likely in Finland and France), or differences between the NFI data available to us and those used by FOREST EUROPE (likely in Spain). One possible cause for over-estimation by the model could be the method used for deciding and allocating site quality classes.

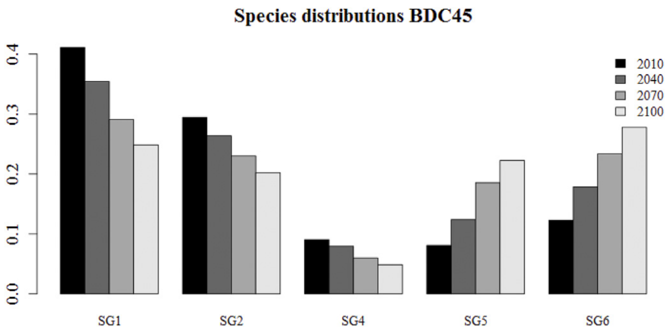

Fig. 8. Species distributions in BDC45 scenario in Central Europe. SG = species group (see Table 2).

Our scenarios of supply-limited cuttings in the Nordic case study demonstrated the largely hypothetical situation that all cuttings are done according to the assumed good management practices without delay. This gives surely an upper limit of harvests for a given set of management recommendations – the level of cuttings obviously depends on the recommended intensity of thinnings and the recommended rotation lengths. Because the initial age structure of managed forests was already influenced by delayed cuttings in the past, under the supply-limited scenarios a large proportion of forest area was immediately cut in the simulations. After that, the cuttings stabilised to

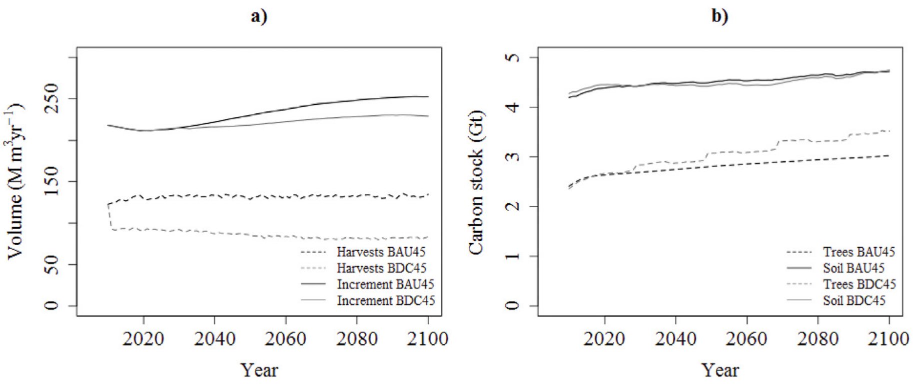

Fig. 7. Comparison of BAU45 and BDC45 scenarios in Central Europe. a) Increment and harvests, b) soil and tree stand carbon pool.

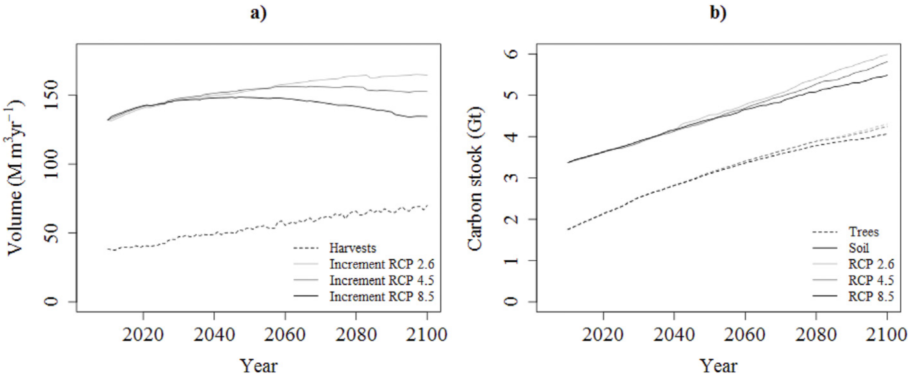

Fig. 9. Development of forests in Mediterranean countries under different climate change scenarios. a) Volume increment and harvests, b) carbon stock in trees and soil (including woody debris).

a somewhat higher level than the constant cutting scenario on average, as virtually all of the stemwood increment was harvested. However, because the initial age structure of the forests was uneven, large fluctuations occurred in the annual harvests. The supply-limited scenarios also resulted in very low and fluctuating growing stocks (Fig. 5) with a low proportion of old stands (Fig. 6).

