SILVA FENNICA

Silva Fennica 42(4) research articles

www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

Effect of the Aggregation of Multi-Cohort Mixed Stands on Modeling Forest Ecosystem Carbon Stocks

Thomas Wutzler

Wutzler, T. 2008. Effect of the aggregation of multi-cohort mixed stands on modeling forest ecosystem carbon stocks. Silva Fennica 42(4): 535–553.

Studies of the carbon sink of forest ecosystems often stratify the studied stands by the dominating species and thereby abstract from differences in the mixed-species, multi-cohort structure of many forests. This case study infers whether the aggregation of forestry data introduces a bias in the estimates of carbon stocks and their changes at the scale of individual stands and the scale of a forest district. The empirical TreeGrOSS-C model was applied to 1616 plots of a forest district in Central Germany to simulate carbon dynamics in biomass, woody debris, and soil. In a first approach each stand was explicitly simulated with all cohorts. In three other approaches the forest inventory data were aggregated in several ways, including a stratification of the stands to 110 classes according to the dominating species, age class, and site conditions. A small but significant bias was confirmed. At stand scale the initial ecosystem carbon stocks by the aggregated approach differed from that of the detailed approach by 2.3%, but at the district scale only by 0.05%. The differences in age between interspersed and dominant cohorts as well as differences in litter production were important for the differences in initial carbon stocks. The amounts of wood extracted by thinning operations were important for the differences in the projection of the carbon stocks over 100 years. Because of the smallness of bias, this case study collects evidence that the approaches, that represent stands or stratums by a single cohort, are valid at the scale of a forest district or larger.

Keywords stand structure, thinning, scale, model, stratification, bias, inventory
Addresses Max Planck Institute for Biogeochemistry, Hans Knöll Str. 10, DE-07745, Jena, Germany **E-mail** thomas.wutzler(at)bgc-jena.mpg.de
Received 13 June 2007 **Revised** 1 July 2008 **Accepted** 18 July 2008
Available at http://www.metla.fi/silvafennica/full/sf42/sf424535.pdf

1 Introduction

Forest ecosystems of the northern hemisphere are currently a large carbon sink in respect to the atmosphere (Myneni et al. 2001, Liski et al. 2003). The direct human-induced part of this sink is accountable with the Kyoto protocol (UNFCCC 1997). However, factoring out the drivers for this sink can only be done with large uncertainties yet (e.g. Vetter et al. 2005, Albani et al. 2006) and studies are required that better represent forest management, especially the effects of age and stand structure (Perry et al. 2008). In line with changes in forest management goals, many forests in Central Europe will become more diverse and the importance of mixed species, multi-cohort stands will increase (Kohm and Franklin 1997, Gamborg and Larsen 2003, Larsen and Nielsen 2007). Many current studies of forest carbon, however, work with stratified forest inventory data (e.g. Vetter et al. 2005) and hence abstract from many details of the stand structure. This involves aggregation of inventory data, which potentially introduces a bias with the application of non-linear models (Harvey 2000). Several aspects of carbon stock quantification are highly non-linear, e.g. the dependence of biomass expansion factors on tree age and site quality. Hence, it needs to be tested, if the aggregation of forest inventory data and the representation of multi-cohort mixed stands results in a bias in carbon stock projections.

Davi et al. (2006) already showed that aggregating several eco-physiological parameters resulted in only a negligible bias on applying the process based CASTANEA model at subplot, stand, and landscape scale. They simulated monospecific stands only. Generally, however, the factors that are generalized or averaged in the process of data aggregation at stand scale concern mostly differences between species and between tree ages. First there are parameters of the growth and management of trees (diameter and height increment, competition, thinning intensities, natural mortality, proportion of extracted biomass on harvest), second, the conversion of inventory data to carbon mass (volume equations, wood densities, biomass expansion factors for stem, branches, leaves, and roots), third, estimation of carbon inputs to the soil (biomass turnover rates), and fourth, litter decomposition parameters (distribution of litter qualities and decomposition rates).

