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HARVESTING ROUTINES WITHIN FOREST ECOSYSTEM MODELS

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Preface

This work is a cumulative dissertation consisting of three individual peer-reviewed papers. They can be found in Appendix 9.1 to 9.3. The formatting of the papers varies due to the requirements of the different journals.

Sections 1 to 7 provide a framework that demonstrates the general topic and the contribution of each paper to the overall work. The specific methodologies, results and discussions can be found in more detail in the respective papers in the Appendix.

Citations to this work should refer to: Thurnher, C., 2014. Harvesting routines within forest ecosystem models. Ph.D. thesis. University of Natural Resources and Life Sciences, Vienna, p. 84. or by reference to the individual papers.

Acknowledgements

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The forest inventory data was provided by the Austrian Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW) by Dr. Klemens Schadauer and by Dipl.-Ing. Clemens Spörk of the forest company 'Ligist, Souveräner Malteser Ritterorden' who also helped me a lot in understanding how forest management works in practice. Climate data was provided by the Austrian Central Institute for Meteorology and Geodynamics (ZAMG).

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List of Papers

Paper I

Thurnher, C., Klopf, M., Hasenauer, H., 2011. Forests in transition: a harvesting model for uneven-aged mixed species forests in Austria. Forestry 84, 517–526.

Paper II

Thurnher, C., Gerritzen, T., Maroschek, M., Lexer, M.J., Hasenauer, H. 2013. Analysing different carbon estimation methods for Austrian forests. Austrian Journal of Forest Science 130, 141–166.

Paper III

Thurnher, C., Eastaugh, C.S., Hasenauer, H. 2014. A thinning routine for large-scale biogeochemical mechanistic ecosystem models. Forest Ecology and Management 320, 56-69

Abstract

Forest management has a large impact on European forests. They have been intensively managed for centuries. In order to ensure sustainable management ecosystem models have been developed to predict future forest development. Due to the high influence of management, harvestings have to be considered within the modelling process. The aim of this study is to develop harvesting models for two theoretically different modelling concepts, (i) single-tree growth and (ii) biogeochemical (BGC) mechanistic process models. The differences of the two concepts are presented and implications for the development of the harvesting routines are explained. Automated harvesting routines based on forest inventory data are developed for mimicking the business as usual management regime. The harvesting routine for the single-tree growth modelling concept is implemented in the forest model MOSES (MOdelling Stand rESponse), whereas the harvesting approach for the BGC process model approach is a general concept that is intended to be used in large-scale BGC process modelling applications.

For the process model application, a preliminary step concerning carbon estimation had to be done. In order to be able to compare model outputs with forest inventory data, tree measurements have to be converted to carbon. Different conversion methods exist and the result of the conversion differs largely based on the underlying methodology. To understand whether the differences are a result of the model or a result of the conversion this effect has to be known because it is an important part in the process modelling application. Therefore four different carbon estimation methods commonly used in Austria have been evaluated.

This thesis presents the overall task to integrate business as usual management into two different forest ecosystem models based on distinct and very different modelling concepts. The developed harvesting routines for these modelling concepts performed well and showed the necessity in considering forest management within forest simulations.

Contents

1 Introduction

In Europe, forests comprise an area of almost 211 million hectare which corresponds to 32.2 % of the total land area (Köhl and San-Miguel-Ayanz, 2011). In Austria the share of 47.6 % representing a forest cover of 3.99 million hectare is even higher (Russ, 2011). National forest inventories were established to be able to monitor these forests (Tomppo et al., 2010). Inventories provide information about the current forest situation. To ensure sustainable forest management mechanisms for predicting future stand development are required. Different tools and models have been developed to predict forest development over time. A first approach was the construction of yield tables (e.g. Assmann and Franz, 1963; Marschall, 1975; Sterba and Griess, 1983). They are models that can predict the stand development based on the tree species, the growth region and the site index/yield class. Their application though is limited to even-aged, single species stands. In order to circumvent this limitation, sophisticated tree growth models based on different modelling concepts have been developed.

A typical example of such models is the single-tree growth model MOSES (Hasenauer, 1994) which simulates the growth of every single tree based on the competition in the stand (Hasenauer, 2006a). Growth and increment functions for tree properties like diameter at breast height (DBH), tree height and height to the live crown are parameterized on repeated tree observations and factors like climate and soil processes are not included. A typical growth model also implements algorithms for mortality and regeneration.

Gap models follow a different concept. The initial idea (Botkin et al., 1972) is that the forest is partitioned into small patches that do not interact with each other and the tree position within the patch is not considered. Growth is driven by biotic and abiotic factors (Bugmann, 2001; Lexer and Hönninger, 2001), thus factors like climate are considered in this approach. More recent gap models have incorporated neighbouring effects between patches (e.g. competition for the canopy light; Lexer and Hönninger, 2001).

The focus of process or biogeochemical mechanistic ecosystem models such as Biome-BGC (Thornton, 1998; Thornton et al., 2002) is the simulation of the processes in an ecosystem like photosynthesis, transpiration, decomposition, allocation, etc. They concentrate on simulating the cycling of matter (i.e. carbon, nitrogen, water) between different pools in the system and are driven by climate as well as site parameters.

Forests in Europe have been managed for centuries (Spiecker et al., 2004). Within the modelling process, management has to be considered since we cannot assume fully stocked stands. The possibility of integrating management into forest models relies on the underlying modelling concept. In single-tree growth models, management can be easily implemented since they directly simulate trees which can be removed during the simulation. Single-tree growth models have been developed for simulating management. Harvestings can be implemented either manually, as simple thinning algorithms (low thinning, random thinning and others; Klopf et al., 2011), rule based approaches (Kahn, 1995) or automatic harvesting routines (Fortin, 2014; Ledermann, 2002; Sterba et al., 2000). In process models like Biome-BGC, this integration is not that easy. Since these models simulate spatially homogenous pools, harvestings have to be defined on a stand level, e.g. as an intensity or proportion in relation to the overall standing timber/carbon. Within Biome-BGC, management was initially not considered because it was developed to simulate natural biomes assuming fully stocked stands. Lately, it has been adapted for European conditions (Pietsch and Hasenauer, 2006, 2002; Pietsch et al., 2005) and applied on managed European forests (Cienciala and Tatarinov, 2006; Eastaugh and Hasenauer, 2011; Merganičová et al., 2005; Tatarinov and Cienciala, 2006). Thus, the abstraction of the underlying data (forest population, carbon pools, etc.) has an impact on the possible management integration in the model. There is a difference if the model operates on a tree level like singe-tree growth models or on a stand level like process models.

Comparing the modelling concepts, single-tree growth models have been specifically developed to simulate management, whereas process models assume fully stocked stands. The focus of process models was not management but the simulation of the forest in relation to, amongst others, climate variables. Process models are an appropriate tool to simulate the impact of climate change (e.g. Eastaugh, 2012; Eastaugh et al., 2011; Pötzelsberger et al., 2012). Single-tree growth models are not intended to simulate climate change since the site conditions are kept constant during the simulation. MOSES, for example uses the site index (dominant height at the reference age of 100 years) as a proxy for the site quality (Hasenauer, 2006a). The application scope thus directly relates to the modelling concept but since European forests are usually managed, management has to be considered in both concepts.

Integrating the business as usual management (BAU) into forest ecosystem models is a crucial step and required for any future assessment which wants to understand the forest development under the current management regime. It is one of the most complicated modelling scenarios because one needs to define and/or conceptualize what is the current management. Once this is done, a comparison of such business as usual management with alternate management scenarios is possible. Business as usual scenarios require forest information to conceptualize and parameterize them. They are often based on forest inventory data. Karjalainen et al. (2003), Nuutinen et al. (2006) and Schmid et al. (2006) define the BAU management as a constant value according to the recorded removal proportion in a reference period whereas Fürstenau et al. (2006) and Seidl et al. (2008) define it as scheduled removals at a certain stand age. Eastaugh and Hasenauer (2012), Fortin (2014) and Ledermann (2002) follow a different approach. They parameterize a harvesting model based on long-term forest inventory data. In that way the BAU is modelled and not a predefined harvesting scenario which makes it possible to integrate it into the forest simulators and automatically apply it throughout the simulation. This approach is used here for incorporating the BAU management within two modelling concepts.

The scale of the modelling application has a great impact on the management implementation. Modelling on a small scale, i.e. just a couple of plots, makes it possible to manually define the harvesting regime. In this case either the management is known or simple assumptions are made that can be directly implemented in the model. This is different on large-scale applications. Data about the exact management on an enterprise or national level are often not available. With the help of repeated observations of forest inventory data (e.g. the Austrian National Forest Inventory; Gabler and Schadauer, 2008) it is possible to derive management patterns and translate them into automatic harvesting routines. With that approach it is then possible to integrate the BAU management assumptions into a harvesting routine based on the observed management from the inventory.

Logistic regression is often used in harvesting algorithms that can be applied on single-tree growth models (Fortin, 2014; Ledermann, 2002; Sterba et al., 2000). It relates the harvesting of a stand and/or the removal of a tree to site and tree properties and calculates a probability of those harvestings and removals. This kind of modelling is possible for dichotomous variables that define the management, but is also used on modelling mortality (Eid and Øyen, 2003; Eid and Tuhus, 2001; Monserud and Sterba, 1999) or regeneration (Hasenauer and Kindermann, 2006, 2002; Schweiger and Sterba, 1997).

Within biogeochemical-mechanistic models a flux approach is applied and no tree populations are used. Thus such BGC models operate on a uniform stand level approach and the thinning intensity cannot be modelled with logistic functions. However such functions can be applied to determine the probability of a stand to be thinned as described in Eastaugh and Hasenauer (2012). On a large scale, however, it is important that harvestings can be calculated automatically because a manual assessment of each single stand is no longer applicable.

For a given forest area the BAU can be derived from repeated observations of the different forest stands. However, on a large scale repeated measurements of every single tree are usually too costly. That is why sampling methods like angle count sampling (Bitterlich, 1948) are often applied. Within these methods not all trees are measured but sample trees are recorded. It is possible to derive information of the management from these inventory methods and calibrate the harvesting models even on an enterprise or national scale. In this study, inventory data from a forest company (Forstbetrieb Ligist, Souveräner Malteser Ritterorden) and the Austrian National Forest Inventory are considered. In both datasets, angle count sampling is applied.

An issue in the implementation of harvesting routines within ecosystem models is related to the general modelling concept. Single-tree growth models directly simulate trees and variables like DBH and height are available during the simulations. The same variables are usually measured in forest inventories allowing a comparison of the model output and the inventory. For BGC models, this comparison is not that easy. Process models directly simulate carbon. To compare the BGC outputs with the inventory data a conversion has to be done to put the datasets in a common unit of measure. Different methods exist that can be used to do this conversion (Brown, 2002; Hasenauer et al., 2012; Hochbichler et al., 2006; IPCC, 2003; Pietsch et al., 2005; Zianis et al., 2005). These methods should be used with caution, since the results of the conversion strongly depend on the underlying methodology and the results might differ largely.

When integrating harvesting into forest ecosystem models, several issues have to be considered: (i) the underlying modelling concept, (ii) the scale of the application, (iii) the available forest data and (iv) the applied methodology. In this study all these aspects are discussed and analysed. Two harvesting algorithms based on two different modelling concepts (single-tree growth and process model) are developed.

2 Objectives and outline of the study

The aim of this study is to develop harvesting routines that can be used within two different ecosystem modelling concepts; (i) single-tree growth models and (ii) biogeochemical process models. The goal is to mimic the management regime that was applied in the past, the so-called the business as usual (BAU) management, and conceptualize this according to the needs and constraints of the two modelling approaches. The BAU management is derived from forest inventory data.

For the first modelling concept, single-tree growth modelling, the model MOSES (MOdelling Stand r*ES*ponse) was selected. The harvesting algorithm was developed based on forest inventory data from a forest company that is currently transitioning from an even-aged to an uneven-aged management regime. The integration of a harvesting regime for forests in transition into MOSES is essential for simulating the BAU management for the future.

The second harvesting algorithm is developed for its use within the biogeochemical ecosystem model Biome-BGC. The idea is to address the key characteristics and limitations of this modelling concept so that the resulting thinning algorithm can be easily integrated within BGC modelling applications. An important focus is spatial scaling because the algorithm should be used in large-scale modelling applications (national scale and bigger). Therefore, amongst other nationwide available datasets, the Austrian Forest Inventory data are obtained

An important preliminary step for the process model application is to choose the correct carbon estimation method. Unlike single-tree growth models, BGC models directly simulate tree carbon. Data from forest inventory are tree measurements that can easily be used to derive the tree volume. Comparing carbon estimates to volume is not a straight forward step; there are different calculation methods resulting in different estimation results. Therefore I analysed different carbon estimation methods commonly used in Austria to enable a proper comparison of model outputs to values derived from inventory data. This step is important for understanding the comparisons because any deviation could be either an effect of the model or an effect of the conversion system (stem volume in stem carbon or vice versa). In conclusion, the following steps have to be accomplished

(i) Development, implementation and application of a harvesting routine for the single-tree growth model MOSES to simulate forests in transition.
(ii) Analysis of different carbon estimation methods used in Austria for the process model application to understand the effect of converting stem volume and/or stem carbon on the resulting model predictions.
(iii) Development of a harvesting routine to be used in large-scale biogeochemical modelling applications.

3 Methods

3.1 Workflow

The objectives defined in Section 2 are addressed in one of the three papers which are an integral part of this thesis. The overall structure of the work is shown in Figure 1. It shows the tasks that were performed and how the different topics are connected and covered by the three papers (see Appendix).

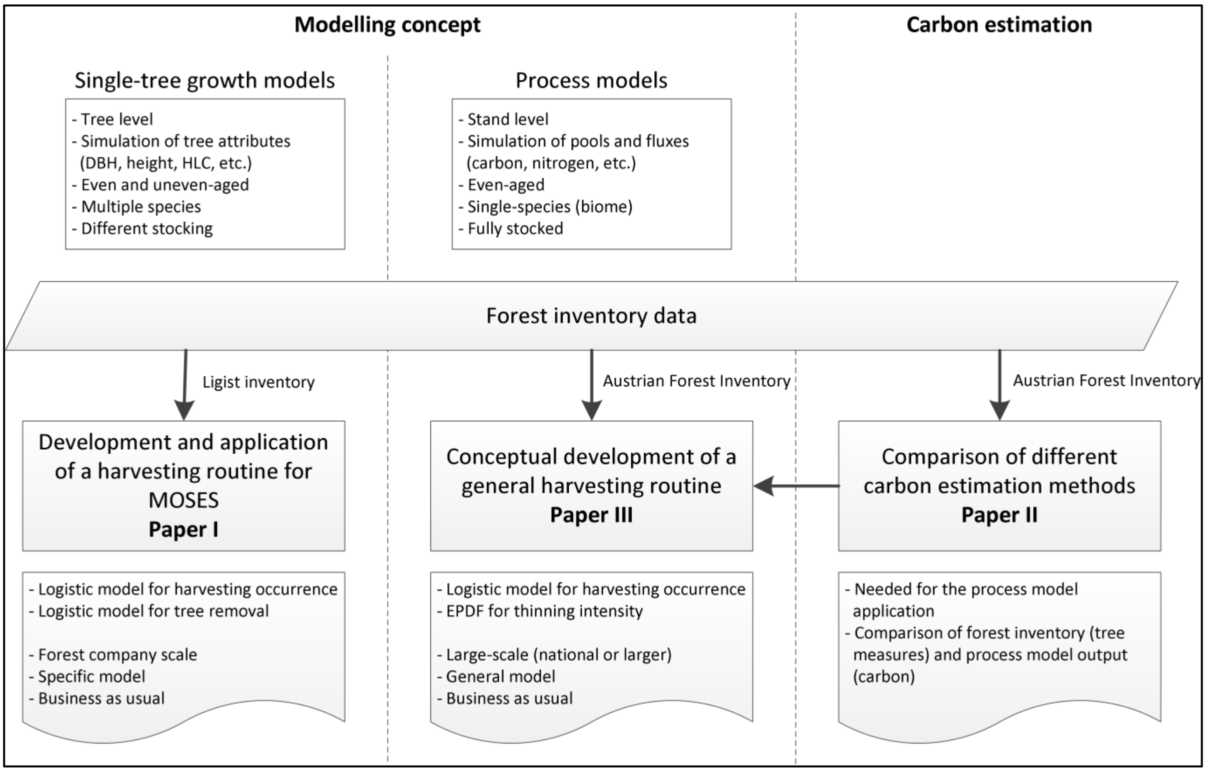

Figure 1: Workflow diagram showing the tasks and content of the thesis and how the published papers are integrated in the overall concept.

Paper I and III provide the two developed harvesting routines. The one for the single-tree growth model was also implemented and applied in MOSES whereas the one developed for the BGC model approach (see Paper III) provides a conceptual description of a harvesting algorithm but is not yet implemented in the ecosystem model.

Paper II describes the work done for ensuring a conceptual understanding of the different carbon estimation methods relevant within BGC modelling. Four carbon estimation methods are applied on the same dataset so that the differences in the results can be compared and evaluated. With this analysis the effect of the carbon estimation method on the comparisons of predicted process model output and observed forest inventory data is addressed.

The main data for all papers are forest inventories based on angle count samplings (Bitterlich, 1948). Some additional data were needed for the process model application, a description can be found in Section 4.3.

3.2 Modelling concepts

The ecosystem models used within this study are the single-tree growth model MOSES and the biogeochemical process model Biome-BGC. The modelling concept within these models is very different and will be briefly described. A detailed description of MOSES can be found in Hasenauer (1994) and Klopf et al. (2011); for Biome-BGC, please refer to Running and Coughlan (1988), Thornton (1998) and Thornton et al. (2002).

Single-tree growth models like MOSES, SILVA (Kahn and Pretzsch, 1997; Pretzsch et al., 2002) or PROGNAUS (Sterba and Monserud, 1997) are models that operate on a tree level and generally simulate the DBH and height increment of every single tree in a stand in relation to competition indices. They can be either distance dependent or distance independent (Hasenauer, 2006a). Distance dependent means that the position of every tree within a stand is needed to calculate the competition index whereas distance independent models do not need tree coordinates. The benefit of a distance dependent approach is that the different reaction of every single tree can be calculated after tree removals due to harvesting and/or mortality according to its position within the stand. Tree growth models can be used to simulate management options within a stand since (i) the removals of single trees can be easily implemented and (ii) the changes of the competition situation as a result of harvesting is an integral part of the models. In fact, tree growth models are explicitly designed to simulate management practices. The time-step of tree growth models is usually five years and site conditions are kept constant (Hasenauer, 2006b). Tree growth models can be initialized with the current stand conditions from measured inventory data. Sophisticated stand generation methods exist to be able to generate representative stands from inventory sampling techniques like angle count samplings so that not each tree within a stand has to be measured (Degenhart, 1998; Kittenberger, 2003; Lewandowski and von Gadow, 1997; Pommerening, 2000; Pretzsch, 1993). Typical model output variables comprise tree dimensions like DBH, tree height and height to the live crown (HLC) and other variables that can be derived from them like volume estimates which are either calculated for each tree or aggregated on a stand/enterprise level.

Biogeochemical (BGC) or process models follow a different approach. The ecosystem is seen as a set of pools and fluxes that change and interact with the pools. The models simulate the cycling of carbon, nitrogen, water and energy within the ecosystem. They are generally driven by climatic and site specific variables and operate on a sub-yearly time-step. Examples are 3-PG (Landsberg and Waring, 1997) that operates on a monthly time-step, Biome-BGC (daily time-step) or ecosys (Grant, 2001) at an hourly time-step. A summary of different process models can be found in Hanson et al. (2004). A species is usually defined by a set of ecophysiological parameters (e.g. White et al., 2000). The current state of the system is defined by a set of pool and flux variables that describe the carbon, nitrogen, water and energy within the system. Typically not all of these variables can be measured. Process model are often initialized by a spin-up or self-initialization procedure (Hanson et al., 2004; Pietsch and Hasenauer, 2006; Thornton and Rosenbloom, 2005). This means that the model is run for many years with constant site and repeated climatic conditions until the system reaches a steady state and all variables are set to their initial values. Being able to mimic the initial stand conditions is already a major step within process modelling since they are not directly initialized with the current stand conditions like tree growth models. Since process models rely on climate variables, they can be used to describe the ecosystem behaviour on climate change (Eastaugh et al., 2011; Pötzelsberger et al., 2012). Typical output variables are the carbon content in different tree compartments and variables that can be directly derived from the pools and fluxes like gross and net primary production (GPP and NPP).

3.2.1 Moses

MOSES is a distance dependent and potential based single-tree growth model that operates on a five year time-step. Potential based means that the height and DBH increment models included in MOSES first calculate a potential increment that is then reduced in relation to the competition indices (Hasenauer, 2006b, 1994). The index according to (Monserud, 1975) is used to describe the current competition situation, the crown ratio is used as a measure for the competition in the past. The potential DBH increment is defined by solitary tree dimensions according to Hasenauer (1997). The potential height depends on top-height relations that are based on yield tables (e.g. Marschall, 1975). The model also comprises a dynamic crown model. In contrast to a static crown model, a dynamic crown model insures that the HLC cannot be reduced. Tree mortality is modelled with a logistic function (Monserud and Sterba, 1999). Regeneration is included by a sub-model according to Golser and Hasenauer (1997) and Kindermann et al. (2002).

3.2.2 BGC

Biome-BGC is a stand level process model that simulates the cycling of matter in the ecosystem. The forest is determined by a set of pools and fluxes. The model works on a daily time-step and is driven by climatic factors (maximum and minimum temperature, precipitation, solar radiation and vapour pressure deficit), site parameters (soil texture, effective soil depth, etc.), CO_2 concentration in the atmosphere and wet and dry nitrogen deposition. The biome is defined by a set of ecophysiological parameters that describe e.g. allocation rates, C/N ratios, mortality rates, etc. Initially, general parameter sets for e.g. evergreen needle leaf or deciduous broadleaf forests have been developed (White et al., 2000). A species specific parameterisation for major European tree species has been done by Pietsch et al. (2005) which is also used in this study. Other improvements are a dynamic mortality routine to simulate virgin forests (Pietsch and Hasenauer, 2006) and the integration of harvesting (Pietsch and Hasenauer, 2002).

3.3 Estimation of carbon from forest inventories

The estimation of carbon stored in the forest from inventory data was a mandatory step within the harvesting routine development for the process model application. Process models simulate carbon. To be able to compare the model outputs to the inventory data either the volume derived from inventory data has to be converted to timber carbon or the carbon estimated with the process model has to be converted volume. This can be done with biomass expansion factors (Brown, 2002; IPCC, 2003; Pietsch et al., 2005). Biomass expansion factors are constant values that directly convert volume estimates to carbon. In contrast, biomass functions (Hasenauer et al., 2012; Hochbichler et al., 2006; Zianis et al., 2005) use allometric relations based on tree variables like DBH, height, HLC, etc. to derive carbon values. They are used to convert tree measures from forest inventories to carbon.

To further analyse such effects on our resulting predictions four different carbon estimation methods used in Austria have been evaluated: (i) the Austrian biomass functions (ABF; Hasenauer et al., 2012; Hochbichler et al., 2006), (ii) biomass functions according to allometric relationships based on data collected by Burger (1929-1953), (iii) biomass expansion factors (BEF) according to Pietsch et al. (2005) and (iv) biomass expansion factors recommended by the Intergovernmental Panel on Climate Change (IPCC, 2003). Different conversion methods may lead to different results due to a potential bias or differences in the random error component. This is important to understand because assumptions based on the modelling output may be due to a modelling problem or a result from the chosen carbon estimation method. In this study, the BEF method according to Pietsch et al. (2005) was chosen. Appendix 9.2 gives a detailed description about this step.

3.4 Harvesting routines

Both developed harvesting routines contain two sub-modules. The single-tree growth harvesting routine estimates in a first step the probability of a plot to be thinned. If the plot is thinned then in a second step it determines for each tree whether the tree is removed or not. In contrast to the BGC approach, this concept is not applicable because BGC models operate at a stand to landscape level. Thus the following approach was chosen: The first sub-module works similar as in the single-tree growth approach; the probability of a plot to be thinned is estimated. The second sub-module estimates the overall thinning intensity.

Logistic regression is a parametric approach that is often used to estimate dichotomous variables like harvesting occurrence or tree removal (Eastaugh and Hasenauer, 2012; Fortin, 2014; Ledermann, 2002; Sterba et al., 2000). The general form of a logistic model can be expressed as:

$$P = \frac{1}{1 + e^{-(bX)}} \tag{1}$$

The probability *P* is estimated by a linear combination bX of independent predictor variables *X* and a set of associated parameters *b*. This approach was used in both sub-modules of the single-tree growth harvesting routine. The resulting probability is then compared to a uniform distributed random number. If the random number is smaller than the calculated probability, the plot is harvested or the tree is removed, depending on the sub-module. A more detailed description of the algorithm can be found in Appendix 9.1.

The harvesting approach for the BGC model follows the methodology as described in Eastaugh and Hasenauer (2012). It was adapted and improved with the focus on its applicability within large-scale modelling applications. The first sub-module is also defined by a logistic function. The second sub-module which predicts the thinning intensity is based on a non-parametric approach. The method uses empirical probability density maps to estimate the thinning intensity based on site parameters. The intensity is a percentage between 0 and 100 based on the basal area. An empirical probability function for the thinning intensity can be extracted for any combination of two site specific parameters. The thinning intensity is then a random number based on this empirical distribution. All the details are given in Appendix 9.3.