Although the cuttings in the supply-limited scenario are clearly exaggerated, they demonstrate the fact that more cuttings lead to lower standing stocks in the forests, and that the shorter the rotation length implied by the management scenario, the lower the standing stocks. A bioenergy scenario therefore generally leads to lower stocks than, e.g., the biodiversity and conservation scenario. Because more carbon is taken out of the forest sites with harvests, the soil carbon stocks are also reduced as a result (Achat et al., 2015). A similar trend was seen in the Central European case study with the BDC scenario, although much less pronounced. In that case the differences between the carbon stocks in the BAU and BDC scenario were also influenced by the change in species from conifers towards broadleaves, influencing the retention time of carbon originating in foliage litter in the soil (Tuomi et al., 2011).

The Mediterranean case study demonstrated that volume increment would start to decline already around 2040 under the most severe climate change projection, RCP8.5, and in general that climate change would have a detrimental effect on the growth potential in the Mediterranean area (Fig. 9). This is consistent with other studies (Morales et al., 2007, Marques et al., 2018), however, we should note that our result is likely an underestimation of the effects in the Mediterranean, as no additional risks, such as increased probability of forest fire, were considered here (Seidl et al., 2014, 2017).

Here, we have demonstrated the use of the model with a number of European-wide alternative management scenarios and climate scenarios produced by one general circulation model. As also demonstrated in the case studies, the actual management questions and management alternatives may be quite different in different regions. The model provides a framework for defining country-wise management scenarios where more realistic details can be included in the management alternatives than here.

Our approach to disturbance was strongly simplified, excluding any dynamic effects. Considerable uncertainty is related to disturbances, and in general, disturbance rates are expected to increase under climate change (Seidl et al., 2014, 2017). Different disturbances act in different parts of Europe, drought events and fires being prevalent in southern Europe, wind disturbances followed by insect attacks in Central Europe and possibly an increase in storm events and insect damage occurring in the northern parts of the continent (Seidl et al., 2014). Accounting for these would likely reduce the projected growth and carbon sequestration rates.

Because FORMIT-M is operating on stand level considering only the mean characteristics of dominant species, the simulations in regions with high share of mixed forests are likely to be more uncertain than in regions where the majority of forest stands is dominated by one species. Also simulations for continuous cover forests were based on a strong simplification, and in reality the development of continuous cover forests can be a much more complex process. Further model development should therefore focus on improving the description of forest structure, which has been found to influence not only the size distribution and species relationships, but also the impacts of climate change on production (De Cáceres et al., 2015; Bohn et al., 2018).

Another important direction of model development is to make the entire growth process more clearly process-based. Currently the model considers the effect of climate to be mediated by photosynthesis, while species differences are accounted for in species-specific allocation of photosynthetic carbon to respiration and organ growth. Inclusion of more direct growth impacts of climate could improve the results particularly in drought-prone areas (Sánchez-Salguero et al., 2017). A better description of nutrient impacts is particularly important for short rotation and bioenergy management which tends to drain the natural nutrient supplies (Schulze et al., 2012). The challenge of model development for large-scale applications is to retain its simplicity in relation to required inputs and parameters, as well as its faithfulness to empirical observation of growth from NFI type data.

Because of the development needs listed above, the present simulation results are likely more realistic in the Northern part of Europe than in Central and Southern Europe. This is due to both simpler species composition and lower share of mixed stands in the north than further south, and due to the fact that drought impacts are probably not properly described. Obviously, the availability of actual NFI data is crucial for the reliability of the results, and the projections for the countries that were simulated using forestry maps and neighboring countries as proxies could be made much more reliable if real NFI data were made available.

Despite the shortcomings in the current formulation of FORMIT-M, its general structure holds a strong potential for descriptions of the future development of European forests. This is because it combines, in a modular manner, a productivity submodel making the system responsive to climate change, and a forest structure and growth module based on large-scale monitoring of actual forest resources. A crucial component of the model development for creating this link was that we had empirical estimates of NPP in different biomass components for a large number of NFI plots, which could be connected to measured tree growth on one hand, and to our process-based estimates of growth on the other hand. Secondly, the linkage of the model with the economic EFI-GTM simulator allowed us to incorporate realistic demand scenarios which influence the future growth and carbon balance dynamics. Our BAU simulations with the demand-limited harvest rates also suggest that we have been able to adequately describe the management in different countries. This basic modular setup provides a framework for future model development and a quantification of the potential amount of harvestable wood. The photosynthesis module and the soil carbon module can be independently replaced by some alternative models, and the growth equations, including site quality allocation, can be improved as more test material becomes available. Also, the integration between this model and economic modelling can be improved, for example by applying dynamic forest sector modelling like shown in Sjølie et al. (2015).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2019.02.009.

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