I categorize the approaches of projecting the forest carbon sink into three classes (Fig. 1). First, with the stratified approach a) the forest area is stratified into classes by dominating species, age structure, and site conditions. Next, the carbon dynamics of each class are simulated (e.g. Vetter et al. 2005, Freibauer et al. 2008). Alternatively, the transitions of forest areas from one class to another class are tracked in a forest scenario model (e.g. Thurig and Schelhaas 2006). Second, the subsampled approach b) differs from the stratified approach by simulating a set of localized stands instead of a set of classes. The approach must assume that the sample of simulated stands is representative for the studied forest area (e.g. Nabuurs and Schelhaas 2002, Lasch et al. 2005). Third, the detailed approach c) simulates each stand of the study area separately (e.g. Le Maire et al. 2005). The level of spatial heterogeneity and the level of detail in forestry management that can be represented in the carbon sink projection increases from (a) to (c). However, also the requirements on input data and execution times increase. Therefore it is desirable to use the detailed approach (a), but it must be shown, that the aggregation of parameters and input data does not lead to a bias.

Hence, the goal of this study was to perform a case study at the scale of a forest district that assesses the effect of the aggregation of the forest inventory data on the carbon stock projections. I used a single-tree based empirical forest ecosystem carbon balance model and compared the simulated carbon stocks between different scenarios of aggregation of forest inventory data. My hypothesis was that the aggregation of multi-cohort forest inventory data to a single cohort results in a bias in simulated forest ecosystem carbons stocks. In order to exclude confounding effects, this study did not consider climate change and changes in management practises.

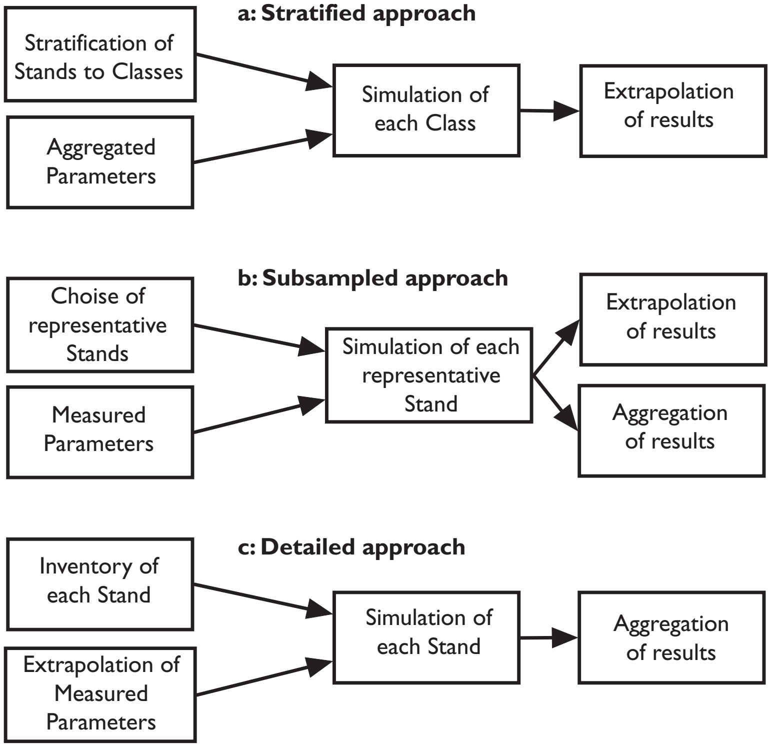

Fig. 1. Classification of approaches of projecting carbon sink of a forest area. The approaches differ by first, the set of stands that are projected, second, by the spatial detail of inputs and parameters that drive the projections, and third by the assumptions involved to extrapolate or aggregate the results of the projections.

2 Methods

2.1 Study Area

I studied a population of forest stands in the Hummelshain forest district. This district was located 50°48′N, 11°35′E at the south-eastern edge of Thuringian basin at altitudes of 270–330 m above sea level. The population was constrained to stands that were owned by the federal state, and where trees with a diameter at breast height (dbh) of at least 7 cm were present, because forestry inventory data were sparse or it were not available for other stands.