Although both harvesting routines were developed to understand the current management practices as they can be derived from repeated observation of empirical data the purpose of the two harvesting routines is different: The aim of the harvesting routine for the single-tree growth model MOSES was to mimic the current practice of the forest company. Thus a calibration and evaluation of the resulting equations was done and implemented in the MOSES framework. An important part here was a model evaluation by running MOSES for 50 years to see the development of the stands of the forest enterprise in the future under current business as usual management assumptions. The goal of the second harvesting approach was the development of a general routine for large-scale biogeochemical ecosystem modelling applications. The approach is designed to meet the requirements within the overall modelling concept. However the resulting equations are not yet implemented. The focus was the development of a general harvesting routine.

4 Data

The inventory data used in the modelling applications came from different sources. The inventory method is angle count sampling (Bitterlich, 1948). The Ligist dataset is forest inventory data from a forest company. It was used in the single-tree growth modelling application (Paper I in Appendix 9.1). The Austrian Forest Inventory Data is a nationwide dataset that was the basis for the process model application (Paper III in Appendix 9.3) and the comparison of the carbon estimation methods (Paper II in Appendix 9.2).

4.1 Ligist

The data used for the single-tree growth harvesting routine came from the forest company 'Ligist, Souveräner Malteser Ritterorden' that is located in Styria and partly in Carinthia, southern Austria. The forest area comprises 3140 ha and ranges from 270 to 1700 m a.s.l. The company changed its management regime from even to uneven-aged management about 40 to 80 years ago, thus it is still in the transition phase. They established an inventory design based on angle count sampling in 1980 with remeasurements every five to ten years. The forest is dominated by Norway spruce (*Picea abies*), with European larch (*Larix decidua*), Scots pine (*Pinus sylvestris*) and common beech (*Fagus sylvatica*). The company is sub-divided in five management regions, not all of them are in the same transition phase and the time of the measurements is not the same for each region. Due to data limitations, three of the five regions were considered in the study. The dataset (all five regions) consists of 1150 angle count sampling points, only points with a full data record were included, thus 618 angle count sampling points remained. All trees with a DBH larger than five cm were considered in the measurement. Each single measurement of a point was treated as an independent observation for model calibration. Please refer to Appendix 9.1 for a more detailed description of the dataset.

4.2 Austrian Forest Inventory

The Austrian Forest Inventory was used for the process model application. The dataset consists of a nationwide grid of repeated angle count measurements for trees larger than 10.4 cm in DBH combined with circular fixed area plots around the point for trees with a DBH between 5 cm and 10.4 cm (Gabler and Schadauer, 2008). The fixed area plots have a radius of 2.6 m ($A = 21.24\ m^2$). The points are arranged in rectangular groups of four, denoted as point 00, 08, 16 and 24 counting clockwise from the lower right position. The groups have a distance of 3.89 km. The available dataset consists of 22327 points. Only points that maintain at least one tree measurement are considered in this study. That reduces the number of points to 9747. The measurements begin in the 1980s (1981 – 1986). The last measurement period contained in this study was in the years 2007 to 2009. Each remeasurement was treated as an independent observation. Points with a recorded clear-cut were excluded from the model development. The dataset was split into a calibration and validation set, comprising points 00 and 16 for the calibration and points 08 and 24 for the validation. The first two measurements only contained point 00 which resulted in a calibration dataset with 12570 and a validation set with 8600 independent observations (see Appendix 9.3).

A subset of the Austrian Forest Inventory data was also used in the comparison of the different carbon calculation techniques (see Appendix 9.2). The goal was to construct a dataset that covers the whole range of the DBH distribution and also maintains realistic DBH-height relations. Therefore, 50 trees per 5 cm DBH class were randomly extracted from the forest inventory data. This was done for Norway spruce, common beech and Scots pine. This resulted in a theoretical dataset of 1000 spruce and 942 beech trees covering the range from 5 cm to 105 cm in DBH and 632 pine trees with a DBH between 5 cm and 75 cm.

4.3 Other data sources

For the process model application, also datasets from other sources than forest inventories were needed. Daily weather data was interpolated with the Austrian version of DAYMET (Hasenauer et al., 2003; Thornton and Running, 1999; Thornton et al., 1997) from the climate station dataset provided by the Austrian Institute for Meteorology and Geodynamics (ZAMG). DAYMET interpolates daily values of minimum and maximum temperature and precipitation and from these values it calculates solar radiation and vapor pressure deficit (Thornton et al., 2000). Soil data, i.e. the sand silt and clay proportion as well as the effective soil depth was interpolated from data of the Austrian National Soil Survey (Englisch et al., 1992). Information about the interpolation can be found in Petritsch (2008). Industrial nitrogen deposition was taken from a GIS map of Austria published in Eastaugh et al. (2011) that is based on the data of Schneider (1998) and Placer and Schneider (2001). Elevation was extracted from a digital elevation model (NASA Land Processes Distributed Active Archive Center (LP DAAC), 2001). The resolution of this dataset is 1 arc second which is about 30 m at the equator.

5 Analysis and Results

This section provides an excerpt of the results of the two harvesting models and the comparison of the carbon estimation methods. For the single-tree growth approach all forest inventory points were used for the calibration. The harvesting routine was then implemented in MOSES and evaluated by simulating the forest for 50 years starting with the first measurement (see Appendix 9.1). The harvesting routine for the process model application was developed as a general concept. Here the forest inventory data was split into a calibration and a validation dataset (see Appendix 9.3). The results of the harvesting routines show the good performance and applicability of the methodologies. The results of the carbon estimation show the necessity of this part of the study for the process model application. The large differences are solely a result of the conversion method.

In both modelling concepts, the harvesting routines did not consider clear-cuts (final harvestings). In the single-tree growth application clear-cuts were not available because the forest company ceased all clear-cuts and the forest is in a transition phase to an uneven-aged forest management regime. In the process model application forest inventory points with a recorded clear-cut were excluded from the model calibration and validation data set.

5.1 Single-tree growth harvesting routine

The harvesting procedure developed for the single-tree growth application determines for each tree whether it is removed or not based on two sub-modules. Both are logistic functions that first determine on a stand level if harvesting occurs and then estimate for each tree on a tree level whether it is removed or not. Both logistic functions return a probability that is compared to a random number. If the random number is smaller than the resulting probability then the plot is harvested or the tree is removed depending on the sub-module. The second sub-module is only applied if the model predicts that a harvesting occurs.

The predictors for the logistic functions had to be chosen based on the level of each sub-module. The first sub-module operates on a stand level and the second one operates on a tree level. Thus, in the first module, only stand level predictors could be used. It was important that the predictors could be derived from the inventory data and had to be available in MOSES, otherwise an implementation would not have been possible. Only parameters at the $\alpha = 0.05$ level were considered in the harvesting procedure. The first sub-module depends on the quadratic mean diameter dg, the crown competition factor CCF (Krajicek et al., 1961) and the period length as a dummy variable since the length between two consecutive measurements is either five or ten years. The second sub-module that handles the tree removals operates on a tree level. The DBH of the tree was integrated as normal and quadratic term. The crown competition factor of larger trees was included as an additional predictor. To take care of species mixture effects, dummy variables for the different tree species were integrated in the model. Please refer to Appendix 9.1 for additional information and the exact equations of the harvesting procedure.

The developed harvesting routine was implemented in MOSES and run for 50 years starting with the first measurement. It showed good results when comparing the predicted and observed proportion of removed trees. The projection into the future suggests a sustainable forest development. Figure 2 a shows the results of the district Sommereben. Other districts had similar results (see Appendix 9.1). All districts showed the highest removal proportions at the low and high DBH classes with the lowest proportion in the middle DBH classes. The harvesting procedure was also implemented in MOSES and run for 10 periods. The result of this model application is shown in Figure 2 b. The first 20 years where observations are available show that the model is able to mimic the development over time in both the remaining and removed trees according to the mean basal area of the stands. The model predicts a constant yet slightly increasing basal are development with ~35 m² ha^{-1} in the year 2030. Similar results can be seen for the other districts (see Appendix 9.1).

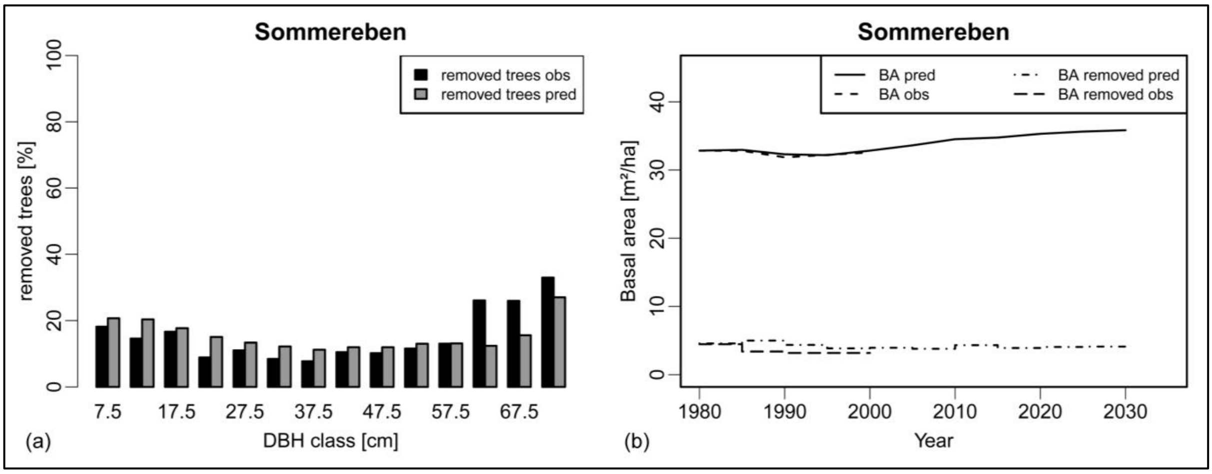

Figure 2: Results of the single-tree growth harvesting application for the district Sommereben. The proportion of observed and predicted removed trees (a) according to 5 cm DBH classes and (b) the predicted and observed standing and removed basal area for the 50 year model run with the harvesting routine applied in each simulation period are shown here. The figures are taken from Appendix 9.1.

Overall, the first sub-module classified 60 % of all plots correctly as being harvested (68 % of harvested and 48 % of non-harvested). The second module categorized 73 % of all trees correctly, of which 34 % of the removed and 83 % of the remaining trees being correctly classified. In combination, the removal of 69 % of all trees was correctly predicted (24 % of the removed and 80 % of the remaining, see Appendix 9.1).

5.2 Carbon estimation methods

BGC models do not simulate tree populations. They assess pools and fluxes like carbon, nitrogen, energy, etc. within ecosystems. Thus a conversion is required for any comparison of carbon data resulting from modelling exercises with terrestrial forest data. For this purpose carbon estimation methods have been developed. One of the important issues of this work is to ensure that the best conversion method has been chosen and to separate potential discrepancies of the resulting model predictions from observed data due to the carbon estimation methods or the developed harvesting algorithm.

Therefore we started the development of the harvesting algorithm for BGC modelling by comparing different carbon estimation methods in a prior step. In principle the following approaches exist.

(i) Biomass expansion factors are constant factors that convert tree volume to carbon of different tree compartments. Since they are constant factors, the conversion can be done in both directions, either from tree volume to carbon or vice versa. The tree volume is calculated before with allometric equations from tree measures, e.g. DBH and height.

(ii) Biomass functions directly derive the carbon values from tree measures according to allometric relationships. Unlike biomass expansion factors, biomass functions in general can only convert tree measures to carbon and not vice versa. Different equations have been developed to estimate different tree compartments.

In this study, we examined four different conversion methodologies: (i) the Austrian biomass functions (ABF; Hasenauer et al., 2012; Hochbichler et al., 2006), (ii) biomass functions according to allometric relationships based on data collected by Burger (1929-1953), (iii) biomass expansion factors (BEF) according to Pietsch et al. (2005) and (iv) biomass expansion factors recommended by the Intergovernmental Panel on Climate Change (IPCC, 2003). They were applied on a generalized dataset to see the differences that are only a result of the applied method.

Figure 3 shows selected examples from Appendix 9.2 to highlight the high deviations that occur by the conversion. More results can be found in Appendix 9.2. The examples presented here show the highest deviations between the methodologies so they best underline the overall problems that may occur as a result of the conversion.

Regarding the stem carbon of Norway spruce trees (Figure 3 a), the Burger method shows by far the highest values, whereas the other three methods reveal comparable results. Similar results can be found for the branch carbon of beech trees (Figure 3 b), yet the ABF method shows the highest values, followed by the IPCC calculations that are still more than twice as high as the remaining two methodologies.

Imagine a model that hypothetically provides the correct predictions. Comparing the model result with the observations might still show a high deviation caused by the conversion methodology. In this case, the deviation is only a result of the methodology because the method calculates stem carbon beyond an acceptable range although the model predictions are correct. Thus, when interpreting model results that compare simulated carbon or biomass values with measured inventory data, the conversion methodology should be investigated and understood in order to figure out if the deviation is a result of the model or the conversion.

Since the dataset is the same for all methods, the difference is only driven by the calculations. This effect has to be considered when comparing model outputs to forest inventory data. It is important to mention that we do not know which method gives the correct result. However, in this study the biomass expansion factors (BEF in Figure 3) described in Pietsch et al. (2005) were used for the process model application because (i) they did not show any unrealistic behaviour like the ABF or Burger method (see Appendix 9.2) and (ii) they were used in the species specific calibration of Biome-BGC for European tree species.

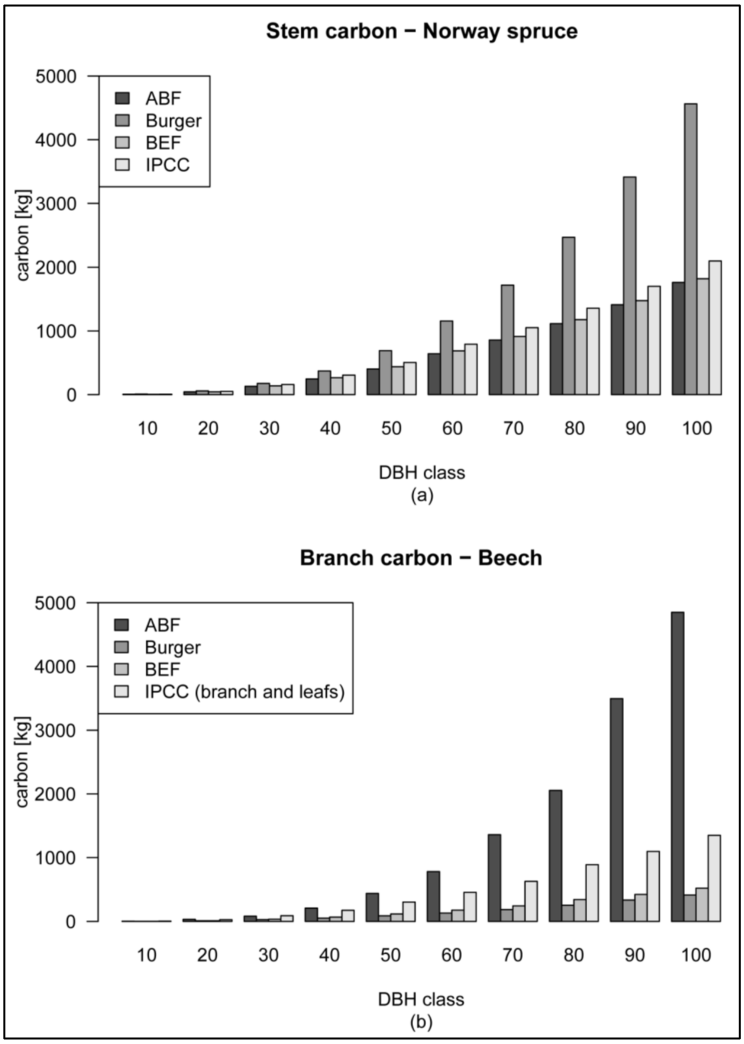

Figure 3: Stem carbon of Norway spruce (a) and branch carbon of beech (b) estimated with the Austrian biomass functions (ABF), biomass equations based on the data collected by Burger, biomass expansion factors (BEF) and recommendations of the Intergovernmental Panel on Climate Change (IPCC). The values presented here are the mean values according to 10 cm DBH classes. The figures are taken from Appendix 9.2.

5.3 Harvesting routine for BGC models

The harvesting procedure for the biogeochemical ecosystem model application was developed as a general concept intended to be used in BGC models. The routine consists of two sub-modules. The first is a logistic function that determines whether a plot is harvested or not. The second is a non-parametric approach that calculates the thinning intensity based on empirical probability density functions. The harvesting routine has been developed with the Austrian Forest Inventory data that was split into a calibration and validation set, more information about that can be found in Section 4.2 and Appendix 9.3.

Both sub-modules of the developed harvesting routine operate on a stand level. The thinning occurrence sub-module is based on logistic regression like the sub-modules in the single-tree growth application. Just like for the other modelling concept, it was mandatory that the parameters are available in the process model (in this case Biome-BGC). The parameters here comprise the timber carbon, the age, the elevation, the species mixture and the site quality. The timber carbon, age and species mixture (conifer, broadleaf and mixed) were derived from the inventory data. The elevation was extracted from the ASTER digital elevation model (NASA Land Processes Distributed Active Archive Center (LP DAAC), 2001). The site quality was determined from the net primary production of the plot that was estimated with Biome-BGC simulation runs. This approach was developed within this study. More information about the approach as well as the equations, statistics and parameter values can be found in Appendix 9.3. The non-parametric thinning intensity model used here depends on the site quality and the timber carbon. Different probability density maps have been calibrated based on the cover type (conifer, broadleaf and mixed).

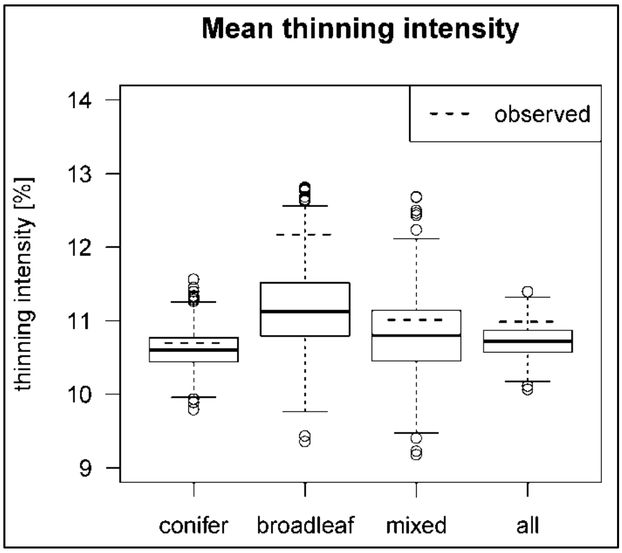

Figure 4: Predicted distribution of the mean thinning intensity after 1000 validations runs of the harvesting routine. The dashed line shows the observed thinning intensity. The results are grouped for conifer, broadleaf and mixed points. The rightmost values show the overall model result. The figure is taken from Appendix 9.3.

To show the applicability of the model, it was run 1000 times on the validation dataset to show the mean prediction as well as its distribution which is a result of the random components within the harvesting procedure. Results of the process model application are shown in Figure 4. The harvesting routine predicts 34.01 % of the available angle count sampling points to be harvested compared to 34.81 % according to the observations (see Appendix 9.3). Concerning the mean thinning intensity (Figure 4), the model predicts 10.72 % in the mean. The observed thinning intensity is 10.99 %. The model also slightly underestimates for all cover types: conifer, broadleaf and mixed (Figure 4). The highest deviation from the observations can be seen within the mixed points. By grouping the predicted and observed thinning intensity into timber carbon, site quality, age and elevation classes it is obvious that the model is able to reproduce the trends that are available in the observations (e.g. higher thinning intensity in low elevation classes; see Appendix 9.3).

6 Discussion

The differences of the examined carbon estimation methods make it crucial to be aware of the effects that may occur and to choose an appropriate methodology in the overall application. Biomass functions are often calibrated only on a certain DBH range, thus the calibration range has to be known which is often not the case (Zianis et al., 2005). Any extrapolation beyond the borders can lead to unpredictable results as can be seen in Figure 3 a for the Burger method and in Figure 3 b for the ABF method. In general, the highest deviations resulting from the methodology were detected in the ABF and Burger method, both use biomass functions. These findings directly influence the process model application since the comparison of the calculated carbon values with the predictions largely differ. Thus, methods that provide results beyond an acceptable range can lead to high biases. When comparing with model predictions, the differences might be an effect of the model or the carbon calculation method.

Additionally, functions that only depend on the DBH do not consider that the height of the trees has an upper limit and thus the biomass cannot increase constantly with increasing DBH. Also, biomass functions used in Europe often have an exponential behaviour (examples can be found in Zianis et al., 2005) so that the results especially for large trees might be above a reasonable range. Biomass expansion factors just convert the volume to biomass with a constant factor, thus the behaviour mainly relates to the volume function (e.g. Kennel, 1973 or Pollanschütz, 1974 for Austria).

The harvesting algorithms developed in this study proved to be helpful and correct within their application areas. They provided consistent and good result compared to the observed data (Figure 2 and 4). The level of detail in the harvesting algorithms is related to the modelling concept. In the harvesting application for the tree growth model MOSES, single trees are simulated and can be removed. Thus the stand structure plays an important role and structural information about the model behaviour can be examined on a tree level. Figure 2 a shows the overall model performance regarding the DBH distribution of the trees, this level of detail is not possible in the process modelling approach. Here only stand variables are available and the model behaviour can only be analysed on the stand level and above (see Appendix 9.3 and Figure 4). Of course, an aggregated analysis on a stand or enterprise level is also possible within the single-tree models (Figure 2 b).

The application scope of the two developed models is different. The single-tree harvesting routine is applied to a certain forest enterprise that is currently in the transition phase from even to uneven-aged management. This is a very specific scope, thus the model cannot be applied to the whole country, yet the methodology could be adapted to other management regimes by a recalibration of the parameters. The results shown in Figure 2 a that depict the removal proportion according to the DBH is similar to other single-tree selection models (e.g. Fortin, 2014 and Ledermann, 2002). Reasons for the high mortality in small and large trees are pre-commercial thinnings of young trees and the final harvest at the end. The application scope of the process model is mainly the typical small-scale clear-cut management regime that is applied in Austria (Mayer, 1992; Weinfurter, 2013). However, we did not exclude any sample points according to their management regime since we were interested in a large-scale simulation. On this scale small areas with a different management regime should be levelled out. The harvesting algorithm for the BGC modelling is more general than for the single-tree growth application. It is intended to be used on a large or national scale, whereas the single-tree growth harvesting routine is developed for a special management regime. The single-tree growth harvesting procedure in general is also not limited in its scale but in its application scope.

The scalability, in the sense of being able to apply the model on a large spatial scale, of the modelling application that implements the harvesting routine strongly relates to the underlying modelling concept. Single-tree growth models like MOSES are initialized with the current stand conditions. That implies, at least for distance-dependent models, that they need the tree coordinates. On a large scale usually only forest inventory data based on a sampling design is available. In this application angle count sampling data of a forest company was used. In the MOSES environment, the stand generation tool STANDGEN (Kittenberger, 2006, 2003) is used to generate representative stands with a similar structure as the original stands. Therefore, additional measurements like the distance and the species of the nearest neighbouring tree have to be available for each sample tree. From these measurements the aggregation index according to Clark and Evans (1954) and the mixture index according to Füldner (1996) are derived and integrated in the stand generation process. This leads of course to an increase in the measurement work in the field. Once the stands are generated, the harvesting routine can be applied in the simulations. Considering scalability this process has several drawbacks. First of all, the model needs inventory data as a prerequisite. Without data of the stands the model cannot be initialized because no information about the current state is available. Furthermore, more parameters, in addition to the usually measured ones, are needed to be able to generate stands with a similar structure. This implies that scalability is limited and the model cannot be applied on areas without inventory data even if the management regime is similar and the harvesting routine as such would be capable of simulation.

Scalability is easier to achieve within process models such as Biome-BGC. Process models often use a self-initialization or spin-up procedure. This means that in general no information about the current stand has to be available for the simulation runs. Of course for calibration and validation purposes, as well as for the development of the harvesting routine, the model output has to be compared to measured data, but not for the simulation as such. In this application we tried to use datasets that are available on a large scale, such as climate data interpolated with DAYMET (Thornton et al., 1997), a nitrogen deposition map of Austria published in Eastaugh et al. (2011), interpolated soil properties (Petritsch, 2008) and a digital elevation model (NASA Land Processes Distributed Active Archive Center (LP DAAC), 2001). The cover type within the harvesting routine is similar to the definition in the CORINE land cover (Bossard et al., 2000) and the site quality index can be derived with BGC simulation runs according to the method presented in Appendix 9.3. The only additional information that is needed is the major tree species or biome type in the area of interest. It is possible to integrate the harvesting routine in the simulation on a large scale and also to apply it on areas where no forest inventory data is available but a similar management strategy can be assumed. The ability of scaling is given in this approach and was the main focus in the development of this harvesting routine since this is inherently given within this modelling concept.

Some considerations about the implementation of harvesting regimes have to be done in relation to the different modelling concepts. Harvestings change the stand density and thus influence the basal area development and the volume increment (Hasenauer et al., 1997). In single-tree growth models, this effect is well covered with the changes in competition indices after harvesting. Biome-BGC, as an example of process models, implies even-aged fully stocked stands. The growth response after harvesting is not considered since it uses constant allocation patterns for each biome throughout the whole simulation. Petritsch et al. (2007) showed that changing the allocation patterns right after thinning improves the model performance since this covers the growth response. This effect has to be considered when implementing harvesting routines in process models that imply fully stocked stands. Since the harvesting routine developed in this study is only a general concept this effect was not of interest. However, awareness of this relationship should be raised.

The harvesting routines do not distinguish between removals due to harvestings and removals that were caused by mortality or natural disturbances. This was done since the procedures should be able to simulate the overall situation and to make them more easily applied. Generally, the mortality in managed forest should be kept to a minimum. A closer look at the mortality in the process model application did not show a very high mortality and the trend in the mortality was similar to the overall trends. MOSES already includes a mortality sub-model (Monserud and Sterba, 1999) and in Biome BGC the annual tree mortality is set to a constant value. That is why the models only focused on harvesting. About natural disturbances, the main disturbance types in Austria are bark beetles and wind throw (Thom et al., 2013). These disturbances usually affect older trees or trees with a large DBH (Albrecht et al., 2010; Hanewinkel et al., 2010; Rich et al., 2007; Seidl et al., 2014). In the process model application we were not interested in final harvest (clear-cuts), thus all points with a recorded clear-cut were not considered. Due to ecologic and regulatory reasons a final harvest is often performed on disturbed stands, so these points were not included in the model. On a large scale, possible effects of mortality due to natural disturbances should level out, that is why they were treated as natural variation.

7 Conclusion

Integrating management into forest models is a crucial step in order to use these models to predict forest development in Europe. This thesis shows how to integrate two different harvesting algorithms within two different modelling concepts. Both algorithms were developed with forest inventory data covering repeated long-term observations to mimic the future business as usual management regime in scenario analysis. The methodology for the BGC model was similar to the approach in the single-tree growth model, yet it had to be adapted since the process model operates on a stand to landscape level as compared to the tree growth model which predicts the removal for each tree within a forest stand.

Comparing model results with the observations from forest inventory is crucial in any modelling application. Here it also depends on the modelling concept. The comparison in the single-tree growth application is straightforward since the same variables are available (DBH, height, etc.). Within BGC modelling a preliminary step was needed because such models simulate pools and fluxes of carbon and no tree populations. Thus the terrestrial observations form the inventory had to be converted to carbon to be comparable with the model predictions. This conversion is a crucial step in assessing the reliability of model predictions. Thus any bias that could be a result of the conversion methodology should be known and understood. The analysis of the conversion methodologies provided great deviations which make it crucial to be aware of the effect that can arise specifically from those calculations.

The scope of the two applications was different. The single-tree growth application was applied on a very specific case (forest in the transition phase from even to uneven-aged) whereas the harvesting routine for the process model is a very general model that is determined for large-scale nationwide applications. The scalability issue also depends on the modelling concept. Both models can be applied on a large-scale. Once the harvesting routine is parameterized and implemented the single-tree growth model needs terrestrial tree measurements for initialization. The process model, however, does not need terrestrial data since it uses a spin-up procedure. This is an advantage in the scalability since the model is independent of tree measurements. This facilitates large-scale modelling applications.

The harvesting routine for the single-tree growth application was implemented in MOSES and a simulation of 50 years showed that applying the business as usual management results in a sustainable forest development. The scope of the model is very specific whereas applying the model to a different management regime would need at least a reparametrization. The harvesting routine for the process model approach is very general as it was developed with a nationwide forest inventory dataset. That makes it possible to apply it to large-scale applications.

In summary, the developed routines proved to be applicable to model the business as usual harvesting assumptions within two different modelling concepts. The differences of the concepts have a great impact on the model development and application. Being aware of the application area, scope and scalability issues due to the modelling concept allowed the developed procedures that showed a very good performance in the forest simulations. The fact that management plays an important role in European forestry shows the importance of the work in this study to facilitate the usage of single-tree growth and process models under consideration of management.

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9 Appendix

9.1 Paper I

Thurnher, C., Klopf, M., Hasenauer, H., 2011. Forests in transition: a harvesting model for uneven-aged mixed species forests in Austria. Forestry 84, 517–526.

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Forests in transition: a harvesting model for uneven-aged mixed species forests in Austria

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Summary

Harvesting models are needed within simulation studies to assess 'business as usual' scenarios in future stand development. Such models require data from repeated observations addressing the removals as they are based on specific silvicultural management regimes. The purpose of this paper was to develop and apply a harvesting model for uneven-aged single-tree forest management based on data from the forest company 'Forstbetrieb Ligist, Souveräner Malteser Ritterorden' in Austria. This company has been known for its transition from even-aged to uneven-aged forest management since the 1930s. Our harvesting model comprises two logistic functions to simulate a single-tree selection process: (1) predicting the probability of harvesting and (2) removal. The set of equations are tested and implemented in the tree growth model MOSES (MOdelling Stand rESponse). MOSES is used as a diagnostic tool to assess different forest management regimes. In this study, we are specifically interested in (1) evaluating the model by comparing predicted and observed removals and (2) predicting future stand development considering the current management practices—the business as usual as it can be derived from the harvesting model. The results suggest that in combination with MOSES, our model correctly mimics the growth development over time since no systematic trends between predicted and observed diameter growth at breast height classes are apparent. Furthermore, it is evident that by applying the current plenter harvesting strategy, a constant stand basal area of ~35 m^2 ha^{-1} will be achieved.

Introduction

The increasing gap between economic demands and ecological considerations influences silvicultural concepts and trends (Schütz, 2001). While in the past the traditional clear-cut system was considered to be a simple and easy solution to ensure sustainable forest management, uneven-aged forest management regimes are experiencing a renaissance. As a result of this development, companies have established permanent inventory systems (Kangas and Maltamo, 2006) and tree growth modelling theories have been developed (Hasenauer, 2006) to address the increasing demand for monitoring and predicting volume growth in uneven-aged mixed species forest stands.

One alternative to traditional even-aged forest management regimes is the plenter or tree selection system. Due to the difficulties in efficiently assessing the sustainability of such prescriptions, this system was disparaged and partly forbidden in Europe in the early nineteenth century (Hockenjos, 2008). It was reintroduced (for forest companies) based on Biolley's control method (Biolley, 1980). Sample inventory combined with modern single-tree growth models like MOSES (MOdelling Stand rESponse) (Hasenauer, 1994) offer a new generation of forest management planning and controlling tools for uneven-aged mixed species forests.

The harvesting strategy in plenter and/or selection forests comprises nearly all working steps that are separately run in even-aged forests (Schütz, 2001). It may also depend on specific needs or strategies such as a certain target diameter, etc. As a consequence, the interventions cannot easily be determined. A possible solution for this problem is the development or definition of a harvesting model (Ledermann, 2002) based on repeated measurements within such forests.

Harvesting models provide a mathematical solution to mimic the selection procedure for trees which are selected for cutting according to a given management regime. This selection process is commonly done by the local foresters and may be seen as the result of the management philosophy based on the existing experience and know-how of a given company. Once these rules are mathematically defined (e.g. in a harvesting model), we can represent the typical management regime of the company which allows us to apply the current regime in the future assuming that the general management routine remains unchanged. With such a model, it is possible to simulate the so called 'business as usual' case and predict stand development for future years with the same harvesting strategy as was applied in the past. Knowledge of these business as usual strategies is needed to assess future stand development under current harvesting conditions and also for comparing alternative and/or new silvicultural management strategies with the existing management.

In this study, a logistic harvesting model is introduced that mimics the plenter management regime of a forest company that is currently in the transition phase from an even to uneven-aged mixed species forest or plenter system. Silvicultural knowledge of such a transition is given by Reininger (2000), Duchiron (2000) and Schütz (2001). The logistic model approach is chosen because the harvesting strategy in mixed species forests during the transition phase is difficult to describe with harvesting rules. The available dataset comprises a large variety of stands at different transition phases and the logistic model provides the theoretical framework for harvesting criteria derived from the available dataset. According to Söderbergh and Ledermann (2003), this harvesting algorithm can be classified as empirical. Other rule-based systems, such as fuzzy–logic, are not applicable because precisely formulated harvesting rules for forests in transition do not exist (Duda, 2006).

For this study, we propose two logistic functions, similar to the harvesting models described in Ledermann (2002). Logistic functions are also capable of modelling the tree selection depending on human preferences in harvesting (Füldner, 1996). Logistic harvesting models have been developed for Austria (Sterba *et al.*, 2000) and the theory of LOGIT functions has been applied on modelling tree mortality (Monserud and Sterba, 1999) and regeneration (Schweiger and Sterba, 1997; Hasenauer and Kindermann, 2006).

The aim of this paper was to develop a harvesting routine for forests in transition (from even to uneven-aged mixed species forests) and implement the algorithm in the tree growth model MOSES to mimic the long-term forest management implications. The specific tasks can be summarized as follows:

1. Develop a plenter harvesting model with data from the forest company 'Ligist'.
2. Evaluate the model by comparing predicted *vs* observed removals.
3. Implement the harvesting model in the tree growth model MOSES to project the current harvesting strategy and predict future stand development.

Methods

The tree growth model MOSES

The distance dependent, potential based single-tree growth model MOSES (Hasenauer, 1994) is used for this study. MOSES consists of increment models for diameter growth at breast height (d.b.h.) and height, a dynamic crown model, a LOGIT function for mortality and a set of LOGIT functions for estimating the regeneration (Kindermann and Hasenauer, 2007). The interaction among trees is described by a distance-dependent competition index (Ek and Monserud, 1974). One simulation period is 5 years and the number of simulated periods is set by the user.

The increment calculation in MOSES is based on the idea that the increment is limited by a predefined potential. This potential is calculated and then reduced to a value according to the competition situation of the tree within the stand. The potential d.b.h. increment is derived from solitary tree d.b.h.–height relations (Hasenauer, 1997). For the potential height increment, the behaviour of top–height curves is defined (Monserud, 1975; Kindermann and Hasenauer, 2005).

Competition is described both for the past and for the present. The past influence of neighbouring trees is given by the crown ratio, whereas the actual situation is estimated with a distance-dependent competition index for each tree. Potential crown projection areas are calculated using the d.b.h. to crown radius or height to crown radius relations (Hasenauer, 1997). Based on the tree positions, overlapping zones of the crown projection areas are calculated and weighted by the height of the trees. By including the change of competition index due to mortality and management, the (non-linear) reaction of a tree due to management can be considered.

Data for calibration and validation of the increment and mortality functions of MOSES came from permanent investigative plots across Austria, Switzerland and parts of Germany. The 57 000 calibration and 225 000 validation increment pairs (repeated observations) cover a wide range of tree species mixtures, age structures, management regimes, etc., and all common silvicultural treatment scenarios are covered. The model has been widely used for typical tree growth model applications and has been proven to provide unbiased and consistent results (Hasenauer, 1994; Hallenbarter and Hasenauer, 2003; Steinmetz, 2004; Hallenbarter *et al.*, 2005; Klopf, 2007)

The harvesting model

We developed a harvesting model based on two separate logistic equations. The general form of a LOGIT function is:

$$P = \frac{1}{1+e^{b \circ X}}, \quad (1)$$

where P is the probability that is calculated by a linear combination $b \circ X$ with a set of independent variables X and their associated coefficients b. The model estimates the probability of a dichotomous-dependent variable.

In the first equation of the harvesting model (described later as equation (7)), the dependent variable is the occurrence of harvesting. This equation operates on the whole plot. It depends on the quadratic mean diameter and the crown competition factor (CCF; Krajicek *et al.*, 1961) of the plot and on the length of the measurement period. The calculated probability is then compared to a uniformly distributed random number between 0 and 1. If the random number is smaller than the calculated probability, harvesting occurs. The CCF is calculated as follows:

$$\mathrm{CCF} = \frac{\sum_{i=1}^{n} r^2 \cdot \pi}{A} \cdot 100. \qquad (2)$$

The CCF describes the proportion of the crown coverage based on open grown trees over the plot area *A*. The crown radius *r* for each tree is calculated using the d.b.h.—crown radius equations with species-specific parameters according to Hasenauer (1997). With data derived from angle count sampling, the crown area of the sample trees has to be multiplied with the representative stem number of the sample tree and the plot area *A* set as 1 ha.

If harvesting occurs, the second equation (described later as equation (8)) is executed which is again a LOGIT function. It operates on a tree level, which means that it is executed to every single tree on a harvested plot. It calculates the probability of a tree being removed. The dependent variables comprise the d.b.h., CCF of larger trees and the tree species. As in the first equation, the period length is also part of the second. Again, the probability is compared to a random number, removing the tree only if the random number is smaller than the estimation results. Both equations were calibrated using the open source statistical software R (R Development Core Team, 2010).

Data

The forest enterprise

About 40–80 years ago, the forest enterprise 'Forstbetrieb Ligist, Souveräner Malteser Ritterorden' began changing its forest management regime from a typical clear cut to a single-tree selection or plenter system. The forests of the company are located in Styria and Carinthia in southern Austria. The dominant tree species with respect to the number of stems per hectare is Norway spruce (*Picea abies*, 78 per cent), followed by European larch (*Larix decidua*, 6 per cent), Scots pine (*Pinus sylvestris*, 5 per cent), silver fir (*Abies alba*, 4 per cent), common beech (*Fagus sylvatica*, 3 per cent) and other tree species (4 per cent). The exact species composition is given in Table 1.

In 1980, a permanent inventory design consisting of 1150 angle count sampling points (Bitterlich, 1948) was established to monitor the forest development over time. The plots were remeasured every 5 or 10 years. The total forest area is 3140 ha and divided into five management regions, three of them were considered in this study. Region Sommereben comprises 900 ha, sits at 270–1700 m a.s.l. and contains 225 angle count sampling points. It is located in the districts Voitsberg and Deutschlandsberg in Styria. The management regime was changed to the plenter system between 1960 and 1970. The second region, Hebalm (1490 ha), is located in Voitsberg with some parts in Wolfsberg in Carinthia. It sits at 390–1280 m a.s.l. and contains 366 sampling points. The plenter management regime was established in the early 1970s. Region Fürstenfeld is in the eastern part of Styria in the districts Fürstenfeld and Hartberg. The size of this region is 450 ha comprising 229 angle count sampling points. The altitude is 270–360 m. This was the first region that changed the management regime, sometime before the 1930s. The time of the measurements and/or the period length is different in each region. The length of a measurement period is either five or 10 years. Region Sommereben was measured in 1980, 1985, 1990 and 2000, Hebalm in 1985, 1995 and 2000 and Fürstenfeld in 1980, 1990 and 2000. Only sample points that have a full data record are considered in the study. This reduces the number of points to 209 for Sommereben, 277 for Hebalm and 132 for Fürstenfeld. Stand characteristics for the three regions can be found in Table 2.

Data preparation

MOSES needs the tree position, d.b.h., height and height to the live crown (HLC) of each tree in a plot. In the dataset,

Table 1: Species composition with respect to the number of stems per hectare in the regions Sommereben, Hebalm and Fürstenfeld for each measurement year used for model calibration

Year	Spruce (%)	Fir (%)	Larch (%)	Pine (%)	Beech (%)	Other (%)
Sommereben						
1980	72.96	11.54	6.33	5.55	2.56	1.04
1985	73.53	10.61	5.57	5.23	3.9	1.15
1990	75.54	9.74	4.88	4.29	4.55	0.99
Hebalm						
1985	97.12	0.22	2.06	0.1	0.13	0.38
1995	95.46	0.16	1.99	0.09	0.14	2.17
Fürstenfeld						
1980	70.83	2.82	1.39	15.15	1.88	7.93
1990	68.47	3.55	0.98	12.54	3.3	11.16

Table 2: Stand characteristics for the regions Sommereben, Hebalm and Fürstenfeld for each measurement year that is used for the model calibration

					Equation 7			Equation 8	
Year	N_{rep}	N_{rep} rem	BA (m^2 ha^{-1})	BA rem (m^2 ha^{-1})	*dg* (cm)	$CCF_{conifer}$	$CCF_{broadleaf}$	d.b.h. (cm)	CCFL
Sommereben									
1980	807 (31–4920)	160 (0–4006)	32.84 (4–68)	4.48 (0–36)	28.38 (8.04–53.27)	166.48 (11.26–409.62)	18.25 (0–274.86)	19.84 (5.1–89.1)	132.35 (0–489.7)
1985	695 (26–4595)	80 (0–3458)	32.83 (4–76)	3.4 (0–32)	29.97 (9.13–56.33)	155.59 (12.8–563.74)	20.81 (0–310.97)	21.34 (5.5–85.3)	125.94 (0–504.5)
1990	668 (31–3878)	148 (0–1857)	31.87 (4–68)	6.37 (0–48)	30.43 (9.51–56.74)	147.42 (12.85–400.21)	21.79 (0–296.58)	21.13 (5.2–79.3)	114.76 (0–465.71)
Hebalm									
1985	839 (5–3907)	145 (0–3225)	28.48 (4–84)	4.88 (0–36)	27.63 (5.3–98)	146.1 (0–347.9)	3.28 (0–150.69)	17.31 (5.1–98)	98.4 (0–308.81)
1995	827 (6–4310)	127 (0–2187)	30.32 (4–76)	4.4 (0–24)	28.94 (9.02–92)	153.3 (7.37–396.37)	6.55 (0–699.63)	18.43 (5.2–100)	120.27 (0–681.74)
Fürstenfeld									
1980	931 (55–5296)	327 (0–2335)	35.88 (4–64)	11.42 (0–48)	24.93 (8.2–53.27)	182.33 (10.86–407.24)	37.56 (0–317.13)	20.24 (5.6–66.5)	137.52 (0–361.94)
1990	736 (58–3962)	223 (0–1455)	33.36 (4–60)	10.51 (0–52)	27.16 (12.42–50.57)	150.25 (0–359.21)	47.02 (0–451.44)	21.55 (6.8–70)	130.84 (0–389.69)

N_{rep} denotes the number of trees per hectare, N_{rep} rem the number of removed trees, BA the basal area, BA rem the basal area of the removed trees, *dg* the quadratic mean diameter, $CCF_{conifer}$ the crown competition factor of conifer trees, $CCF_{broadleaf}$ the crown competition factor of broadleaf trees, d.b.h. the diameter at breast height and CCFL the crown competition factor of larger trees. The numbers in the cells show the mean values with minimum and maximum in parenthesis. The indices are grouped by their inclusion in equations (7) and (8).

only the d.b.h. of the sample trees is provided. Trees with a d.b.h. smaller than 5 cm are not measured. Since with a basal area factor of 4, each tree in an angle count sample represents 4 m², a representative number of trees (N_{rep}) can be calculated according to the d.b.h.. Thus, for each sample tree, N_{rep} trees with the same d.b.h. are generated. The position of the trees is determined using the program STANDGEN (Kittenberger, 2003). Structural information about the aggregation of the plot is incorporated by the Clark–Evans index (Clark and Evans, 1954). Properties of species mixtures are integrated using the Füldner index (Füldner, 1996). Both indices are needed for the stand generation routine in STANDGEN. For each angle count sampling point, a representative 1 ha plot was generated and used for model simulation.

Measurements for the height of the trees are only available in the year 2000 for the trees with the median of the basal area distribution on each point and for each tree species. Based on these trees, height curves according to Pollanschütz (Pollanschütz, 1973), Petterson (Schmidt, 1956) and Kern (Prodan, 1965) are parameterized to calculate the missing heights.

Pollanschütz:

$$h = e^{a+\frac{b}{\mathrm{DBH}}} + 1.3. \quad (3)$$

Petterson:

$$h = \frac{1}{\left(a + \frac{b}{\mathrm{DBH}}\right)^2} + 1.3. \quad (4)$$

Kern:

$$h = e^{a+b\cdot\ln\left(\frac{\mathrm{DBH}}{\mathrm{DBH}+1}\right)} + 1.3, \quad (5)$$

whereas *a*, *b* and *c* are species-specific coefficients. The HLC is calculated according to Kahn and Pretzsch (1997) with parameters defined in Wurzer (2009):

$$\mathrm{HLC} = h\cdot\left(1 - e^{a+b\cdot\frac{h}{\mathrm{DBH}}+c*\mathrm{DBH}}\right). \quad (6)$$

Analysis and results

Model calibration

Modelling a single-tree selection process for the simulation of a harvesting regime has already been applied by Sterba *et al.* (2000) and Ledermann (2002). The concept of using two logistic functions – one to determine the harvesting probability of a plot and another to calculate the removal probability of a single tree – is similar to the approach described in Ledermann (2002). However, in our application, the resulting probabilities are compared with random numbers to define if a plot is harvested and which tree is removed, while in Ledermann (2002), two thresholds are defined to determine whether the tree removals take place.

Next, we need to define the set of independent variables for our harvesting equations. Since the d.b.h. was the only repeated measurement for every tree of the available dataset, we decided to integrate the d.b.h. in both equations.

The first equation predicts the probability of harvesting which may take place at a given plot. The quadratic mean diameter (*dg*) was calculated and used as an independent predictor. For the second equation of our harvesting tool, the d.b.h. for each tree is used to predict the removal probability. The squared d.b.h. term in equation (8) was introduced because the available removal data suggest a parabolic shape of the removal probability of the trees with a minimum in the middle d.b.h. classes.

Our tree data come from permanent angle count sampling plots. Thus, we decided to choose the distance-independent CCF according to Krajicek *et al.* (1961) as an additional driver for tree harvesting. Since the length of a remeasurement period was either 5 or 10 years, a dummy variable addressing the length of the period (*pl*) was introduced. If the remeasurement period was 5 years, the dummy variable is set to 1, otherwise to 0. With this dummy setting, the differences in the harvesting probabilities according to the differences in the length of the remeasurement period are addressed.

Species mixture influences tree mortality and the harvesting strategy of uneven-aged mixed plenter forests. Thus, we calculated a species-specific CCF for conifer and broadleaf trees and integrated them separately in the first equation that calculates the harvesting probability. In the second equation that operates on a tree level and calculates the removal probability, there are five dummy variables for the different tree species (spruce, fir, larch, pine and beech).

Other variables such as the proportion of conifer and broadleaf trees at a given plot were also tested but only those that were significant at a $\alpha = 0.05$ level were selected. Only the d.b.h. was repeatedly measured. Thus, we decided not to include tree height or height – diameter ratios (H/D – ratio) since they would have been derived from d.b.h. and such smoothed height information reduces the variation *vs* observed height data and may effect the error structure of model results (Hasenauer and Monserud, 1997).

The harvesting model was calibrated using the full company dataset covering the three regions Sommereben, Hebalm and Fürstenfeld. The first equation that calculates the harvesting probability of a plot has the following form:

$$P_{\text{Harvest}} = \frac{1}{1 + e^{a_0 + a_1 \cdot dg + a_2 \cdot \text{CCF}_{\text{conifer}} + a_3 \cdot \text{CCF}^2_{\text{conifer}} + a_4 \cdot \text{CCF}_{\text{broadleaf}} + a_5 \cdot pl}}, \quad (7)$$

where P_{Harvest} is the resulting probability of harvesting a plot. Variable *dg* denotes the quadratic mean diameter; CCF is the crown competition factor (Krajicek *et al.*, 1961). As mentioned before, the CCF is calculated independently for conifer ($\text{CCF}_{\text{conifer}}$) and broadleaf ($\text{CCF}_{\text{broadleaf}}$) trees to be able to take care of mixture effects. *pl* denotes the dummy variable for the period length. Wald chi-square test statistics (Wald, 1943) were used for independent variable selection at a significance level of $\alpha = 0.05$. The results are given in Table 3.

The second equation of our harvesting model calculates the removal probability of every tree on a plot where harvesting occurred. It has the following form:

$$P_{\text{Remove}} = \frac{1}{1 + e^{b_0 + b_1 \cdot \text{DBH} + b_2 \cdot \text{DBH}^2 + b_3 \cdot \text{CCFL} + b_4 \cdot pl + b_5 \cdot \text{spruce} + b_6 \cdot \text{fir} + b_7 \cdot \text{larch} + b_8 \cdot \text{pine} + b_9 \cdot \text{beech}}}, \quad (8)$$

where P_{Remove} denotes the probability of a tree to be removed; d.b.h. is the diameter at breast height and is included in the equation in two ways, the actual d.b.h. and the squared d.b.h. So it is possible to calculate a minimum or maximum probability for a particular d.b.h. Similar to the first equation, the period length (*pl*) is included because different probabilities are expected within a different period length. The mixture effect is maintained by five

Table 3: Estimated coefficients of equations (7) and (8), the standard error, the Wald chi-square statistics and the *P*-values

Variable	Coefficient	SE	Wald chi-square	*P* > chi-square
Equation 7				
a_0	3.257	0.394	8	<0.0001
a_1	−0.05095	0.006446	62	<0.0001
a_2	−0.02058	0.002829	53	<0.0001
a_3	0.00002048	0.000007667	7	0.007563
a_4	−0.01016	0.001747	34	<0.0001
a_5	0.9899	0.1223	66	<0.0001
Equation 8				
b_0	0.8808	0.02036	1871	<0.0001
b_1	0.05136	0.0008188	3935	<0.0001
b_2	−0.0007128	0.00001476	2331	<0.0001
b_3	−0.001567	0.00003523	1979	<0.0001
b_4	0.3003	0.005354	3145	<0.0001
b_5	−0.6965	0.01558	1998	<0.0001
b_6	−0.3547	0.01937	335	<0.0001
b_7	−0.7561	0.02096	1301	<0.0001
b_8	−1.082	0.01859	3388	<0.0001
b_9	1.278	0.03529	1312	<0.0001

For the calibration process, N_{rep} trees were generated for each sample tree of the angle count sampling in order to take care of the weighting effect in the sampling method. This resulted in the total number of 1 131 820 trees used for the calibration.

dummy variables for the different tree species (spruce, fir, larch, pine and beech). All selected independent coefficient variables had to be significant ($\alpha = 0.05$) according to the Wald chi-square test statistic. The results are given in Table 3.

Model evaluation

Long-term permanent inventory data from uneven-aged mixed species forests across larger forest areas are very difficult to obtain. Thus, in our calibration process, we used all the available information to mimic the typical silvicultural forest management system of the company. The disadvantage of this approach is that no independent data for a classical model validation were available. Therefore, we decided to evaluate our harvesting model as follows:

1 We implement the harvesting model in the tree growth model MOSES.
2 We initialize the forest stands using the permanent plot data information at plot establishment: 1980 for Sommereben and Fürstenfeld and 1985 for Hebalm.
3 We run MOSES for 50 years and apply the developed harvesting model in each period. Thus, each forest stand covers ten 5-year period since the prediction period in MOSES comprises 5 years.
4 Compare predicted results *vs* observed harvesting data supplied by the company districts.

After running the model on the available dataset, 69 per cent of all trees were classified correctly. Among the removed trees, the proportion of correct classified trees was 24 per cent, whereas 80 per cent of the remaining trees were classified correctly. The model also predicted 60 per cent of all plots correctly as being harvested or not: 68 per cent of the harvested and 48 per cent of the non-harvested plots. The small percentage of correct classified removed trees is an effect of overall model interpretation. If harvesting a plot is not classified correctly in the first step, then all trees that are removed on that plot are not taken into consideration for step 2. If however we applied the second equation only on the plots where harvesting was observed according to the dataset, the proportion of correctly classified removed trees increased to 34 and to 83 per cent for the remaining trees (73 per cent for all trees).

Figure 1 shows the probability of a tree being removed in relation to d.b.h. on all plots where harvesting was applied. Only the probabilities for spruce, fir and beech are depicted; other tree species behave similarly. The probability exhibits a parabolic shape with the highest values for trees with low and high d.b.h. This is a result of the squared d.b.h. term in equation (8). It is also evident that trees are more likely to be removed in a 10-year period than in a 5-year period. The tree species with the highest removal probability is spruce, followed by fir. Beeches are very unlikely to be taken out since the current management regime tries to increase the species diversity by supporting other species than spruce.

Next, we were interested in a comparison of observed *vs* predicted proportions of removed trees evident from the dataset and the MOSES simulations (Figure 2). The proportions are grouped into 5 cm d.b.h. classes. The figure depicts the mean values per 5-year period and plot. The parabolic shape is most evident in the region

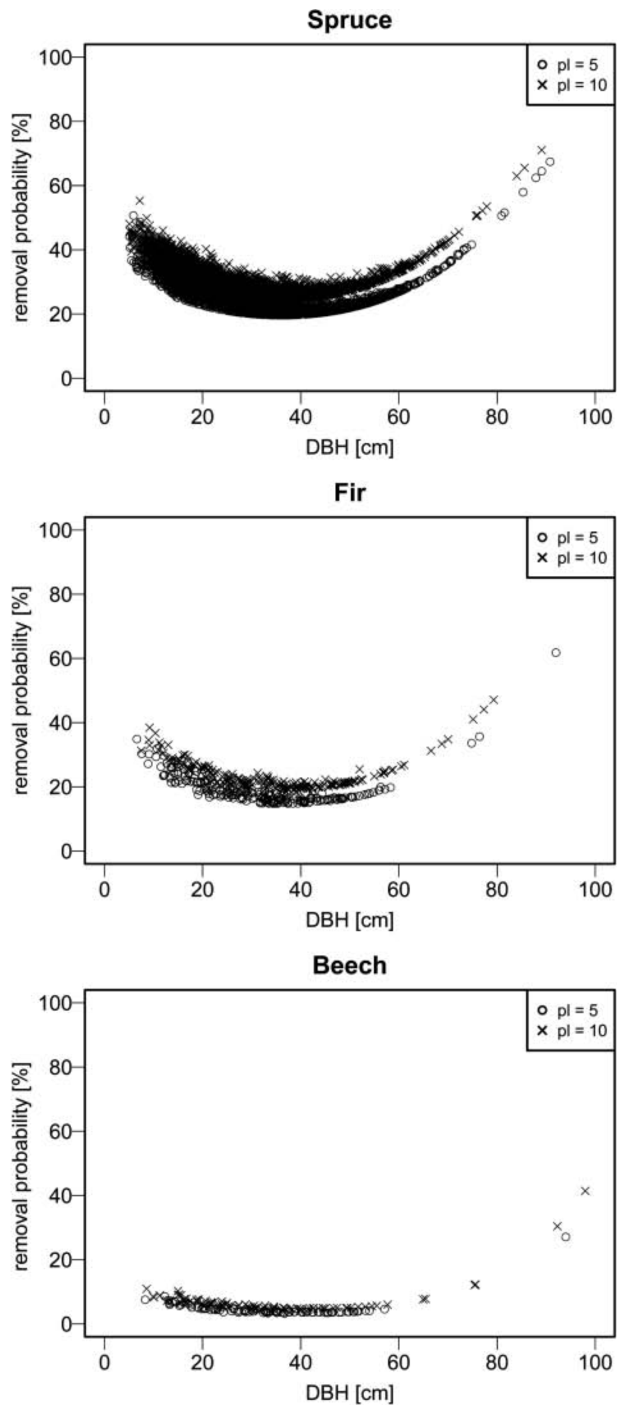

Figure 1. The probability of a tree being removed according to its d.b.h. (centimetre), calculated by the harvesting model. Only trees on plots on which harvesting is predicted are shown. The cycles show the probability of trees in a 5-year period; the probabilities denoted by an 'x' show trees of a 10-year period. The first graphic shows the probability of spruce, the second of fir and the last of beech.

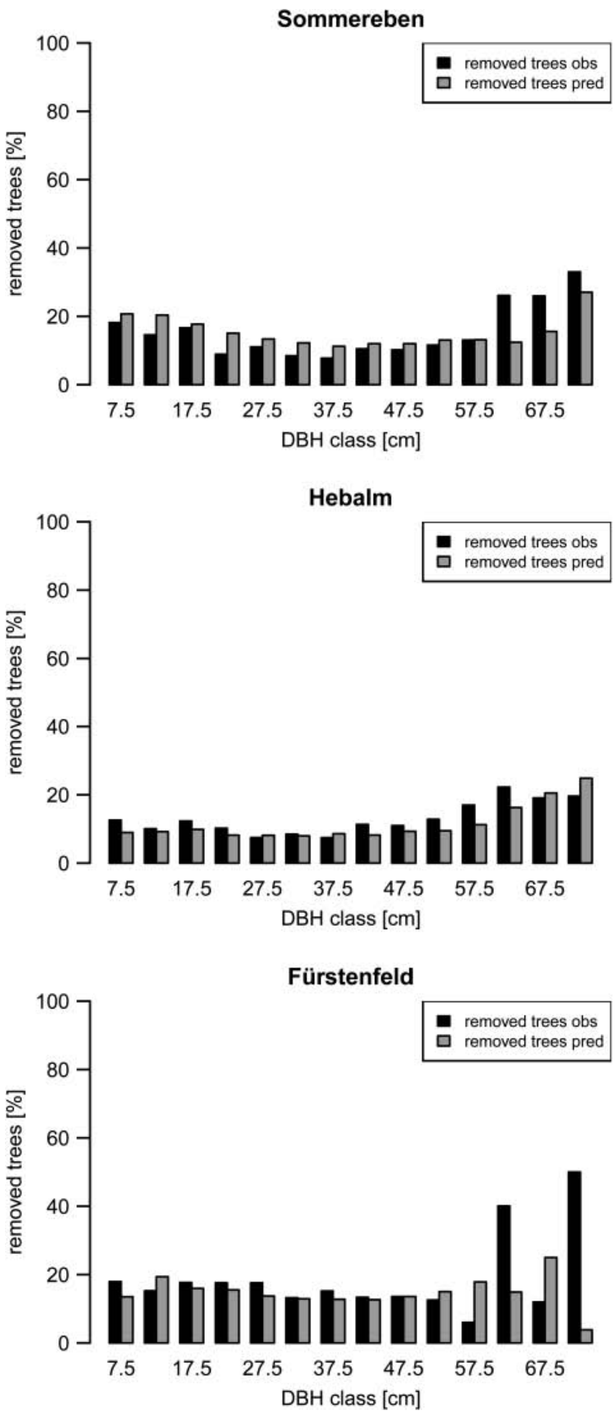

Figure 2. The predicted (pred) and observed (obs) proportion of removed trees (stem number) per 5-year period. The figure shows the mean value per plot. The first graphic shows the proportion in region Sommereben, the second in Hebalm and the third in Fürstenfeld.

Sommereben. This suggests that the MOSES simulation slightly overestimates tree harvesting in the low and medium d.b.h. classes and underestimates in the high ones. There are not many trees in the high d.b.h. classes (>60 cm), so the variance is high. In region Hebalm, the parabolic shape is not so evident as in Sommereben, but the relationship between predicted and observed probabilities is consistent. There is a minor underestimation in the low d.b.h. classes and in the classes between 40 and 60 cm. The results for region Fürstenfeld do not depict the expected shape of the removal probability, but the comparison of predicted and observed removals also suggests that the harvesting model in combination with MOSES creates a valid result. It is important to note that with each new remeasurement, more data for model calibration are available and this enhances the reliability of the calibrated models and the resulting predictions.

One important issue within uneven-aged forest management is the existence of a continuous harvesting regime so that a plenter harvesting balance may be created. A simple measure for such a balance is basal area and its change over time (O'Hara *et al.*, 2007). In Figure 3, the predicted *vs* observed basal area development is shown. Only trees with a d.b.h. >5 cm are used for calculation. Observed values are only available until the year 2000. The predicted development is calculated for 10 periods (50 years) starting at the first measurement and ending in 2030 in Sommereben and Fürstenfeld and 2035 in Hebalm. The basal area development is shown for both the remaining and the removed trees. In Sommereben, the predicted and observed development of the remaining stand is almost identical, the removals are slightly overestimated between 1985 and 2000. The simulated remaining stand basal area is almost constant at the beginning and increases to ~35 m^2 ha^{-1}. In Hebalm, the harvesting model underestimates the predicted basal area development; the removed basal area is overestimated from 1985 to 1995. The predicted and observed basal area development shows an increasing trend with a smaller magnitude in the predictions. At the end of the simulation, the basal area levels-out at ~32 m^2 ha^{-1}. In the last region, Fürstenfeld, the decreasing trend in the remaining basal area development is evident in the observation as well as in the prediction, although the prediction clearly overestimates from 1990 to 2000. This is also shown in the underestimation of the removals between 1990 and 2000. In the long term, the prediction shows a constant development suggesting a basal area of ~35 m^2 ha^{-1} across all sites.

Discussion

Uneven-aged forests or plenter forests require a sophisticated management regime with selective, individual and regular harvesting (Reininger, 2000). The selection of the trees to be removed cannot be easily translated into defined harvesting rules since each company may have different silvicultural strategies according to their history as well as existing stand and site constraints. Thus, a probabilistic plenter harvesting model with two logistic functions, similar to Ledermann (2002), was fit to a dataset of three forest regions where plenter harvesting is applied. The potential of logistic functions to model tree selection

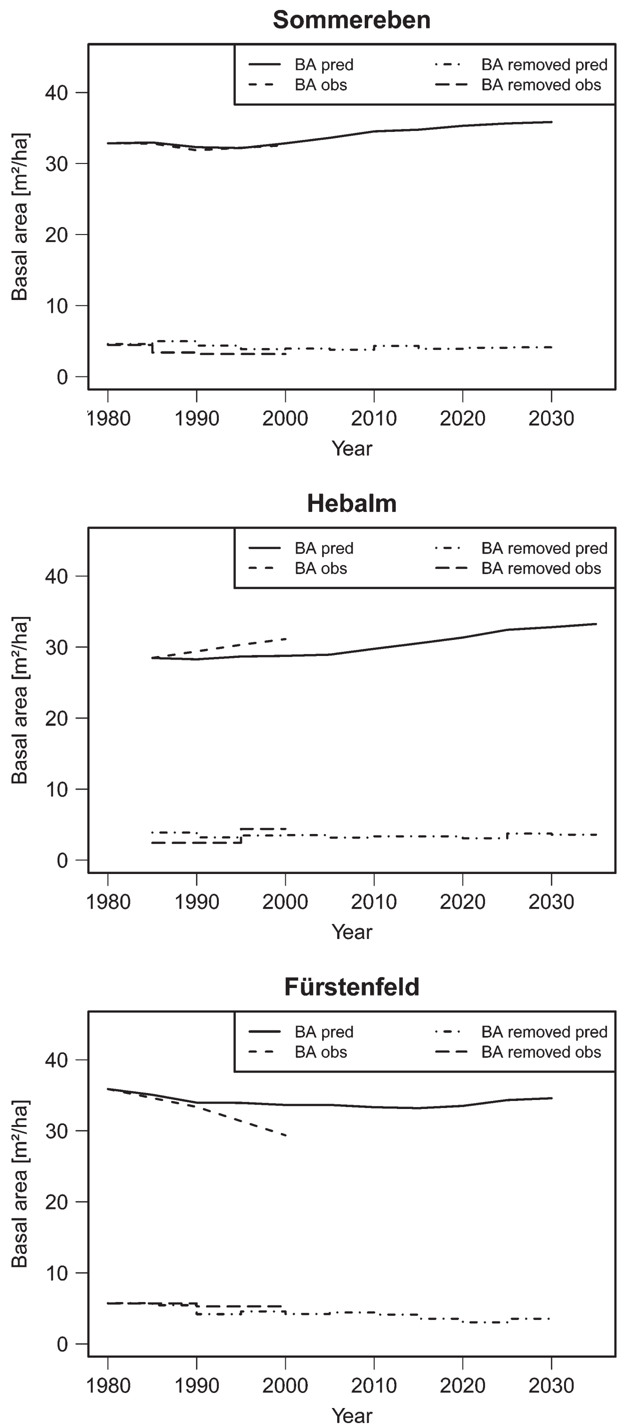

Figure 3. The predicted (pred) and observed (obs) basal area development (square metres per hectare) for the remaining stand (BA) and the removed trees (BA removed), respectively. The figure shows the mean values per plot. The first graphic shows the proportion in region Sommereben, the second in Hebalm and the third in Fürstenfeld.

preferences was shown by Füldner (1996). All regions are still in the transition phase from even to uneven-aged treatment, the beginning of the management change varied from 40 to 80 years. Not every plot in the plenter forest of the available dataset is harvested in a constant 5-year time period. The prediction of the probability of a plot to be harvested makes the model robust to inconsistent harvesting periods because the harvesting of a plot depends on site characteristics and not on a constant time period. For the model calibration, only 5- and 10-year measurement periods are available. The LOGIT functions of the two equations contain the period as a dummy variable that is set to one if the length of the period is 5 years. That results in a lower probability of trees being removed in a 5-year period (Figure 1). Possible species mixture effects are integrated in equation (7) by calculating the CCF (Krajicek *et al.*, 1961) for conifer and broadleaf trees, respectively. In equation (8), there are dummy variables for spruce, fir, larch, pine and beech that take care of existing species-driven selection criteria for harvesting.

The parabolic shape of the removal probabilities of the trees according to the d.b.h. (Figure 1) is a result of the squared d.b.h. term in equation (8). A higher probability of small trees being removed is plausible in the plenter management regime due to the stem reduction or pre-commercial thinning on young plots. Since in uneven-aged mixed species forests, a high natural regeneration is expected, a lot of small trees have to be removed. The model predicts the lowest removal probability at a d.b.h. between 30 and 50 cm. Trees with a larger d.b.h. are again more likely to be removed as they reach their harvesting volume or target diameter.

According to Figure 1, the management regime supports other trees than spruce, especially beech, in order to increase the species diversity. This is a desired characteristic in uneven-aged managed forests in this area. Only pine has a higher removal probability than spruce (result not depicted). Pine trees are mainly located in region Fürstenfeld followed by Sommereben (Table 1). The current management regime does not support pine in this area because the conditions there are not suitable for a light-demanding tree species such as Scots pine. All other tree species show a lower removal probability than spruce.

Figure 2 shows the predicted and observed mean proportion of removed trees per period in the observation time span until the year 2000. Compared with the parabolic shape of the removal probabilities of the model in Figure 1, the expected shape is mainly evident in region Sommereben followed by Hebalm. Fürstenfeld shows a more or less constant removal proportion over all d.b.h. classes. Especially in region Sommereben, it is obvious that the model smoothes the removal proportion to the expected parabolic shape over the d.b.h. classes.

The predicted stand suggests that the basal area of all regions will level-out at ~32 to 36 m^2ha^{-1} with a more or less constant removal over time (Figure 3). This leads to a sustainable forest assuming that the current management regime is applied continuously. One problem of our current results may be an underestimation of the basal area in Hebalm and an overestimation in Fürstenfeld (see Figure 3). However, the harvesting regime is not constant during the transition phase from even to uneven-aged forest management and the timing of the silvicultural management change is an important factor. Hebalm changed the harvesting regime at the beginning of the 1970s and thus was the last region that entered the transition phase from an even-aged mainly spruce-dominated forest to an uneven-aged mixed species plenter forest. Fürstenfeld had already changed in the 1930s. In this region, the model overestimates the basal area of the remaining stand (underestimates the removals), whereas in the region with the most recent change, the basal area is underestimated. For Sommereben, where the timing of the management change was between that of Fürstenfeld and Hebalm, the model predictions show the best result. This suggests that the timing of the management change is important for the modelled harvesting results. The company established a permanent forest inventory in the early 1980s with remeasurement intervals of 5–10 years. With each remeasurement, the database will be improved and any recalibration of our model approach by adding new data will enhance the reliability of the resulting predictions.

One problem of the dataset and the calibration process is the lack of regeneration information because only trees with a d.b.h. greater than 5 cm were measured. Therefore, the harvesting model could not be calibrated for smaller trees which might have a much higher removal probability than shown in Figure 1. In the simulation, a lot of small trees are generated within the regeneration model provided in MOSES (Hasenauer and Kindermann, 2006). Again, we can assume that with an increasing number of repeated measurements and recalibration of our approach, the quality of the resulting harvesting model for the three different districts will be systematically improved.

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Conflict of interest statement

None declared.

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9.2 *Paper II*

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Analysing different carbon estimation methods for Austrian forests

Eine Analyse unterschiedlicher Kohlenstoffschätzmethoden für Wälder in Österreich

Christopher Thurnher*, Thomas Gerritzen, Michael Maroschek, Manfred J. Lexer, Hubert Hasenauer

Key words: Carbon estimation, Austrian biomass functions, expansion factors, biomass allometries

Schlagwörter: Kohlenstoffschätzung, österreichische Biomassefunktionen, Biomasseexpansionsfaktoren, Biomasseallometrien

Abstract

Terrestrial tree measurements of diameter at breast height (DBH) and height are used to estimate the carbon of different tree compartments. In this paper we will present four different carbon estimation methods for three major tree species (Norway spruce, common beech and Scots pine) in Austria and demonstrate the differences in the resulting predictions ac-

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cording to the chosen method. Carbon estimations of single trees can be generally based on biomass equations or biomass expansion factors. The investigated methods are the Austrian biomass functions (ABF), biomass functions based on allometric relationships of tree data collected by Burger (Burger), biomass expansion factors (BEF) and calculations recommended by the Intergovernmental Panel on Climate Change (IPCC). Since we were interested in the theoretical impacts of the chosen method we generated a standardized data set representing a similar number of trees within each diameter class. We calculated the overall above ground carbon as well as the carbon of different tree compartments (stem, branches, needles/leafs). All four approaches show similar results for trees with a DBH below 50 cm across all three investigated tree species. With an increasing DBH the differences in the resulting carbon estimation methods increase, suggesting that the method chosen has a strong impact on the results.

Zusammenfassung

Messungen von Brusthöhendurchmesser (BHD) und Höhe von Bäumen können verwendet werden um den Kohlenstoff von verschiedenen Baumkompartimenten zu schätzen. In dieser Arbeit werden vier verschiedene Methoden der Kohlenstoffschätzung für drei Baumarten (Fichte, Buche und Kiefer) hinsichtlich ihrer Unterschiede im berechneten Kohlenstoffgehalt analysiert. Die Kohlenstoffschätzungen können grundsätzlich auf Biomassefunktionen oder Biomassenexpansionsfaktoren basieren. Die untersuchten Methoden umfassen die österreichischen Biomassefunktionen (ABF), Biomassefunktionen, die anhand von Allometrien von gemessenen Baumdatensätzen aufgenommen von Burger berechnet wurden (Burger), Biomasseexpansionsfaktoren (BEF) und Empfehlungen des Weltklimarates (IPCC). Einige dieser Methoden benutzen entweder Biomassefunktionen oder Biomasseexpansionsfaktoren, andere benutzen eine Kombination aus beiden. Das Datenmaterial für diese Studie besteht aus ca. 50 Bäumen je Durchmesserklasse. Für jeden Baum je Durchmesserklasse wird der oberirdische Kohlenstoffgehalt sowie aufgeteilt auf verschiedenen Baumkompartimenten (Stamm, Äste, Nadeln/Blätter) berechnet und verglichen. Alle vier Verfahren zeigen ähnliche Ergebnisse für Bäume bis zu einem BHD von ca. 50 cm. Bei größeren BHD Klassen nehmen die Unterschiede zwischen den Methoden zu und es zeigt sich damit sehr deutlich, dass die Kohlenstoffschätzungen von Waldgebieten sehr wesentlich von der gewählten Methode abhängen.

1. Introduction

Forests play an important role in the global carbon cycle since they mitigate a large amount of CO_2. About 30 % of the global CO_2 emissions remain in the land biosphere (Canadell et al., 2007). In Austria, 47.6 % of the country is covered with forests; this comprises an area of 3.99 million hectare (Russ, 2011). According to the Austrian forest inventory (Büchsenmeister, 2011), the volume stored in Austrian forests encompasses 1.135 million m³ and has steadily increased since 1971 (827 million m³). The above ground biomass stored in these forests is 647 million tons.

Since the forest area and the stored biomass have been increasing, the role of forests in Austria within carbon sequestration has become more and more important. Mechanisms to measure and monitor the carbon that is stored in the ecosystem are essential. A common method is to use terrestrial measurements that are derived from inventories using sampling techniques (Gallaun et al., 2010; IPCC, 2003; Lecointe et al., 2006; Mohren et al., 2012). The DBH and the height of sample trees are measured to calculate the standing timber volume and volume increment. In Austria, the common methods for forest monitoring at the national and company level are angle count sampling techniques (Bitterlich, 1948; Gabler and Schadauer, 2008). However other methods, such as fixed area plots are also common, depending on the purpose of the data recording.

There are two different conceptual approaches for deriving the above and belowground carbon or biomass from terrestrial data sources:

1. Biomass expansion factors (Brown, 2002; IPCC, 2003; Pietsch et al., 2005)

2. Biomass functions (Hasenauer et al., 2012; Hochbichler et al., 2006; Zianis et al., 2005)

Biomass expansion factors are usually species specific constant parameters to derive the biomass from tree volume. Various methods or equations exist to obtain tree volume from terrestrial data, such as the volume function according to Pollanschütz (1974) or equations that calculate merchantable timber volumes (e.g. Kennel, 1973). Depending on the expansion factor, the biomass obtained with the expansion factor can express different tree compartments: the stem biomass (Pietsch et al., 2005) or the above ground biomass (IPCC, 2003).

In contrast to biomass expansion factors, biomass functions are used to calculate the biomass of a given tree or of different tree compartments from tree attributes. They are commonly based on allometric relationships using the DBH and/or the tree height for calculating tree biomass. Various stem volume and biomass functions have been developed and calibrated for European forest conditions, a summary is given in Zianis et al. (2005).

Biomass functions and biomass expansion factors are used to assess and/or derive carbon estimates for forests. Since the carbon content of trees cannot be measured directly, it is common that, based on the chosen method, we first estimate tree parameters (see biomass functions) or tree or stand volumes (see biomass expansion factors) to predict the carbon content for the different compartments (leaves, branches, stem, etc). The terrestrial tree or forest stand data is obtained from forest inventories or other tree measurements. Since forest inventories are mainly based on tree measurements, the carbon estimation method directly influences the resulting forest carbon stocks and the derived changes over time, e.g. the estimated carbon decrease and source potential of our forests.

The same approach is chosen for initializing the carbon pools within ecosystem modelling. Population models such as tree growth models (e.g. MOSES; Hasenauer, 1994 or PROGNAUS; Sterba and Monserud, 1997) predict the DBH and height development as well as the volume increment over time. This information can easily be used for deriving the carbon pools of the corresponding forests. A similar approach is common within succession or gap modelling (Bugmann, 1994). Based on the DBH development, a biomass function is used to predict the carbon development of tree species over time. Hybrid model approaches (e.g. PICUS; Seidl et al., 2005) use the biomass functions as an integral part in the model logic to partition assimilated carbon to different tree compartments. The carbon or biomass development by species over time reflects the interspecific and intraspecific competition situation of trees within the forest. Thus, any conceptual difference in the carbon estimation method may change e.g. resulting species compositions and thus the simulation output of gap models. This is similar for carbon estimates derived from tree growth models. The only difference is that the estimated tree population development over time is independent from the carbon estimation method. This is because the tree dimensions are predicted first; and these predictions are independent from the chosen carbon/ biomass transfer procedure. The only exception are biogeochemical mechanistic (BGC) ecosystem models (Thornton, 1998; Thornton et al., 2002), since they estimate carbon uptake and carbon partitioning directly by incorporating a photosynthesis routine. BGC models are flux models which usually do not provide tree lists. Therefore, this modelling approach uses biomass expansion factors or biomass functions to allow for a comparison of the model output with terrestrial forest data (Pietsch et al., 2005).

In this paper we are interested in analysing and assessing potential differences in four different terrestrial data driven carbon estimation methods used in Austria: (i) Austrian biomass functions (ABF), (ii) biomass functions based on allometric relationships of tree data collected by Burger (Burger), biomass expansion factors (BEF) and calculations recommended by the Intergovernmental Panel on Climate Change (IPCC). Since we are interested in the theoretical impacts of the chosen method we will generate a standardized data set representing a similar number of trees within each diameter class and calculate the overall above ground carbon, as well as the carbon of three different tree compartments (stem, branches, and needles/leaves).

The specific tasks of the paper can be summarized as follows:

1. Presentation of available carbon calculation methods for Austria

2. Application of the different methods for a standardized terrestrial data set

3. Demonstration of differences in the carbon estimates according to chosen method

2. Data

The data for this study comes from a generated theoretical data set by DBH class. To ensure a realistic coverage in the range of the tree data, we randomly extract about 50 trees for each 5 cm DBH class from the Austrian National Forest Inventory data (Gabler and Schadauer, 2008) for Norway spruce (*Picea abies* (L.) Karst), beech (*Fagus sylvatica* L.) and Scots pine (*Pinus sylvestris* L.). The idea was that, in our generated data, we wanted to cover the full range of (i) DBH classes but also the (ii) DBH – height variations by species in Austria. Selecting only about 50 trees by DBH class versus obtaining all available tree data allows us to assess the theoretical differences by carbon estimation method, independent from the amount of trees within a given DBH class.

For Norway spruce and beech the DBH ranges from 5 cm – 105 cm; for Scots pine from 5 cm – 75 cm. This resulted in 1000 spruce, 942 beech and 632 pine trees (see Table 1). This procedure provides a consistent 'theoretical' data set which allows for an in depth analysis of the different carbon estimation methods.

Table 1: DBH and height of the different tree species used in this study. The values show the mean, standard deviation (s.d.), minimum (min), maximum (max), the 25. percentile (25.p.) and the 75. percentile (75.p.). N denotes the number of trees.

	mean	s.d.	min	max	25.p.	75.p.
Spruce (N = 1000)						
DBH	54.94	28.83	5.20	105.00	30.10	80.03
height	26.54	10.01	3.00	49.00	20.60	33.60
Beech (N = 942)						
DBH	52.20	27.31	5.20	105.00	29.22	75.40
height	23.77	7.97	3.20	41.70	18.10	30.00
Pine (N = 632)						
DBH	36.55	18.24	5.10	74.80	21.20	51.42
height	20.71	7.42	4.00	40.30	14.88	26.02

3. Methods

In our study we examined four different methods commonly used for estimating the above ground carbon content of forests:

1. ABF: The Austrian biomass functions (Hasenauer et al., 2012; Hochbichler et al., 2006)

2. Burger: Allometric biomass functions according to allometric relationships based on data collected by Burger (1929-1953), e.g. Bugmann (1994); Seidl et al. (2005)

3. BEF: Biomass expansion factors according to Pietsch et al. (2005)

4. IPCC: Biomass conversion and expansion factors recommended by the Intergovernmental Panel on Climate Change (IPCC, 2003)

A detailed summary of these calculation methods and equations can be found in Gerritzen (2013) and will be described in the next sections. The parameters of the functions needed for our comparative study are given in Table 2.

Table 2: Parameters used within the four calculation methodologies. The number of the equation, the result, the parameter name, the unit of the parameter and the values for the different tree species are displayed. The reference for the used parameter are depicted in the last column.

Method	Equation	Result	Parameter	Unit	Spruce	Beech	Pine	Reference
ABF	1	$C_{above\ ground}$	CC	kgC kg^{-1}	0.503	0.486	0.500	Pietsch et al. (2005)
	4	dsm	D	kg m^{-3}	800	950	820	
	4	dsm	1-WC	-	0.440	0.440	0.500	
	5	dbm	b0	-	-5.16890	-3.54015	-3.34766	Hochbichler et al. (2006)
	5	dbm	b1	-	2.69049	3.93514	2.04663	
	5	dbm	b2	-	0	-1.59363	0	
	6	dnm	b0	-	-6.17165	-	-3.78862	
	6	dnm	b1	-	2.83519	-	1.78458	
Burger	7	$C_{above\ ground}$	CC	kgC kg^{-1}	0.503	0.486	0.500	Pietsch et al. (2005)
	8	dsm	b0	-	0.03007189	0.2222500	0.04750124	Burger (1929-1953) Bugmann (1994) Seidl et al. (2010)
	8	dsm	b1	-	2.74001367	2.2503739	2.52715533	
	8	dbm	b0	-	0.022	0.022	0.036	
	8	dbm	b1	-	2.3	2.3	2.0534	
	8	dfm	b0	-	0.095565	0.021708	0.072981	
	8	dfm	b1	-	1.56	1.7	1.4	
BEF	11	dsm	D	kg m^{-3}	800	950	820	Pietsch et al. (2005)
	11	dsm	1-WC	-	0.440	0.440	0.500	
	12	$C_{above\ ground}$	CC	kgC kg^{-1}	0.503	0.486	0.500	
	12	$C_{above\ ground}$	MT	-	0.700	0.825	0.694	
IPCC	13	$C_{above\ ground}$	CC	kgC kg^{-1}	0.51	0.48	0.51	IPCC (2003)
	13	$C_{above\ ground}$	D	kg m^{-3}	400	580	420	
	13	$C_{above\ ground}$	BEF	-	1.3	1.4	1.3	

3.1 The Austrian biomass functions

The Austrian biomass functions describe a set of allometric functions commonly used in Austria to calculate the carbon content in needles, branches, and roots. The stem carbon part is estimated with expansion factors by a multiplication with the volume according to Pollanschütz (1974). A detailed summary can be found in Hasenauer et al. (2012). To obtain the overall above ground carbon content, different tree compartments are calculated and summed up; these are the dry stem mass, the dry branch mass and the dry needle mass. The following equation is used:

(1) $$C_{aboveground} = CC * (dsm + dbm + dnm)$$

CC denotes the carbon content, *dsm* the dry stem mass, *dbm* the dry branch mass and *dnm* the dry needle mass. The dry stem mass is calculated using the Pollanschütz volume equations (Pollanschütz, 1974):

(2) $$V_{Pol} = f * d^2 * \frac{\pi}{4} * h$$

Whereas *f* denotes the species specific form factor calculated as follows:

(3) $$f = b_0 + b_1 * \ln(d)^2 + b_2 * \frac{1}{h} + b_3 * \frac{1}{d} + b_4 * \frac{1}{d^2} + b_5 * \frac{1}{d * h} + b_6 * \frac{1}{d^2 * h}$$

The DBH (*d*) and the height (*h*) are measured values, b_0 – b_6 are species specific parameters that can be found in Pollanschütz (1974) and are summarized in Table 3. V_{pol} denotes the stem volume. The dry stem mass is then calculated as follows:

(4) $$dsm = V_{pol} * D * (1 - WC)$$

D is the wood density and *WC* is the water content. Both are species specific parameters cited in Pietsch et al. (2005) from Hager (1988), Hochbichler et al. (1994) and Sekot (1982). The dry stem mass is thus not calculated with allometric functions; it uses a biomass expansion factor that relies on specific factors of wood density and water content to derive the biomass from the volume.

The equations for the dry needle mass and the dry branch mass are allometric functions according to Hochbichler et al. (2006).

(5) $$dbm = e^{b_0 + b_1 * \ln(d) + b_2 * \ln(h)}$$

Variable *d* is the DBH, *h* denotes the height and b_0 – b_2 are species specific parameters.

The dry needle mass is calculated as follows:

(6) $$dnm = e^{b_0 + b_1 * \ln(d)}$$

The *dnm* only depends on the DBH (*d*) and two species specific parameters (b_0 and b_1). The leaf carbon for deciduous trees is set to zero.

3.2 Burger

These biomass functions were calibrated with data collected by Burger (1929–1953) and predict the stem, branch and foliage biomass with a set of allometric functions. The overall above ground carbon is calculated as follows:

(7) $$C_{aboveground} = CC * (dsm + dbm + dfm)$$

The only difference between Equation 7 and Equation 1 is that the Burger methodology calculates the dry foliage mass (*dfm*) instead of the dry needle mass (*dnm*). Thus, also deciduous trees have parameters for the leaves. The dry stem mass, dry branch mass and the dry foliage carbon are calculated as follows (Bugmann, 1994; Seidl et al., 2005):

(8) $$dsm, dbm, dfm = b_0 * d^{b_1}$$

All three values (*dsm, dnm* and *dfm*) are based on the same equation scheme (Seidl et al., 2005), only the species specific parameters b_0 and b_1 differ; *d* denotes the DBH.

3.3 Biomass expansion factors

The biomass expansion factor method derives the above ground carbon content from the merchantable timber volume according to Kennel (1973). The merchantable volume describes the volume of the stem and branches that have a diameter larger than 7 cm (Mitscherlich, 1970).

(9) $$V_{ken} = fh * d^2 * \frac{\pi}{4}$$

fh denotes the form height that is calculated with the following equations:

(10) $$fh = e^{a+b \cdot ln(h)+c \cdot ln^2(h)}$$

$$a = a_0 + a_1 * \ln(d) + a_2 * ln^2(d)$$

$$b = b_0 + b_1 * \ln(d) + b_2 * ln^2(d)$$

$$c = c_0 + c_1 * \ln(d) + c_2 * ln^2(d)$$

The volume is calculated with the DBH (*d*) and the height (*h*); a_i, b_i and c_i are species specific parameters defined by Kennel (1973) and summarized in Table 3. The dry stem mass is then calculated similarly to Equation 4; it just uses the merchantable volume (V_{ken}) instead of the stem volume (V_{pol}).

(11) $$dsm = V_{ken} * D * (1 - WC)$$

Dividing the *dsm* by the merchantable timber fraction (*MT*), as defined in Pietsch et al. (2005), gives us the overall timber biomass. The needle biomass is calculated in the same way as in the Austrian biomass functions in Equation 6 and added to the timber biomass. The result is multiplied with the carbon content to get the above ground carbon value.

(12) $$C_{aboveground} = CC * \left(\frac{dsm}{MT} + dnm\right)$$

To get the branch biomass, we subtracted the stem biomass from the timber biomass obtained with the merchantable timber fraction.

(13) $$dbm = \frac{dsm}{MT} - dsm$$

Pietsch et al. (2005) propose different values for lowland and highland spruce. For this study, the value defined for highland spruce was chosen (Table 2).

3.4 IPCC functions

The functions recommended by the Intergovernmental Panel on Climate Change (IPCC, 2003) define a set of conversion and expansion factors, but no allometric functions. The above ground carbon is a function of the merchantable timber (V_{ken}), wood density (*D*), biomass expansion factor (*BEF*) and carbon content (*CC*).

(14) $$\mathbf{C}_{aboveground} = \mathbf{V}_{ken} * D * BEF * CC$$

The IPCC defines different values for the wood density and the carbon content in comparison to the other methods (Table 2). We calculated the dry stem biomass (*dsm*) by multiplying the merchantable timber volume (V_{ken}) with the wood density (*D*) defined by the IPCC (2003).

(15) $$dsm = \mathbf{V}_{ken} * D$$

The wood density defined here directly converts the volume into dry mass, whereas the wood density in Equations 4 and 11 converts it to fresh weight, so that it has to be multiplied with the water content to achieve the dry mass. This explains the large differences in parameter *D* between the different methods (Table 2). The IPCC also defines different *BEF* values depending on the climatic zone (IPCC, 2003); the values for the temperate zone were chosen for this contribution.

We were not able to distinguish between branch and foliage biomass as we could within the previous defined methodologies. The branch and foliage mass (*dbfm*) can be estimated together, though.

(16) $$dbfm = dsm * BEF - dsm$$

All species specific parameters of the four methods are summed up in Table 2.

Table 3: Coefficients of the Pollanschütz stem volume and the Kennel merchantable timber volume equations.

Volume	Parameter	Spruce	Beech	Pine
Pollanschütz stem volume (Pollanschütz, 1974)	b0	4.68180e-01	6.86253e-01	4.35949e-01
	b1	-1.39190e-02	-3.71508e-02	-1.49083e-02
	b2	-2.82130e+01	-3.10674e+01	5.21091e+00
	b3	3.74740e-01	-3.86321e-01	0
	b4	-2.88750e-01	2.19462e-01	2.87020e-02
	b5	2.82790e+01	4.96136e+01	0
	b6	0	-2.23719e+01	0
Kennel merchantable timber volume (Kennel, 1973)	a0	-3.59624e+00	-2.72840e+00	-5.80915e+00
	a1	1.80213e+00	8.37563e-01	3.38700e+00
	a2	-2.88243e-01	-1.05343e-01	-4.94392e-01
	b0	1.06247e+00	1.62283e+00	3.67116e+00
	b1	-1.28993e-01	-2.14812e-01	-1.83211e+00
	b2	3.53434e-02	2.89272e-02	2.73999e-01
	c0	1.42264e-01	-8.79719e-02	-4.59282e-01
	c1	-5.82590e-02	3.25667e-02	2.99890e-01
	c2	4.59854e-03	-4.46295e-03	-4.44931e-02

4. Analysis and Results

We start our analysis by calculating the carbon by species specific biomass functions and expansion factors for each of our selected trees. This allows us to assess the methodological differences by method and/or by compartment (stem, branch, needles/leaves), if they are part of the estimation procedure. Note that the results differ only in the selected estimation method since the tree data set for doing this comparative study is identical.

4.1 Total above ground carbon

The calculated above ground carbon for all Norway spruce trees by calculation method is shown in Figure 1 and provides the results of the Austrian biomass functions (ABF), the biomass functions based on the Burger data (Burger), the biomass expansion factor method (BEF) and the results of the IPCC approach. All methods show a similar behaviour for DBH classes below about 50 cm. With increasing DBH, the difference in the resulting carbon predictions of the Burger approach increase. The difference between the ABF, BEF and IPCC method are small across the DBH range.

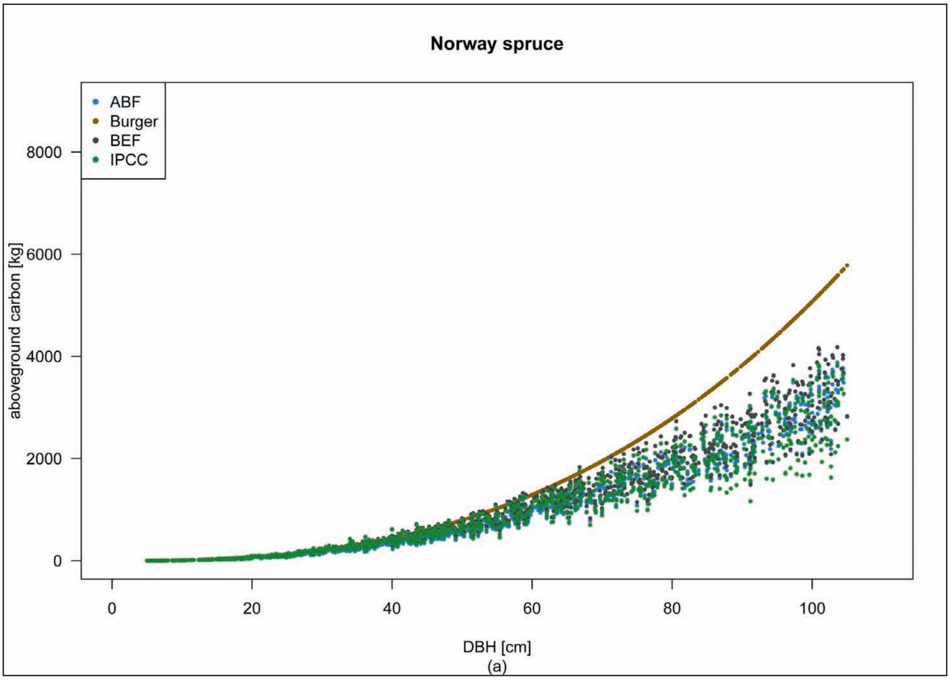

Figure 1: Above ground carbon for each Norway spruce tree according to the DBH. All four estimation methods (ABF, Burger, BEF and IPCC) are displayed.

The results for common beech by calculation method are presented in Figure 2. The carbon of the ABF method shows the highest results. The Burger results range between the BEF, which is the lowest, and IPCC results.

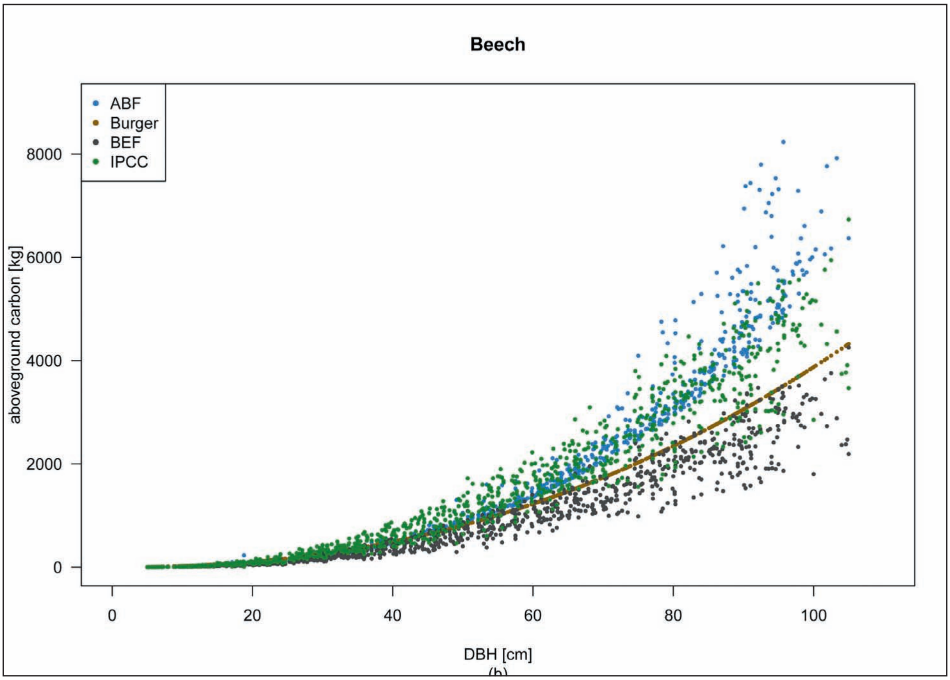

Figure 2: Above ground carbon for each beech tree according to the DBH. All four estimation methods (ABF, Burger, BEF and IPCC) are displayed.

The results for Scots pine are given in Figure 3. No distinct differences by method are detectable. The above ground carbon is rather low compared to spruce and beech and the expected DBH range in Austria is only between 5 cm and 75 cm.

4.2 Stem, branch and needle/leaf carbon

Next we were interested if certain discrepancies may exist in the applied estimation method and compartment. Thus we assessed potential differences in the stem, branch, and needle/leaf estimation in those methods which have explicitly included this as part of their overall carbon estimation procedure.

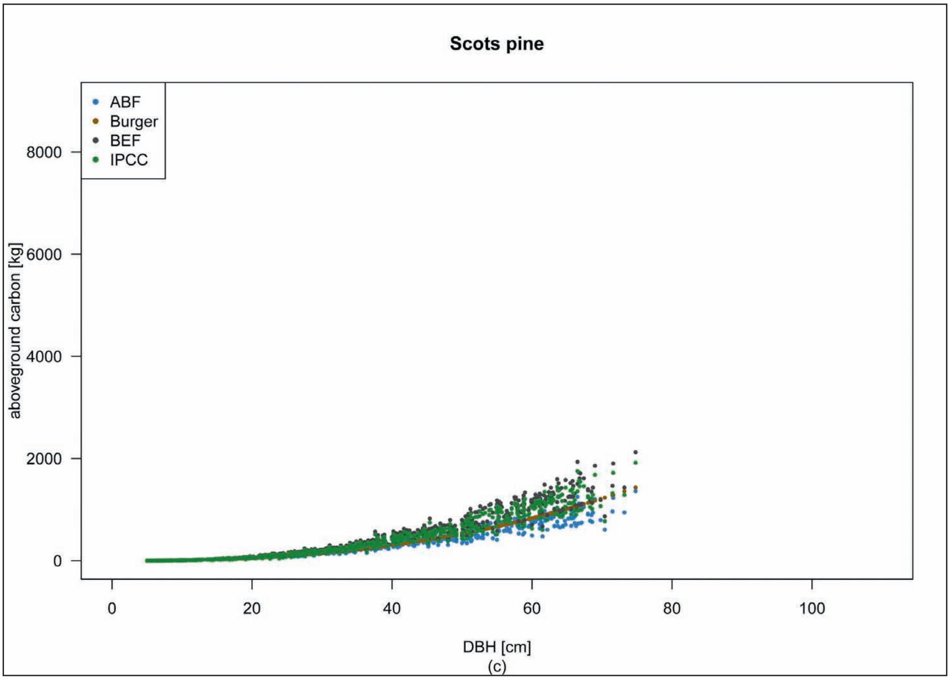

Figure 3: Above ground carbon for each Scots pine tree according to the DBH. All four estimation methods (ABF, Burger, BEF and IPCC) are displayed.

Figure 4 gives the results of the different carbon compartments for Norway spruce. The stem carbon is depicted in Figure 4 a, the branch compartment in Figure 4 b and Figure 4 c presents the needle carbon. The trees are grouped into ten DBH classes. Each DBH class shows the mean value of the trees within the group (DBH class 40 contains e.g. all trees with a DBH from excluding 35 cm to including 45 cm). The stem carbon shows the highest values for the Burger method. For large DBH classes, the stem carbon is more than twice as high as within the other methods. The IPCC results show the second highest values followed by the BEF and the ABF methodology. The branch carbon shows minor impact on the overall carbon since its values are much smaller than the stem carbon results but unlike the stem carbon, the results of the branch carbon show the smallest values for the Burger method. Lastly, the needle carbon of the ABF and BEF calculations is much higher than the Burger results. The IPCC does not distinguish between branch and needles, thus the values are depicted together in Figure 4 b.

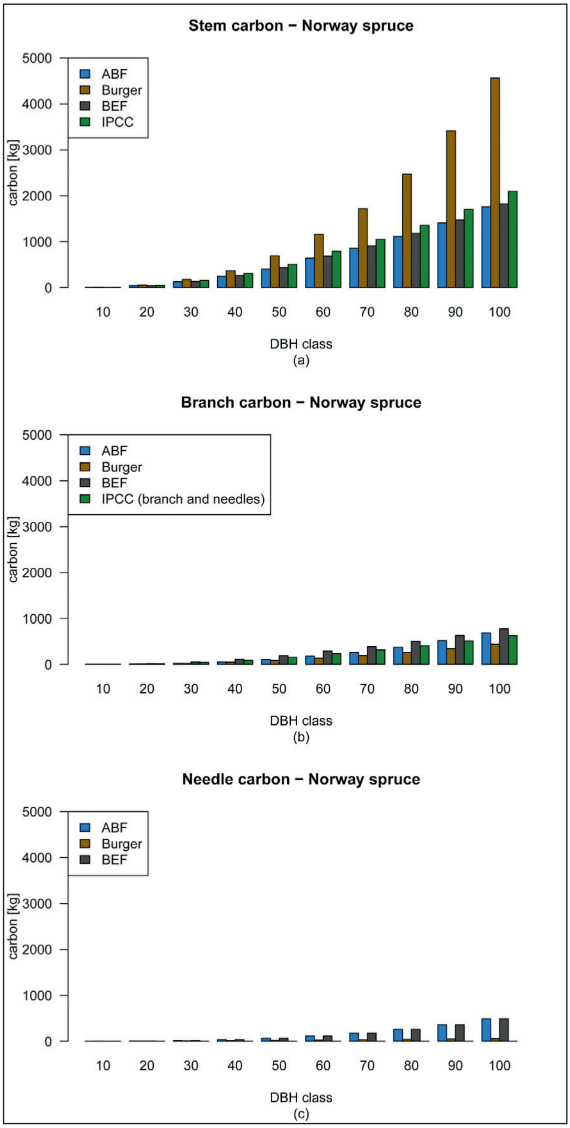

Figure 4: Carbon for the (a) stem, (b) branch (branch and needles for the IPCC method) and (c) needle carbon of all Norway spruce trees. The mean carbon values are displayed for each of the four presented methodologies (ABF, Burger, BEF and IPCC) according to 10 cm DBH classes. DBH class 40 e.g. denotes the mean carbon for all trees between excluding 35 cm to including 45 cm.

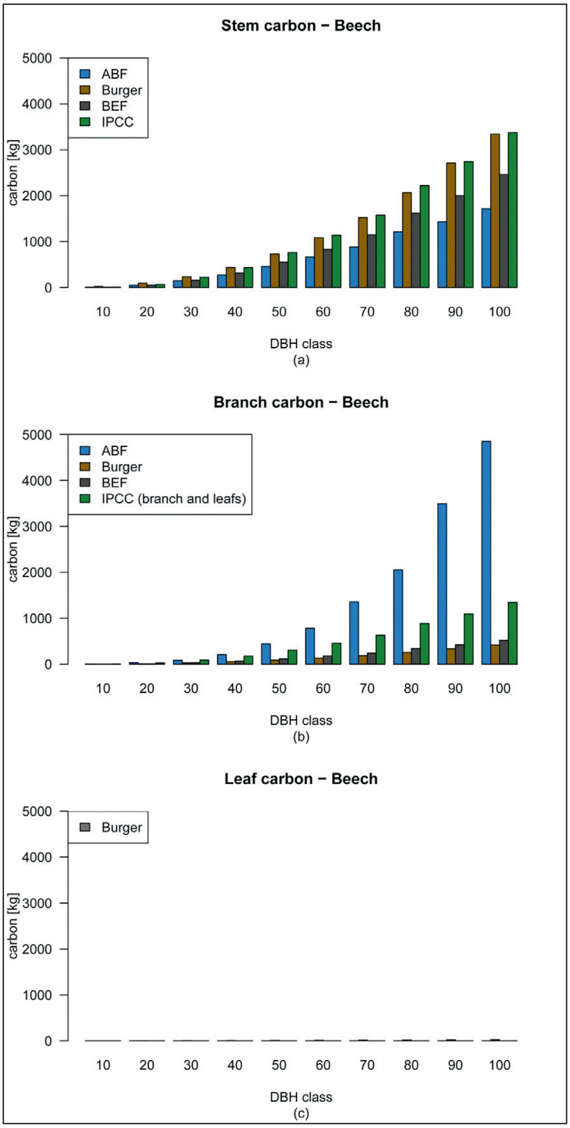

Figure 5: Carbon for the (a) stem, (b) branch (branch and leafs for the IPCC method) and (c) leaf carbon of all beech trees. The mean carbon values are displayed for each of the four presented methodologies (ABF, Burger, BEF and IPCC) according to 10 cm DBH classes. DBH class 40 e.g. denotes the mean carbon for all trees between excluding 35 cm to including 45 cm.

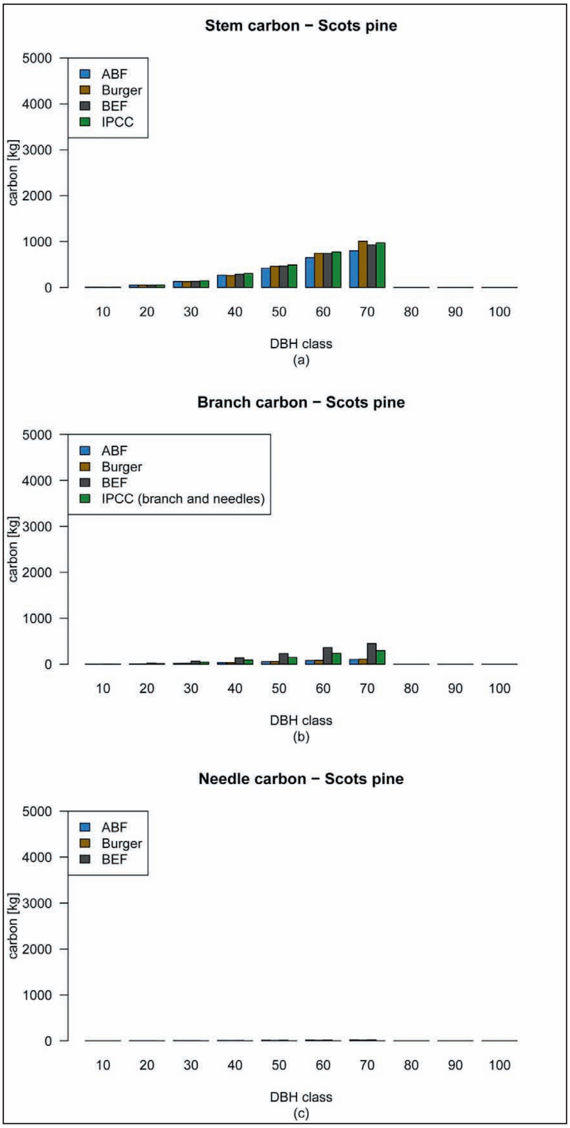

Figure 6: Carbon for the (a) stem, (b) branch (branch and needles for the IPCC method) and (c) needle carbon of all Scots pine trees. The mean carbon values are displayed for each of the four presented methodologies (ABF, Burger, BEF and IPCC) according to 10 cm DBH classes. DBH class 40 e.g. denotes the mean carbon for all trees between excluding 35 cm to including 45 cm.

Concerning beech trees (Figure 5), the Burger and IPCC results are very similar for the stem carbon. The ABF method shows the smallest values, the BEF is in between. The branch carbon estimates exhibit different results (Figure 5 b). The carbon values of the ABF method increase for DBH classes greater than 50 cm. The IPCC values provide the second highest results, but are still much smaller that the ABF method. The BEF and the Burger results are the smallest and very close together. Leaf carbon is only calculated within the Burger approach but does not have a big impact to the overall result of the above ground carbon (Figure 5 c). Within the IPCC methodology, the results of Figure 5 b again depict branch and leaf carbon since it is not possible to distinguish between these two compartments.

For Scots pine, only trees with a DBH of less than 75 cm were available in our data set and the results for the stem carbon are similar throughout the different methods. The braches show the highest values for the BEF method followed by the IPCC calculations. The smallest values are visible for the ABF and Burger results. Again, the IPCC result has the same branch and needle carbon. The needle carbon as such (Figure 6 c) plays a minor role with regard to the overall result.

5. Discussion

As the results indicate, the estimated carbon stored and/or accumulated within Austrian forests strongly depends on the carbon estimation method chosen (by tree species) for calculating the above ground carbon. The only exception was Scots pine, for which the four different carbon estimation methods are very similar (see Figure 3) while for Norway spruce (Figure 1) and common beech (Figure 2) the selection of the estimation method will strongly affect the result.

Although we are unable to judge and/or assess which method may be the 'best' or the 'correct' method, the results clearly show that, with an increasing DBH the variation, and consequently the uncertainty in the resulting carbon predictions of Austrian forests strongly increases.

For Norway spruce the highest above ground carbon values were produced with the Burger approach (Figure 1), mainly due to high estimates for the stem carbon compartment (Figure 4 a). This may have several reasons: (i) the nature of the equation used to calculate the stem biomass only depends on the DBH and therefore continues to rise along with the increasing DBH, which may lead to unrealistic behaviour; (ii) volume and stem biomass are directly related to the DBH of trees, but also to their height, since it is limited to the site quality of the stand (Gerritzen, 2013; Marschall, 1975).

Note that in the Burger approach, all compartments (dsm, dbm and dnm) are a function of the DBH. Thus, the above ground carbon is only derived from the DBH. All other methods incorporate DBH and height into their calculations. Thus they show an increase in variation with an increasing DBH. (Figures 1 - 3).

It seems unrealistic that the biomass constantly increases with an increasing DBH. Thus most volume equations take the height and the DBH as input parameters (Kennel, 1973; Pollanschütz, 1974). Marschall (1975) shows the asymptotic behaviour of the top height of stands with different site indices. Biomass functions are calibrated with tree data and cover a certain range, depending on the available calibration data. Any application of generalized functions beyond the range of the calibration data set may lead to systematic and/or biased results. For example, the parameters of the biomass function based on the data of Burger (1949) exhibited a range in DBH of less than 60 cm, suggesting that an extrapolation beyond this DBH range may be crucial. Another important issue is the theoretical behaviour of the Burger equation (Equation 8) which does not follow an upper asymptote to compensate for the site and species specific limitations.

For common beech (Figure 2), the Austrian biomass functions (ABF) exhibit the highest values, whereas the other approaches show similar results. This again can be explained by the behaviour of the functions for the different compartments. The branch compartment, calculated with the ABF functions, shows the highest values (Figure 5 b). With increasing DBH classes, this seems unrealistic, since the branch compartment is more than twice as high as the stem compartment (Figure 5 a). According to Hochbichler et al. (2006), the DBH range for the calibration data was 6.6 cm to 52 cm.

The Burger and the IPCC methods show similar results for the stem compartment of common beech (Figure 5 a), although Burger uses a biomass function, while the IPCC methodology is based on biomass expansion factors multiplied with the merchantable timber volume (Equations 8 and 15). The difference between the IPCC and the BEF (biomass expansion factor) approach is the result of the expansion factor. Both methods use the merchantable volume but it is important to note that the expansion factor in the IPCC approach is 580 kg m-3, whereas the expansion factor used in the BEF approach is 418 kg m-3. The results for pine trees are almost identical (Figures 3 and 6) for all four investigated methods.

Different compartments may also result from differences in definitions across estimation methods. For example the stem carbon in the BEF and IPCC functions denote the merchantable timber, whereas the ABF and Burger methods rely on the stem volume. Merchantable timber is the woody biomass of stem and branches greater than 7 cm. Thus the stem volume is usually higher for beech trees since this species contains more branches that are above this 7 cm threshold. For common beech, the results in the stem compartment for the ABF and the BEF method (Figure 5 a) differ only in the volume calculations - the expansion factors to derive the stem carbon are identical. Thus the stem carbon of the ABF has to be lower than the BEF carbon estimates, since they do not exhibit the same tree volume (stem vs. merchantable timer). The difference in stem and merchantable timber is also evident for Norway spruce (Figure 4 a) and Scots pine (Figures 6 a), but it is less important for the overall results in comparison to common beech with its higher proportion of branches.

The branch carbon compartment of the IPCC approach is not comparable with the other three methods, since the IPCC approach does not distinguish between branch and leaf/needle carbon. It was expected that this results in higher estimates for branch carbon in contrast to the other three methods. However, this is neither detectable for spruce (Figure 4 b) nor for pine (Figure 6 b). If we do not consider the results of the ABF branch carbon estimates (Figure 5 b) due to unrealistic high values for braches of common beech within this methodology, the branch carbon estimates of beech are higher for the IPCC compared to the Burger and BEF results.

Leaf biomass is only considered in the Burger procedure, the IPCC approach does not distinguish between leaf and branch carbon and the other two methods set the leaf carbon equal to zero. The needle carbon estimates for Norway spruce are calculated the same way in the ABF and BEF methodology (Figure 4 c).

From our results we conclude that there is a strong impact on the retrieved carbon estimates depending on the carbon estimation method used. Although we are unable to judge which estimation method is 'correct', the results clearly demonstrate that any interpretation of estimated forest carbon numbers must consider: (i) Which carbon estimation approach was chosen and (ii) how the chosen carbon estimation method influences or even derives any future predictions in assessing the sink and source potential of our forests. At this point the conceptual approach of the inventory and/or the ecosystem model structure is essential since it determines which carbon transfer functions and at which point in the carbon calculation procedure they are used. It also suggests that a careful assessment of any carbon estimation method is needed to understand the underlying variations. This holds for both, carbon estimations derived from forest inventory data and its change over time, as well for any estimations derived from forest ecosystem models. Our study clearly shows that with increasing tree dimensions and/or increasing forest growing stock, the selection of the biomass/carbon estimation approach strongly derives the resulting estimates regardless if terrestrial inventory data or ecosystem models are applied.

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9.3 Paper III

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A thinning routine for large-scale biogeochemical mechanistic ecosystem models

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ABSTRACT

Biogeochemical mechanistic models (BGC models) are used to model the carbon balance of forest ecosystems. Since European forests are managed intensively, a crucial part of carbon modelling is integrating management and thinning routines in the modelling process. In this study, forest inventory data are used to derive information concerning forest management practice. Based on this, a harvesting model is calibrated for simulating the 'business as usual' management that can be used in large-scale BGC models. Our approach is based on data from the Austrian National Forest Inventory. The model comprises two submodels: (1) a logistic model to assess the probability of an inventory point to be thinned and (2) a non-parametric model based on empirical probability density maps to assess the thinning intensity. Since BGC models operate on the stand level, only stand level parameters are integrated in the model such as standing timber carbon, site quality, cover type, elevation and age. A comparison of the predicted and observed proportion of thinned points and the thinning intensity suggests that the model is able to correctly mimic the management regime derived from the inventory data. No systematic trends in the results are evident. Using this thinning model in combination with a mechanistic model will enable assessment of the overall carbon stored in managed forest ecosystems, especially in large-scale modelling applications.

1. Introduction

European forests have been managed for several centuries (Spiecker et al., 2004). As a result forest laws were instituted to avoid over cutting and forest management practices such as tending, thinning and shelter wood cutting were developed and applied to ensure sustainable timber production (Assmann, 1970, 1961). Forest management influences the carbon storage in forests and thus strongly depends on tree species, site quality, time of thinning and the intensity of thinning (Assmann, 1970; Hasenauer and Monserud, 1997; Pretzsch, 2005). It is also an important factor determining the mitigation potential of forests to climate change.

Forest growth and yield models have been developed which are specifically designed to address the diameter and height growth response of individual trees according to changes in competition (see Hasenauer, 1994; Monserud and Sterba, 1996; Pretzsch et al., 2002). Although tree growth models have been proven to be important silvicultural management tools they do not explicitly consider the water, carbon, nitrogen, and energy cycles and how these fluxes will change according to different thinnings, expressed as the biomass removal from the forest (Aber et al., 1978; Hix and Barnes, 1984; White, 1974). However an option to understand the impact of thinning on ecosystem fluxes is the application of biogeochemical mechanistic models (BGC models).

Conceptually BGC-models consist of a formal description of ecosystem processes such as photosynthesis, transpiration, allocation and decomposition. They are explicitly designed to study the complex interactions between ecosystems, the lithosphere and the atmosphere and thus they may be seen as diagnostic tools to investigate potential impacts on forest ecosystems. Such potential impacts may be attributed to changing environmental conditions or forest management practices.

An important limitation of BGC models is that they operate on fully stocked even-aged stands. Compared to tree growth models (Hasenauer, 2006) they are not explicitly designed to be sensitive to varying stand density. For certain applications this may be a reasonable approach, however, if we are interested in the carbon balance of managed forests and how this may change under potential climate change, the conceptual integration of thinning is essential. This is particularly important as forest management has been and still is the main driving impact for changes in forest growth within Europe (Kauppi et al., 1992).

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Simulating forest development in managed forests needs algorithms to account for harvesting and thinning. Normally we integrate the management history and the thinning of the current stand based on a defined management history (Petritsch, 2008; Pietsch and Hasenauer, 2002). Usually the thinnings applied to a site have to be either known or fixed management scenarios/assumptions have to be developed to account for management (Cienciala and Tatarinov, 2006; Eastaugh and Hasenauer, 2011; Petritsch, 2008; Pietsch and Hasenauer, 2002; Tatarinov and Cienciala, 2006).

Key sources for deriving information about the forest are inventory data. Inventory datasets cover large areas and are applied on a rather coarse grid; the Austrian forest inventory for example is defined on a ~3.9 km grid (Gabler and Schadauer, 2008). Usually this kind of data consists of repeated measurements and thus inherently comprises information about the 'business as usual' management. Management information derived from these datasets can be included in the process models to simulate managed forests. One way to achieve this is to develop a thinning model based on the management that was applied in the past (derived from the inventory data) according to different site and stand characteristics. This is a common approach within population models that are specifically designed to integrate thinning operations because they operate on a tree level (Ledermann, 2002; Sterba et al., 2000; Thurnher et al., 2011).

Logistic regression is often used in single-tree based population models to describe the occurrence of harvesting and/or thinning (Ledermann, 2002; Sterba et al., 2000; Thurnher et al., 2011). It is also used to model other dichotomous variables like mortality (Monserud and Sterba, 1999), regeneration (Hasenauer and Kindermann, 2006; Schweiger and Sterba, 1997) or wildfire occurrence (Botequim et al., 2013). The models described in Ledermann (2002) and Thurnher et al. (2011) describe thinning models that use two logistic regressions, one to determine the occurrence of thinning and a second one to model the possibility of removal of each individual tree.

Eastaugh and Hasenauer (2012) proposed a thinning algorithm for process models using spruce-dominated inventory points in Austria. The model comprises a logistic sub-model to estimate the occurrence of thinning on an inventory point and a second non-parametric sub-model to estimate the thinning intensity; the thinning intensity is defined as the proportion of basal area removed.

The purpose of this paper is to develop a stand-level thinning model to be used within large-scale mechanistic or process models using data from the Austrian forest inventory. In Austria, the common management regime is a small scale clear-cut system with thinnings occurring in the first half of the rotation period (Mayer, 1992; Weinfurter, 2013). We develop a thinning model that is able to address the management regime within a given region and that can be integrated into a large-scale biogeochemical mechanistic modelling tool such as Biome-BGC. Since a dual logistic approach is not possible with BGC models, which define the ecosystem as a set of pools rather than single trees, the thinning model is developed and applied at the stand level. A logistic regression is developed to predict the thinning occurrence. For estimating the thinning intensity, the non-parametric approach as described in Eastaugh and Hasenauer (2012) is adopted.

The specific tasks of our study can be summarized as follows:

(i) Definition of the input parameters for the thinning model.
(ii) Development and calibration of a thinning model for large-scale mechanistic ecosystem models.
(iii) Demonstration and validation of the thinning model using the Austrian National Forest Inventory data.

2. Data

The calibration and validation data were obtained from Austrian National Forest Inventory – NFI (Gabler and Schadauer, 2008). The sampling method is based on angle count sampling (Bitterlich, 1948). The dataset consists of 22327 points. The points are organized in groups of four at the corners of a 200 m square. The groups are arranged on a regular square grid across the whole country with a resolution of 3.89 km. The four points in a group are referred as point 00, 08, 16 and 24 counting clockwise from the lower right position. Five measurements are available, covering the years 1981–1985 for the first measurement, 1986–1990 for the second, 1992–1996 for the third, 2000–2002 for the fourth and 2007–2009 for the fifth measurement (Eastaugh and Hasenauer, 2012). The first two measurements are only available for point 00. Only points that have at least one tree measurement in one measurement period are considered in this study. This gives a total of 9747 points. Fig. 1 shows a map of the inventory points that contain at least one tree measurement.

At each sample point, all trees greater than 10.4 cm in DBH are included in the angle count sample. Smaller trees (5 cm $\leqslant$ DBH $\leqslant$ 10.4 cm) are measured in a circular fixed area plot around the point with a radius of 2.6 m (A = 21.24 m^2). Since we are interested in whether a given sample point has (i) experienced any thinning and if yes, (ii) what was the thinning proportion, we need two consecutive measurement periods. Thus we excluded the fifth measurement from further calculations, since we cannot derive the thinning intensities that occurred in the next period. The fifth measurement was used only to obtain the thinning intensities between the fourth and the fifth measurement. Each measurement was treated as an independent observation for the model. A tree was treated as being thinned, when it had a measurement in one period, but no information in the next. Only points with at least one tree measurement are taken into account, so the number of points is not constant across the measurement periods. The summary statistics of our available data are presented in Table 1.

3. Methods

3.1. Biome-BGC

For this study we use the ecosystem model Biome-BGC (Running and Coughlan, 1988; Thornton, 1998; Thornton et al., 2002) as adapted for central European conditions. This includes a species-specific parameterization for the major European tree species (Pietsch et al., 2005), a dynamic mortality routine to simulate virgin forests (Pietsch and Hasenauer, 2006) and a historic land management tool (Pietsch and Hasenauer, 2002). This Biome-BGC model version has been used for a variety of purposes in several studies in central Europe (Eastaugh et al., 2011; Hasenauer et al., 2012; Eastaugh and Hasenauer 2014; Merganičová et al., 2012, 2005; Pietsch et al., 2003).

Biome-BGC operates on a stand level and simulates the cycling of carbon, nitrogen, water and energy within an ecosystem. The ecosystem, in this case the forest, is not seen as a collection of single trees, but as a set of pools and fluxes between the pools. It operates on a daily time-step. The net primary production used within this study is the gross primary production (GPP) minus the maintenance and growth respiration. GPP is calculated with the Farquhar photosynthesis routine (Farquhar et al., 1980). The allocated carbon is partitioned into different plant compartments (leaf, roots and stem). A more detailed description of the model can be found in Running and Coughlan (1988), Thornton (1998), White et al. (2000), Pietsch and Hasenauer (2002, 2006) and Thornton et al. (2002).

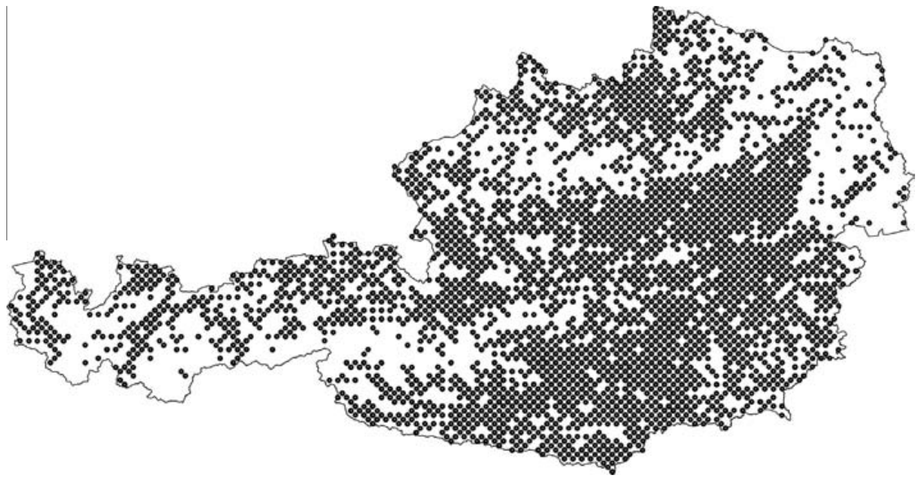

Fig. 1. Map of all forest inventory points that were used for model calibration and validation.

Table 1
Site characteristics of the Austrian forest inventory points.

Period	Nr. points	Elevation (m)	Age (years)	Timber carbon (kg m^{-2})	Site quality index	Thinned points (%)	Thinning (%)
All							
1	2014	929.62 (±408.52)	75.55 (±38.52)	7.75 (±5.65)	0.54 (±0.17)	27.71	7.57 (±17.14)
2	2107	927.07 (±408.10)	76.09 (±39.77)	8.02 (±5.84)	0.54 (±0.17)	29.81	8.55 (±18.35)
3	8910	908.05 (±417.31)	74.14 (±39.36)	8.03 (±5.86)	0.54 (±0.17)	32.00	9.85 (±20.32)
4	9165	904.53 (±417.14)	75.37 (±39.69)	8.80 (±6.18)	0.54 (±0.17)	35.23	12.03 (±22.71)
Total/mean	22,196	910.36 (±415.65)	74.96 (±39.46)	8.32 (±5.99)	0.54 (±0.17)	32.74	10.41 (±20.95)
Conifer							
1	1465	1023.77 (±400.46)	78.18 (±39.58)	7.84 (±5.81)	0.52 (±0.17)	27.71	7.39 (±16.53)
2	1528	1023.94 (±398.99)	78.31 (±40.96)	8.07 (±5.97)	0.52 (±0.17)	28.34	8.31 (±18.40)
3	6261	1025.19 (±401.23)	77.47 (±40.25)	8.35 (±6.05)	0.52 (±0.17)	30.95	9.64 (±20.27)
4	6345	1028.04 (±399.13)	78.47 (±40.79)	9.14 (±6.39)	0.52 (±0.17)	34.20	11.95 (±22.89)
Total	15,599	1026.09 (±400.05)	78.03 (±40.48)	8.60 (±6.18)	0.52 (±0.17)	31.71	10.22 (±20.93)
Broadleaf							
1	266	593.89 (±289.15)	61.28 (±33.82)	6.36 (±4.98)	0.63 (±0.16)	26.69	9.19 (±21.54)
2	279	585.67 (±281.46)	63.41 (±36.06)	6.57 (±5.15)	0.62 (±0.16)	29.03	8.74 (±19.98)
3	1443	541.53 (±289.58)	59.04 (±35.32)	6.15 (±4.95)	0.61 (±0.16)	31.60	10.39 (±21.72)
4	1526	530.49 (±282.83)	61.78 (±35.05)	6.89 (±5.36)	0.61 (±0.17)	35.52	13.16 (±24.84)
Total	3514	544.21 (±286.58)	60.75 (±35.17)	6.52 (±5.16)	0.61 (±0.17)	32.73	11.36 (±23.02)
Mixed							
1	283	757.80 (±313.30)	75.38 (±33.97)	8.60 (±5.21)	0.59 (±0.19)	28.62	6.98 (±15.50)
2	300	751.14 (±314.05)	76.60 (±34.43)	9.15 (±5.52)	0.59 (±0.19)	38.00	9.61 (±16.39)
3	1206	738.46 (±299.87)	74.93 (±34.84)	8.65 (±5.42)	0.59 (±0.17)	37.89	10.32 (±18.79)
4	1294	739.99 (±300.33)	76.20 (±35.85)	9.36 (±5.61)	0.58 (±0.18)	39.95	11.14 (±18.90)
Total	3083	742.11 (±302.63)	75.67 (±35.14)	8.99 (±5.50)	0.59 (±0.18)	37.92	10.28 (±18.36)

Biome-BGC needs a species definition expressed as a set of eco-physiological parameters (Pietsch et al., 2005; White et al., 2000), daily climate input data, site specific parameters (elevation, latitude, soil texture and effective soil depth) and CO_2 and nitrogen deposition rates. For our study the major tree species by sampling point was extracted from the forest inventory data. Daily climate for the forest inventory points came from weather station data interpolated using DAYMET (Thornton et al., 1997). The version used in this study has been adapted and validated for Austrian conditions (Eastaugh et al., 2010; Hasenauer et al., 2003; Petritsch, 2002). DAYMET creates daily interpolated values of maximum and minimum temperature and precipitation. It then calculates solar radiation and vapour pressure deficit according to Thornton et al. (2000). The weather station data for Austria were provided by the Austrian Central Institute for Meteorology and Geodynamics (ZAMG). We also include station data from surrounding countries to eliminate edge effects (Hasenauer et al., 2003). Elevation was extracted from a digital elevation model (NASA Land Processes Distributed Active Archive Center (LP DAAC), 2001) and the latitude of each point is known from the NFI. The soil texture is defined by the sand, silt and clay proportion. These parameters, as well as the effective soil depth, were interpolated from the Austrian National Forest Soil Survey (Englisch et al., 1992) based on the algorithm described in Petritsch (2008).

3.2. Model input parameters

For our thinning model it is important that we only consider input parameters which are drivers and/or variables within the Biome-BGC model to ensure that they can be updated in a future simulation run. Typical examples are timber carbon, age and cover type, which are derived directly from the available forest inventory. Elevation was extracted from a digital elevation model (DEM). Site quality was estimated with Biome-BGC, using methods developed in this study.

3.2.1. Timber carbon

Biogeochemical mechanistic models such as Biome-BGC define the ecosystem as a set of pools (i.e. carbon, nitrogen and water content in the leaves, branches, stem, roots, etc.). The inventory data consists of measured sample trees, which allow a calculation for the standing volume at a given sampling point. Within mechanistic flux models, the terrestrial tree information such as standing timber volume must be converted to above ground timber carbon (kgC m^{-2}). Therefore the first step is to calculate the merchantable timber volume V_{merch_timber} (the merchantable volume describes the volume of the stem and branches that have a small end diameter larger than 7 cm; Mitscherlich, 1970) of each tree within an angle count sampling point according to Kennel (1973).

$$V_{\text{merch\_timber}} = fh * d^2 * \frac{\pi}{4} \tag{1}$$

Whereas *fh* denotes the form height calculated as follows, based on Korsuň's function (Korsuň, 1935):

$$fh = e^{a+b*\ln(h)+c*\ln^2(h)} \tag{2}$$

$$a = a_0 + a_1 * \ln(d) + a_2 * \ln^2(d)$$
$$b = b_0 + b_1 * \ln(d) + b_2 * \ln^2(d)$$
$$c = c_0 + c_1 * \ln(d) + c_2 * \ln^2(d)$$

The diameter at breast height (d) and the tree height (h) are measured values, a_i, b_i and c_i are species specific parameters that can be found in Kennel (1973) and are presented in Appendix A. The resulting volume for each tree can be used to derive the per-hectare value by multiplying it by the number of represented trees (N_{rep}). As each sampled tree larger than 10.4 cm DBH represents a basal area of 4.0 m^2 (4 is the basal area factor used in the Austrian NFI), N_{rep} for each tree can be calculated by dividing the basal area factor k with the basal area of the tree g ($N_{rep} = k/g$). For smaller trees, N_{rep} is 470.87, since one tree in the 21.24 m^2 fixed area plot is equivalent to 470.87 trees per hectare.

The volume is converted into dry biomass (bm_{merch_timber}) by multiplying by the wood density (*WD*) and one minus the water content (*WC*):

$$bm_{\text{merch\_timber}} = V_{\text{merch\_timber}} * WD * (1 - WC) \tag{3}$$

The biomass is then multiplied by the dry matter carbon fraction (*DC*) to obtain the merchantable timber carbon. The merchantable timber carbon is then divided by the merchantable timber fraction (*MT*) to get the overall timber carbon (including the whole branch carbon).

$$C_{\text{timber}} = \frac{bm_{\text{merch\_timber}} * DC}{MT} \tag{4}$$

The values of *WD*, *WC*, *DC* and *MT* for the different tree species as cited in Pietsch et al. (2005) are from Sekot (1982), Hager (1988), Hochbichler (1993) and Hochbichler et al. (1994). They are listed in Appendix B.

Pietsch et al. (2005) defined different parameters for lowland and highland spruce. In this application, the results of the timber carbon for spruce based on the two parameter sets were interpolated according to the elevation of the corresponding sample point. The resulting value is divided by 10000 to convert it from kgC ha^{-1} to kgC m^{-2}. An analysis of the process of converting terrestrial tree data to above ground timber carbon can be found in Thurnher et al. (2013).

3.2.2. Site quality

Growth response to thinning strongly depends on the tree species, age of thinning and site quality (Hasenauer, 2006; Petritsch et al., 2007). Thus we next need to define site quality of the forests on our inventory points and use this information in the thinning model. As sites with a high quality are more productive versus low site quality points we assume that net primary production (NPP) as it is derived from Biome-BGC can be used as an indicator for site quality.

Biome-BGC uses a spinup-routine as a self-initialization process to initialize the pools (Thornton and Rosenbloom, 2005). In our study this was done with the species-specific parameter sets (see Pietsch et al., 2005) and the dynamic mortality routine (Pietsch and Hasenauer, 2006). The parameterization for oak was mainly done in floodplains and the parameterization for larch was based on a very small number of plots. We considered the results of these parameterizations as unlikely to be valid at the national scale, thus these points were treated respectively as coniferous and broadleaf points. All inventory points with coniferous species not included in the species-specific parameterization were treated as *Picea abies* points, for minor broadleaf species we used the parameters of *Fagus sylvatica*.

For the spinup, pre-industrial CO_2 (277.97 ppm) and nitrogen deposition values (0.0001 kg N m^{-2} $year^{-1}$, Holland et al., 1999) were used. The values for CO_2 originate from the IPCC mean global atmospheric CO_2 concentration dataset IS92a (Enting et al., 1994; IPCC, 1992). The dynamic mortality values for conifer species were set to 6% for high and 0.74% for low mortality (Merganicová et al., 2012). For broadleaf species, the values from Pietsch and Hasenauer (2006) were chosen (6% for high and 0.9% low mortality). The total cycle time for the dynamic mortality was set to 300 years (225 years for the low and 75 years for the high mortality phase).

After the spinup, the simulation was continued for 10 rotation periods with the dynamic mortality routine provided in Pietsch and Hasenauer (2006). During this second simulation stage, the CO_2 and nitrogen deposition values were increased to industrial levels. The CO_2 (390.299 ppm after 2009) and nitrogen deposition values were kept constant at the industrial level. The industrial nitrogen deposition was taken from a GIS map of Austria (Eastaugh et al., 2011) based on the data of Schneider (1998) and Placer and Schneider (2001). This was done to mimic the development and growth of a virgin forest under current CO_2 and nitrogen deposition rates.

The mean in NPP from the last mortality cycle (final 300 years) was then used as an indicator for site quality. The resulting site quality indices are normalized values of the average annual NPP. The values range between 0 and 1, so that a simulated point with a site quality index of 0 denotes a poor site while a point with index 1 indicates a very high site quality.

3.2.3. Elevation, age and cover type

Elevation was extracted from the ASTER Global Digital Elevation Model (NASA Land Processes Distributed Active Archive Center (LP DAAC), 2001). This dataset comprises the elevation on a 1-arc second resolution, which corresponds to ~30 m at the equator. This is the same DEM that was used in the site quality simulation run with Biome-BGC as described in the previous section. Stand age was extracted from the inventory data using the mean age of the standing trees. The cover type was also derived from the sample trees. All points with a sampled conifer tree proportion greater or equal than 75% based on the basal area were classified as conifer points. The same was done with broadleaf points. Other points were classified as mixed. This classification is in accordance with the classification within the CORINE land cover definitions (Bossard et al., 2000). Although the CORINE land cover classification is not used here, the same classification was chosen since this model is intended to be used in large-scale ecosystem applications. The use of definitions common to CORINE will make it easier to parameterize and apply the model in other geographical locations.

Table 1 shows the timber carbon, site quality index, elevation and age for the different cover types and measurement periods for the forest inventory points.

3.3. Development of a thinning model

Our thinning model is defined by two equations: The first equation is a logistic function that determines whether a given inventory point is thinned or not. The second equation predicts the thinning intensity and is based on a non-parametric approach using empirical probability density maps.

3.3.1. Thinning occurrence model

The general form of a logistic model is shown in Eq. (5).

$$P = \frac{1}{1 + e^{-(bX)}} \tag{5}$$

where P is the resulting probability of a point being thinned and bX denotes a linear combination of the independent predictor variables X and their associated parameters b. The resulting probability is then compared with a uniformly distributed random number between 0 and 1. If the calculated probability is smaller than the random number, the point is thinned and the second sub-model is applied. This approach of comparing the probability with a random number is widely used in thinning models (Eastaugh and Hasenauer, 2012; Sterba et al., 2000; Thurnher et al., 2011).

3.3.2. Thinning intensity model

The second equation provides a non-parametric approach and follows the suggestion presented in Eastaugh and Hasenauer (2012); a modified version based on different input parameters is used here. The equation relies on empirical probability density maps that contain a density value for each combination of thinning intensity and two other input parameters. This density map is created by a kernel smoothing algorithm (Bowman and Azzalini, 1997). The general approach is depicted in Fig. 2. It shows the density map created with the variables thinning intensity, timber carbon and site quality index. The shades of grey of the resulting map indicate the density, depicting high densities with dark grey.

For each point, the timber carbon and site quality index are known. It is possible to extract an empirical probability function for the thinning intensity taking the density values of the density map as a measure for the probability. The black solid line in Fig. 2a indicates the empirical probability function that can be extracted from the density map for an example point with 5 kg m^{-2} timber carbon and a site quality index of 0.4. The resulting probability function is shown in Fig. 2b. For the presented combination of the two variables a high probability for thinnings with an intensity that ranges from 10% to 30% is evident. There is a low probability for thinnings with an intensity of 60–80%. The thinning intensity is a random number derived by the empirical probability function extracted from the density map. The random number is generated using the R package *Runuran* (Leydold and Hörmann, 2012).

4. Analysis and results

4.1. Model calibration

The Austrian forest inventory points were split into a calibration and validation dataset. The calibration data consists of the 00 and 16 point of the inventory data, the validation was done with points 08 and 24. Each single point measurement was treated as an independent observation.

As outlined the first sub-model or equation determines whether a given inventory point is thinned or not. Since we are only interested in thinning events, all points with a recorded clear-cut were excluded from the calibration. This results in a total of 12570 calibration points (8903 conifer, 1943 broadleaf and 1724 mixed). All calibration and validation statistics were done with the statistical language R (R Development Core Team, 2011).

First, the possible input parameters for the logistic sub-models were investigated for multicollinearity. This was done by calculating the variance inflation factors for each independent variable: site quality index (*sqi*), timber carbon (*tc*), elevation (*elev*), age and cover type. All variance inflation factors were smaller than 1.5 (Table 2) indicating that there is no correlation between the predictors ensuring their independence (Field et al., 2012). The

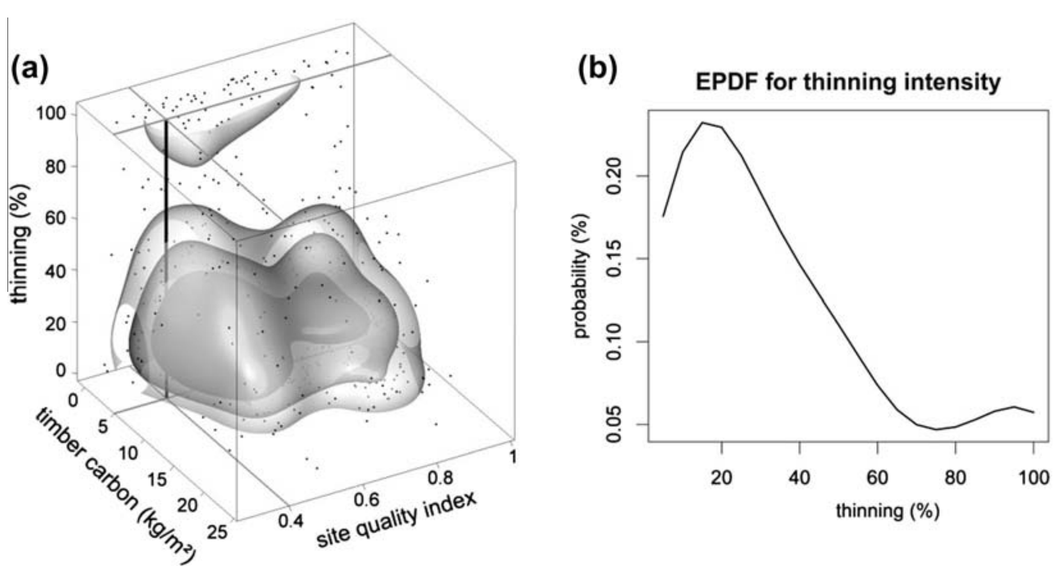

Fig. 2. The concept of obtaining the empirical probability density function (EPDF) for the thinning intensity (b) from the probability density map (a).

Table 2
Variance inflation factors of the variables used in the thinning occurrence model.

Variable	Variance inflation factor
sqi	1.061e+00
tc	1.271e+00
age	1.392e+00
elev	1.429e+00
Cover type	1.302e+00

calculation was done with R using the *car* library (Fox and Weisberg, 2011).

4.1.1. Thinning occurrence model

For the development of the model, only variables significant at the $\alpha = 0.05$ level were considered. We checked each of the described variables as well as their quadratic term as a possible model input. Eq. (6) shows the final logistic equation for predicting the thinning occurrence $P_{harvest}$.

$$P_{harvest} = \frac{1}{1 + e^{-(a_0 + a_1 * sqi + a_2 * tc + a_3 * tc^2 + a_4 * elev + a_5 * age + a_6 * age^2 + a_7 * conifer + a_8 * mixed)}} \quad (6)$$

where *sqi* is the site quality index of the point simulated with Biome-BGC, *tc* is the standing timber carbon, *elev* denotes the elevation, *age* is the mean stand age, *conifer* is a dummy variable for coniferous points and *mixed* for mixed points. The parameter values a_0–a_8 and their statistics by species are given in Table 3.

4.1.2. Thinning intensity model

The second sub-model calculates the thinning intensity. Only thinned points are taken into account within the calibration process. This results in a total of 4199 points (2918 conifer, 630 broadleaf and 651 mixed). The model is based on empirical probability density functions (EPDF). Each combination of thinning intensity, site quality index and timber carbon is assigned to a certain density that serves as a probability. This is done with the R package *sm* (Bowman and Azzalini, 2010). The resulting thinning intensity is then a random number based on the extracted empirical probability of the thinning intensity. The probability function is determined by the values of the timber carbon and the site quality index of the given point.

We calibrated three empirical probability density maps, one for each cover type (Fig. 3) because we assume that the cover type affects the actual thinning intensity. Within the density map, it is only possible to combine two variables and the thinning intensity. By defining one density map per cover type factor, we are able to integrate the effect of the cover type to the overall model approach. The fact that the cover type is important for the thinning is demonstrated by the differences in the shapes of the three density maps (see Fig. 3).

4.2. Model validation

The validation dataset consists of the 08 and 24 point of the forest inventory data. Since period one and two only contain the 00 point (Table 1), these two periods are not represented in the validation data. Again, all clear-cut points were excluded from the validation, since we are only interested in thinning events. This provides 8600 points (5931 conifer, 1426 broadleaf and 1243 mixed). The thinning occurrence and intensity model were validated (i) independently (or separately) and (ii) in combination.

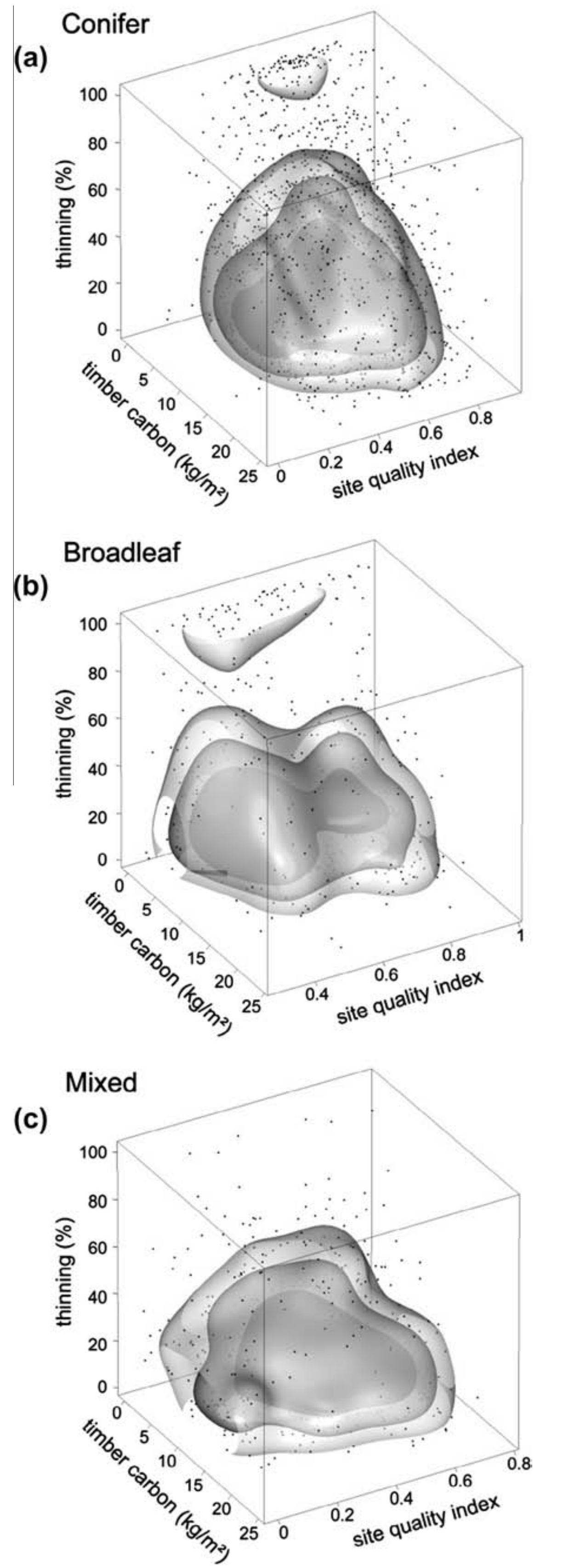

Fig. 3. Probability density maps of the thinning intensity model for (a) conifer, (b) broadleaf and (c) mixed points.

Table 3
Estimated coefficients of Eq. (6), the standard error, the Wald chi square statistics and the *p*-values. Variable *sqi* denotes the site quality index, *tc* the timber carbon, *elev* the elevation, *age* the age of the point, *conifer* is a dummy variable for conifer and *mixed* is a dummy variable for mixed points.

Parameter	Variable	Coefficient	Std. error	Wald chi-square	*p*
a_0	intercept	−7.858e−01	1.186e−01	4.390e+01	3.460e−11
a_1	*sqi*	5.482e−01	1.175e−01	2.178e+01	3.060e−06
a_2	*tc*	1.816e−01	1.088e−02	2.786e+02	<1e−15
a_3	tc^2	−3.942e−03	4.217e−04	8.740e+01	<1e−15
a_4	*elev*	−9.694e−04	6.096e−05	2.529e+02	<1e−15
a_5	*age*	−1.707e−02	2.403e−03	5.046e+01	1.210e−12
a_6	age^2	6.839e−05	1.341e−05	2.600e+01	3.410e−07
a_7	*conifer*	3.842e−01	6.223e−02	3.812e+01	6.640e−10
a_8	*mixed*	2.592e−01	7.359e−02	1.241e+01	4.270e−04

For the validation of the thinning intensity model only points where thinning was reported were taken into account. This reduces this validation dataset to 2994 (1985 conifer, 501 broadleaf and 508 mixed). For the validation of the combined approach (tinning occurrence and intensity), the full validation dataset with the 8600 points as mentioned above was used.

Both sub-models are stochastic models. The probability of the thinning occurrence relationship is compared to a uniformly distributed random number and the thinning intensity of the second sub-model is a random number based on the empirical probability function extracted from the density map. Validation is done by applying the model 1000 times on the validation dataset to see the mean as well as the ranges of the results.

4.2.1. Thinning occurrence model

We first validate the thinning occurrence model independently. Fig. 4 shows the validation result of the thinning occurrence submodel. The dotted line in Fig. 4 shows the observed proportion of the thinned points; the boxplots denote the results of the 1000 validation runs. The results are grouped by the cover type of the simulated points, i.e. conifer, broadleaf and mixed; the overall result comprising all cover types is also displayed. The best results are achieved for the conifer points, which can be explained by the fact that the conifer points comprise about 70% of all points. Overall, the occurrence of thinning is slightly underestimated across all points. The mixed points show the greatest underestimation but they also have the highest observed proportion of thinned points. The overall difference between predicted and observed is rather small: in the mean, the predicted proportion of thinning occurrence is 34.01% compared to 34.81% for the observations. Table 4 shows the exact numbers of the predicted and observed proportion of thinned points.

The proportion of thinned points was also validated according to timber carbon, site quality index, age of the forest stand and elevation classes. We sorted the validation data set by the variable of interest and split it in 8 equally sized classes ($n = 1075$, the exact class boundaries can be found in Appendix C since the number of points in a class is constant, not the class width). Fig. 5 shows the predicted and observed proportion of thinned points according to the different classes. Timber carbon class 1 for example comprises the 1075 points with the lowest timber carbon; class 8 denotes the points with the highest standing timber carbon. For all four different class types, the predicted and observed values are similar and no bias in the predictions for any of the variable is evident. Fig. 5a shows that points with a high timber carbon are more likely to be thinned. Fig. 5b shows that in both predictions and observations, points with a high site quality are thinned more often (except for site quality class 1). The thinning proportion according to the age classes (Fig. 5c) show a parabolic shape with the highest proportion in the middle classes. This is modelled through the quadratic age predictor in Eq. (6). Finally, the thinning proportion declines with elevation class (Fig. 5d).

4.2.2. Thinning intensity model

Next we validated the thinning intensity routine as a standalone model. We selected only points that were actually thinned. Fig. 6 shows the thinning intensity of 1000 model runs, the boxplots indicate the range of the mean thinning intensity; the dotted line shows the observed value. The best result is achieved for the broadleaf points. The results of the mean thinning intensity match the observed values very close, the highest difference is found on the mixed points. Here, the model overestimates the observations.

As for the thinning occurrence model, the intensity model was also validated according to timber carbon, site quality index, age of the forest stand and elevation classes. The results are shown in Fig. 7. The thinning intensity according to the timber carbon class (Fig. 7a) reveals that the highest thinning intensity is evident in the low timber carbon classes and the lowest intensity in the high classes. The trend is evident in both the predictions and the observations, but the very high intensity of the observation in the first class and the low intensity in the highest class are beyond the predicted output. The results of site quality index class (Fig. 7b) show a similar behaviour for the predictions versus the observations. The elevation class results (Fig. 7d) are also similar to the site quality index and both the predictions and the observations exhibit no trend. With respect to the age classes (Fig. 7c), the intensity is overestimated in the low and underestimated in the high age classes.

4.2.3. Combined validation of the two models

Finally we validated the thinning occurrence model in combination with the thinning intensity model to test for the overall quality of the approach by running both models in combination 1000 times. The mean predicted thinning intensity is 10.72 compared to 10.99 for the observations. The results grouped by the different cover types again show a very good result (Table 4). The boxplots in Fig. 8 provide the range of the mean thinning proportion grouped by the cover types for the 1000 validation runs; the dotted lines denote the observed value. The thinning intensity is very similar for conifer and mixed points, only the broadleaf points show a higher observed thinning intensity.

Next we were interested in assessing potential biases in the predictions according to the different classes: timber carbon, site quality, stand age and elevation. The validation of the thinning intensity here used in combination with the thinning occurrence model was examined exactly the same way as compared to the independent validation of the thinning occurrence model (see Section 4.2.1) and thinning intensity model (Section 4.2.2). Fig. 9 shows the mean of the predicted versus observed thinning inten-

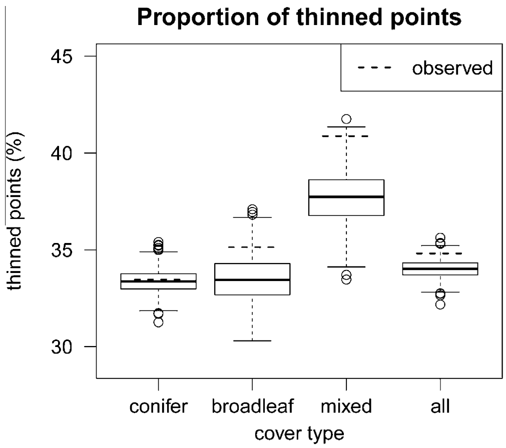

Fig. 4. Proportion of thinned points after 1000 runs of the thinning occurrence model.

Table 4
Observed and predicted mean proportion of thinned points and thinning intensity for the different cover types of the validation data set.

Cover type	Thinned points (%)		Mean thinning intensity (%)	
	Observed	Predicted	Observed	Predicted
Conifer	33.47	33.38	10.70	10.60
Broadleaf	35.13	33.47	12.17	11.15
Mixed	40.87	37.69	11.01	10.80
All	34.81	34.01	10.99	10.72

sity according to the four classes: (a) timber carbon, (b) site quality, (c) stand age and (d) elevation.

The results in (Fig. 9a) demonstrate that for the low timber carbon classes the model seems to underestimate the thinning intensity but tends to overestimate thinning for the large ones. For the site quality and age classes (Fig. 9b and c), no bias was evident. A small overestimation in the low elevation classes and an underestimation for the high elevation classes (except the first elevation class) was detectable (Fig. 9d),

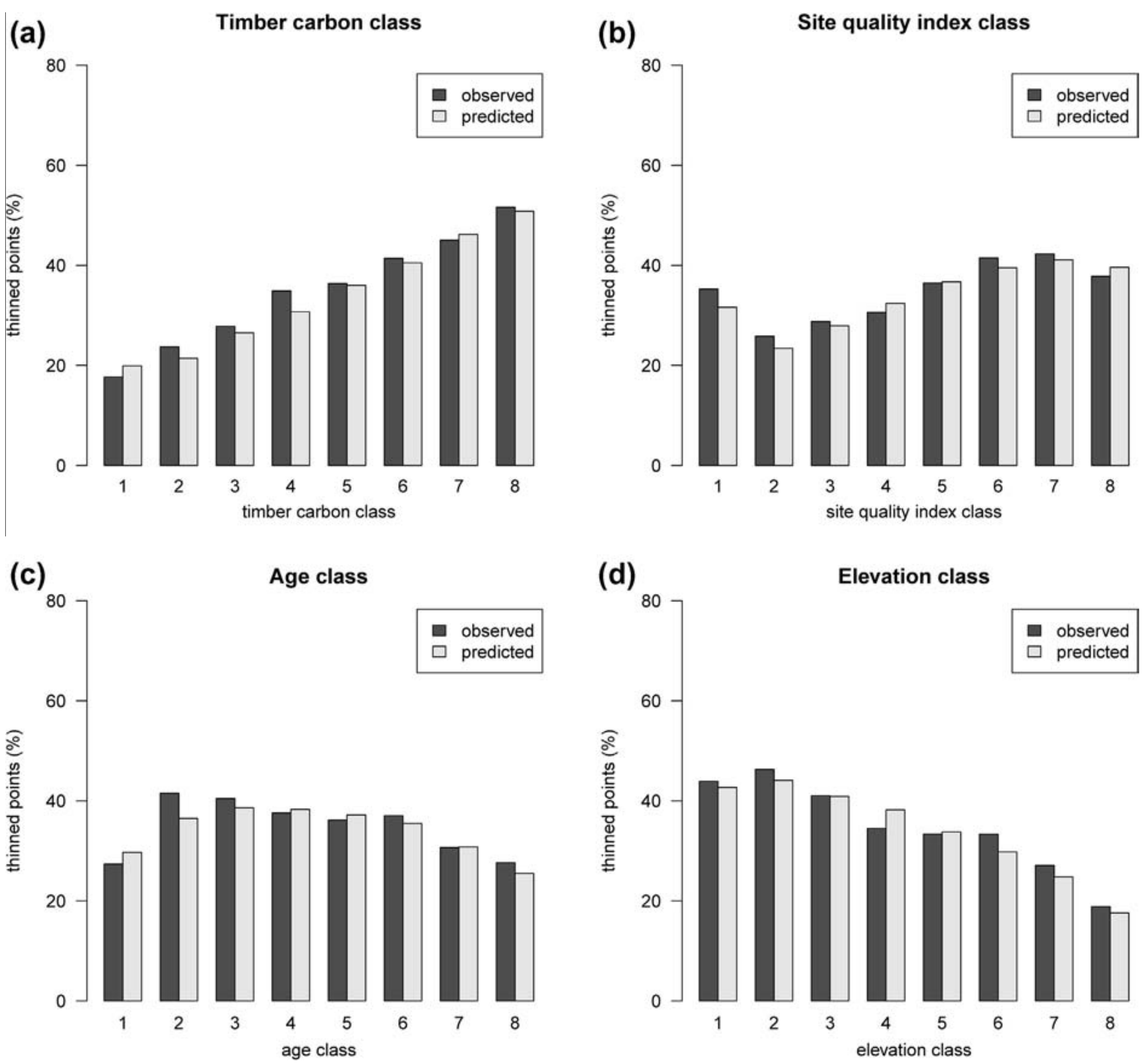

Fig. 5. Predicted and observed proportion of thinned points according to (a) timber carbon class, (b) site quality index class, (c) age class and (d) elevation class. All classes have the same size. The exact class boundaries can be found in Appendix C. The predicted values are the mean proportion of thinned points in each class resulting from 1000 validation runs of the thinning occurrence model.

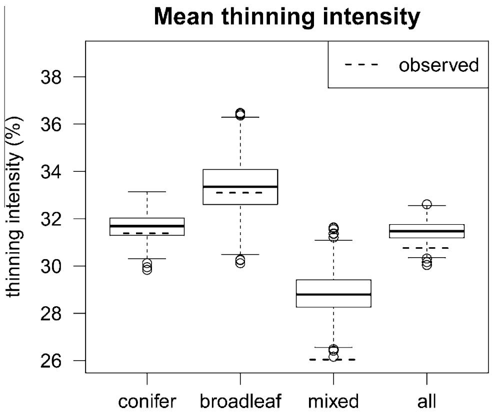

Fig. 6. Mean predicted and observed thinning proportion of 1000 validation runs of the thinning intensity model.

5. Discussion and conclusion

We introduced a stand-level thinning model that comprises two sub-models and is intended to be used in large-scale process models. The application case described in this paper is Austria with data of the National Forest Inventory. The model is based on the methodology described in Eastaugh and Hasenauer (2012) that only used points where 50 % or more of the basal area is covered by Norway spruce (*Picea abies* (L.) Karst). The inclusion of the cover type to the model by dummy variables in the thinning occurrence and different probability density maps in the intensity model extend the use of the model to a nationwide application and unleash it from the limitation to be used only for a single tree species. The cover type definition was designed to meet the requirements of large-scale applications since it is not bound to single tree species parameterizations that happen to exist in process models. The definition of simple cover types (conifer, broadleaf and mixed) based on existing cover type maps like the CORINE land cover (Bossard et al., 2000) simplifies the usage and parameterization of the model.

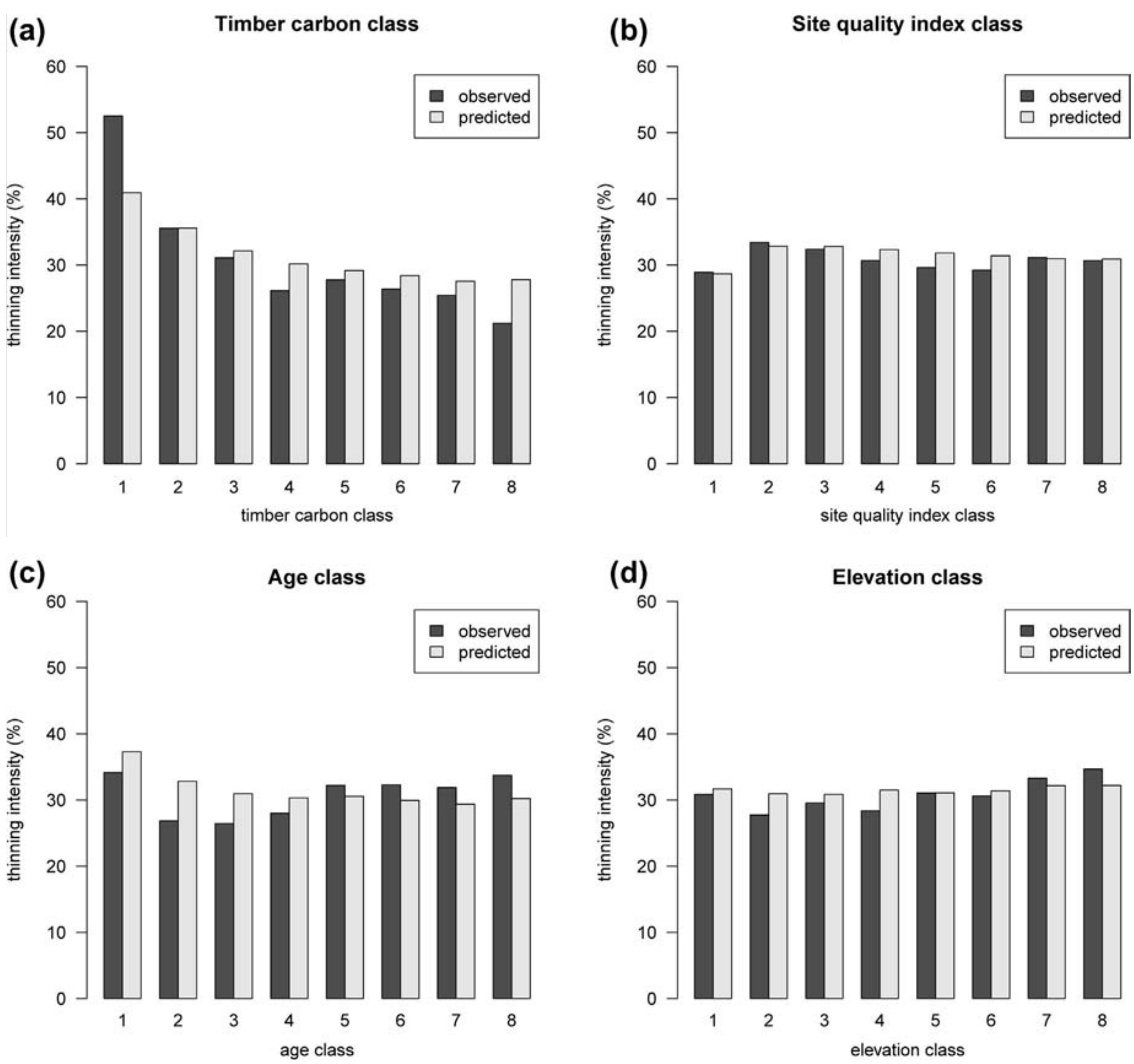

Fig. 7. Predicted and observed thinning proportion according to (a) timber carbon class, (b) site quality index class, (c) age class and (d) elevation class. All classes have the same size. The exact class boundaries can be found in Appendix C. The predicted values are the mean proportion of removed timber in each class resulting from 1000 validation runs of the thinning intensity model.

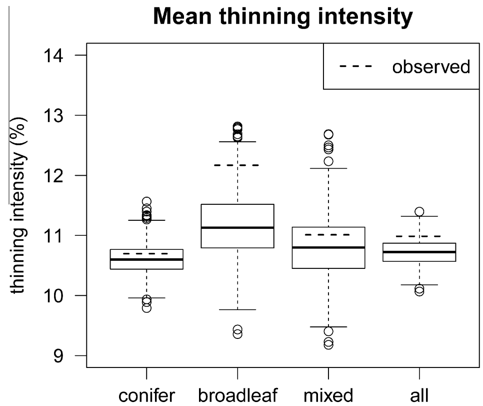

Fig. 8. Mean predicted and observed thinning proportion of 1000 validation runs of both models.

The model does not distinguish between trees that are removed via thinning and trees that are removed through natural disturbances. The main disturbances in Austria are bark beetles (*Ips typographus*) and wind throw (Thom et al., 2013). Bark beetle disturbances of *Ips typographus* mainly affect older trees (Netherer and Nopp-Mayr, 2005) and wind throw damage is more prevalent in tall trees or trees with a large DBH (Albrecht et al., 2010; Hanewinkel et al., 2010; Rich et al., 2007; Seidl et al., 2014), which relates to the tree age. For ecological and regulatory reasons (forest health) a final harvest is often performed after a serious natural disturbance. Thus, these trees are not included in the model environment since we excluded all clear-cut points. It is also important to know that thinnings in Austria are performed in the first half of the rotation period (Mayer, 1992; Weinfurter, 2013) when these disturbances do not play such an important role. We are aware that an increase of these disturbances due to e.g. climate change can change the overall thinning patterns and therefore impact the results of the model as shown in Eastaugh and Hasenauer (2012) for large bark beetle disturbances.

The model presented in Eastaugh and Hasenauer (2012) suggested elevation may be a proxy for site quality. In this study, we use the NPP simulated with Biome-BGC to describe the quality or potential of each angle count sampling point in Austria. Hasenauer et al. (2012) showed that the NPP derived from

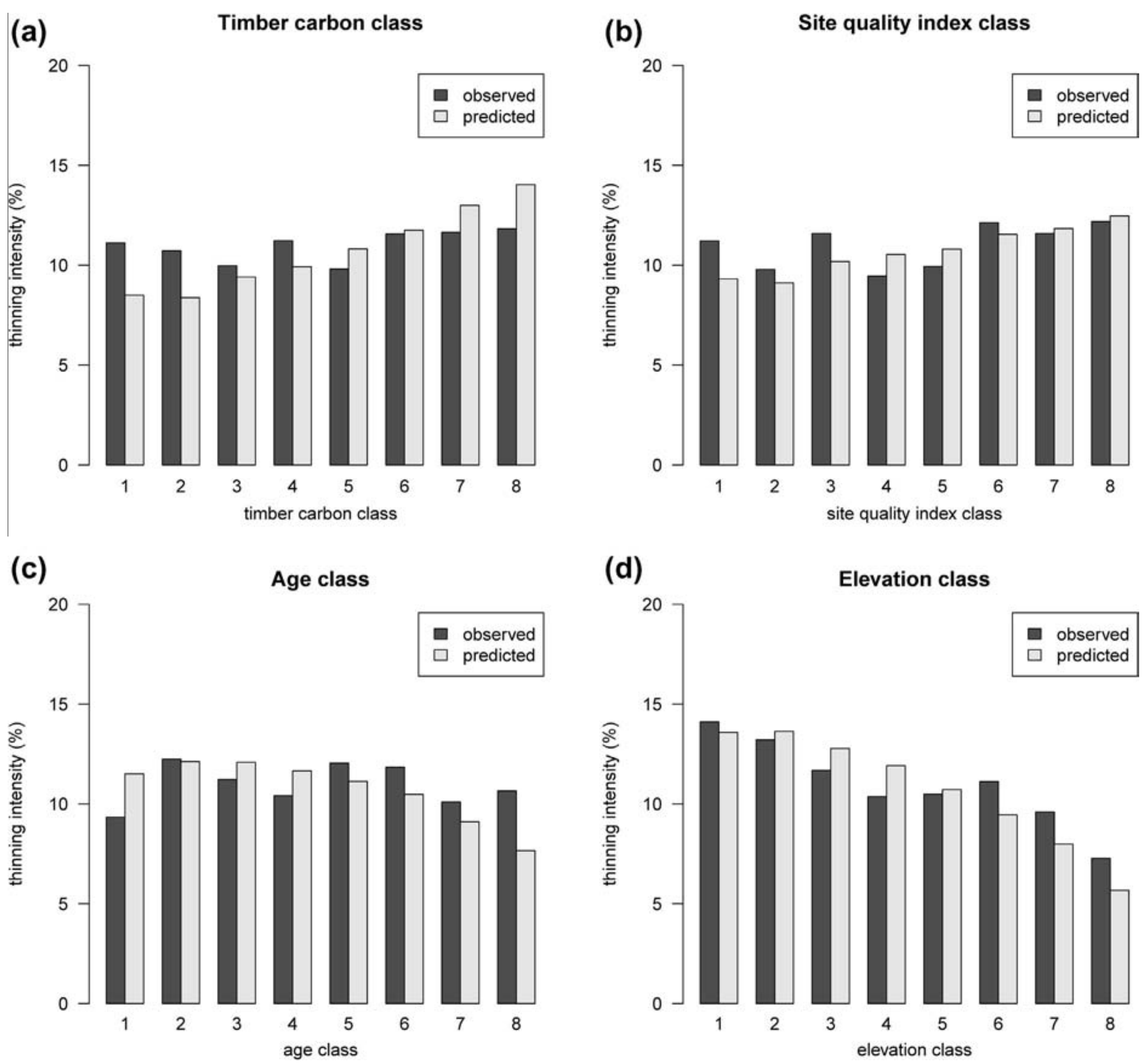

Fig. 9. Predicted and observed thinning proportion according to (a) timber carbon class, (b) site quality index class, (c) age class and (d) elevation class. All classes have the same size. The exact class boundaries can be found in Appendix C. The predicted values are the mean proportion of removed timber in each class resulting from 1000 validation runs of both models.

Biome-BGC after the spinup can be seen as the potential NPP for a given site by comparing it to MODIS satellite-driven NPP estimates (Running et al., 2004). The length of our data records is relatively short. Thus it is difficult to derive a reliable measure for site productivity directly from our inventory data. The estimation of site productivity is also complicated by the fact that stand management prior to the first inventory period is unknown. The lack of site index data for the Austrian forest inventory points makes it impossible to formally validate the site quality estimations shown here, but with regard to the model behaviour the presented site quality index gives us confidence that we have a valid estimate. Site index is highly significant in the occurrence model (Table 3) and our initial expectations that high quality sites would have a higher proportion of thinnings (Fig. 5b) are met. Modelling the site quality also bypasses the problem that quality indices might not be easily available (Skovsgaard and Vanclay, 2013). This approach of using a mechanistic model to describe the site productivity has also been applied in Swenson et al. (2005) who used the process model 3-PG (Landsberg and Waring, 1997) to predict the site index on several forest inventory plots across Oregon, USA. Although they use a different methodology, the overall concept of using a process model to obtain the productivity of a forest site is similar.

In the parametric occurrence model, only significant parameters were used. The intensity model uses a non-parametric approach. According to Fig. 7, only the timber carbon showed a clear trend in the thinning intensity in the observations, so we took that parameter as the first input for the intensity model. Even though no trend is visible in the site quality index (Fig. 7b), we chose this parameter as second input. The non-parametric approach implicitly includes the interaction between these parameters. Keeping the timber carbon constant, different empirical probability distributions are obtained according to the site quality index. Analysing the density map for conifer species (Fig. 3a), the probability of a thinning intensity above 80% is higher for points with low timber carbon and a site quality index between 0.4 and 0.8. This is different for points with a site quality index above or below that value. In this case, the combination of the two variables results in different probability density functions for the thinning intensity and thus influences the overall model result. A similar effect can be seen in the broadleaf points (Fig. 3b). Considering the conifer points (Fig. 3a) with high timber carbon, an increased probability of a thinning intensity above 80% is not evident, but the probability of a thinning intensity below 60% is still higher for points with a site quality index between 0.2 and 0.8. The thinning intensity is based on the combination of the timber carbon and the site quality (Figs. 2 and 3), thus the fact that there is no trend for the site quality does not impose such a problem since the interaction with the timber carbon is implicitly contained in this non-parametric approach.

The overall model performance is good, especially for conifer and mixed points (Fig. 8). The underestimation in the broadleaf points does not really influence the overall model performance (small number of points). The separate model validation (see Fig. 4 for the occurrence and Fig. 6 for the intensity model) shows a different behaviour. For the mixed points, the proportion of thinned points is underestimated for the occurrence model and the thinning intensity is overestimated in the intensity model. The combined two models provide a very good result in the overall model performance (Fig. 8). For broadleaf points, the underestimation in the occurrence model and the slight overestimation in the intensity model results in an underestimation in the combined model. Conifer points are well predicted in both sub-models and in the combination because the number of conifer points is the highest (Table 1), allowing for a more precise estimation of parameter values and better-defined empirical probability density functions.

The thinning intensity of the combined model according to the timber carbon class shows no trend in the observations (Fig. 9a), but a trend in the predictions. Looking at the sub-models, the occurrence model shows a positive trend in the predictions and the observations (Fig. 5a). A negative trend can be seen in the intensity model (Fig. 7a). The high positive trend in the occurrence model has a stronger influence on the combined model in the predictions; that is the reason for having an overall trend in the predictions but not in the observations (Fig. 9a). Similar effects occur at the other output classes. The elevation trend in the occurrence model can be seen in the combined model although it has no trend in the intensity model as such. The slight trend in the predictions according to the site quality index of the combined model (Fig. 9b) is a result of the trend in the occurrence model.

In this study, we did not distinguish whether a tree was removed due to harvesting or due to mortality. We were only interested in modelling the overall proportion of removed trees for each point. The mortality proportion on the overall thinning intensity is 16.20%. Looking at the result of the intensity model (Fig. 7), about 25% of the high peak in the thinning intensity for the first timber carbon class (Fig. 7a) are based on mortality. A similar effect can be seen in the age classes. For the site quality and elevation classes, the thinning proportion is rather constant. The same effect can be seen on the combined model. Looking only at the thinning intensity without the mortality does not appreciably change the trends of the thinning intensity based on the output classes shown in Fig. 9; although some of the extreme values in the low and high classes are flattened. The major effects on the overall thinning intensity are due to deliberate site interventions. As one of the motivations for thinning is to avoid mortality in the site, including mortality in the model seems a reasonable way to predict the overall thinning/removal proportion which is the main purpose of this model.

The validation of the overall model performance shows very good results (Table 4). The model is based on forest inventory data, so it is able to mimic the 'business as usual' management according to the information it derives from the inventory. Our result suggests that the model can be integrated into a process model to simulate the area of interest and automatically include management operations to obtain a valid estimation of the carbon balance within forest ecosystems. Additional data (perhaps derived from remote sensing or more sophisticated inventory interpretation) will directly influence the model performance.

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Appendix A

Coefficients of the Kennel volume function (Kennel, 1973) used in Eq. (2) according to the tree species. The beech coefficients were used for all broadleaf species.

Species	a_0	a_1	a_2	b_0	b_1	b_2	c_0	c_1	c_2
Spruce	−3.59624e+00	1.80213e+00	−2.88243e−01	1.06247e+00	−1.28993e−01	3.53434e−02	1.42264e−01	−5.82590e−02	4.59854e−03
Pine	−5.80915e+00	3.38700e+00	−4.94392e−01	3.67116e+00	−1.83211e+00	2.73999e−01	−4.59282e−01	2.99890e−01	−4.44931e−02
Fir	−7.41365e+00	3.33667e+00	−4.26419e−01	4.00998e+00	−1.39533e+00	1.65198e−01	−3.21612e−01	1.44010e−01	−1.65461e−02
Larch	−9.26182e+00	4.75438e+00	−6.72495e−01	5.17159e+00	−2.27654e+00	3.11633e−01	−5.55379e−01	3.02799e−01	−4.12510e−02
Douglas fir	−1.25017e+01	6.62441e+00	−9.11185e−01	7.27277e+00	−3.58346e+00	4.89149e−01	−8.77150e−01	5.15586e−01	−7.14395e−02
Other conifer	−6.10993e+00	3.40736e+00	−5.28642e−01	1.89417e+00	−7.25279e−01	1.29421e−01	1.00078e−01	−8.69222e−03	−4.49328e−03
Beech	−2.72840e+00	8.37563e−01	−1.05343e−01	1.62283e+00	−2.14812e−01	2.89272e−02	−8.79719e−02	3.25667e−02	−4.46295e−03

Appendix B

Coefficients used in Eqs. (3) and (4) according to Pietsch et al. (2005). *WD* denotes the wood density, *WC* the water content, *DC* the dry matter carbon fraction and *MT* the merchantable timber fraction. The spruce parameters were used for coniferous species not contained in the list, for other broadleaf species, the beech parameters were used.

Species	*WD* (kg m^{-3})	1 − *WC*	*DC* (kgC kg^{-1})	*MT*
Spruce lowland	800	0.440	0.503	0.850
Spruce highland	800	0.440	0.503	0.700
Pine	820	0.500	0.500	0.694
Larch	800	0.440	0.503	0.850
Beech	950	0.440	0.486	0.825
Oak	1000	0.500	0.504	0.760

Appendix C

The boundaries of the equally sized classes used in Figs. 5, 7 and 9. The size of the class is determined by the number of points. Thus the width of the classes vary. The boundary is specified by the percentile. Variable *tc* denotes the timber carbon, *sqi* the site quality index, *age* the age and *elev* the elevation classes. The timber carbon class 1 in Figs. 5 and 9, e.g. includes all points with timber carbon larger or equal than 1.876e−02 (0 percentile) and smaller than 1.648e+00 (12.5 percentile). Since Figs. 5 and 9 include all points and Fig. 5 only the thinned points, the boundaries are not similar for these figures.

Variable	Figures	Boundary (percentiles)								
		0	0.125	0.25	0.375	0.5	0.625	0.75	0.875	1
tc	5, 9	1.876e−02	1.648e+00	3.485e+00	5.350e+00	7.279e+00	9.480e+00	1.189e+01	1.552e+01	3.895e+01
sqi	5, 9	0	3.190e−01	4.277e−01	4.922e−01	5.400e−01	5.889e−01	6.404e−01	7.088e−01	9.899e−01
age	5, 9	6.000e+00	2.886e+01	4.200e+01	5.400e+01	6.833e+01	8.300e+01	1.000e+02	1.253e+02	1.580e+02
elev	5, 9	1.170e+02	4.040e+02	5.577e+02	7.060e+02	8.630e+02	1.026e+03	1.214e+03	1.435e+03	2.190e+03
tc	7	2.114e−02	2.972e+00	5.372e+00	7.311e+00	9.436e+00	1.130e+01	1.393e+01	1.727e+01	3.605e+01
sqi	7	0	3.151e−01	4.539e−01	5.166e−01	5.655e−01	6.093e−01	6.568e−01	7.158e−01	9.829e−01
age	7	6.333e+00	3.000e+01	4.220e+01	5.203e+01	6.537e+01	7.747e+01	9.300e+01	1.177e+02	1.580e+02
elev	7	1.290e+02	3.801e+02	4.930e+02	6.064e+02	7.410e+02	8.916e+02	1.087e+03	1.303e+03	2.110e+03

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