The population consisted of 1616 stands that covered an area of 3619 ha. Limestone in the west and sandstone at the east of the district formed a plateau that was carved by the Saale river and several smaller rivers. The forest areas were located at the plateau areas and the ridges between the Saale and several contributing rivers. Mean annual temperature was 8.5 °C and annual precipitation was 602 mm according to the lower climate stratum of Vetter et al. (2005). Most stands were dominated by Scots pine (*Pinus sylvestris*) and interspersed with spruce (*Picea abies*), birch (*Betula pendula*), and oak (*Quercus rubra*). On several sites also common beech (*Fagus sylvatica*) was dominating. There were differences in species composition between the western sandstone dominated growing region and the eastern limestone dominated growing region (Fig. 2 bottom). The forest area has been managed until 1993 by a smallstrip clearcutting system leading to homogeneously managed stands of size 0.5–5 ha. However, the distribution of stands showed a

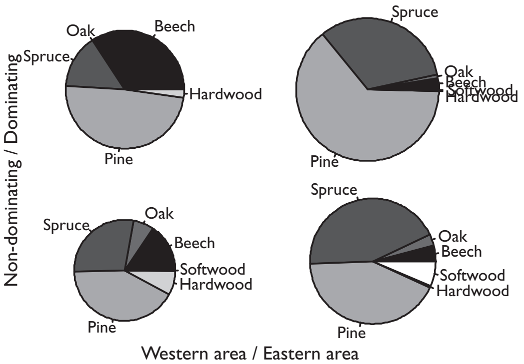

Fig. 2. Distribution of Species Groups in the Hummelshain forest district in 2003. There are less broadleaved species within the dominating cohorts compared to the interspersed cohorts in the Eastern growing region and more Beech dominated stands in the dominating cohorts of the Western region.

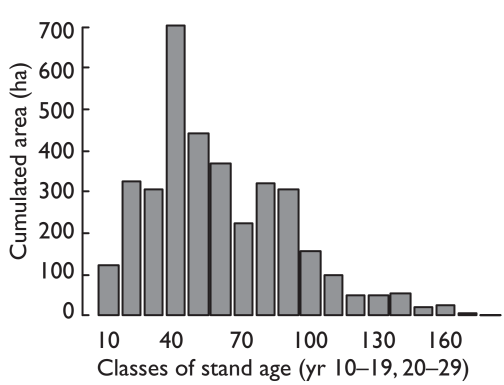

Fig. 3. Age-class structure of the Hummelshain forest district in year 2003.

Table 1. Inventory information for the A stand (forest inventory id „10,S,1,3,189,a,2“). n.a.: no data available.

Species	Age yr	Diameter cm	Height m	Coverage % area	Basal area m^2/ha	Volume m^3/ha
Spruce	55	18	24	65	27	311
Pine	50	26	22	15	27	271
Birch	50	23	24	20	27	271
Spruce	45	10	15	40	9	72
Pine	95	41	n.a.	n.a.	n.a	6

strong domination of stands of 40–50 years (Fig. 3). For more than two third of the stand area the forest inventory recorded one or more cohorts in addition to the dominating cohort. Within the non-dominating cohorts there was a larger proportion of oak and other softwood and hardwood species (Fig. 2, compare bottom to top).

I exemplify some of the stand-scale results at the specific stand with the forest inventory id “10,S,1,3,189,a,2”, here referred to as the A stand. It consisted of 4 cohorts, for which basal area data was available (Table 1): the dominating Spruce cohort of age 55 years, a younger spruce cohort of age 45 years, a pine cohort and a birch cohort, which were both of age 50 years. The forest inventory additionally listed a remnant of a pine cohort of age 95 year, for which no further information, such as basal area, was available. Site conditions were described as a dystric Cambisol (class “BBn: Normbraunerde” in the used site map) on sandstone bedrock with no seasonal changes in intermediate soil moisture (class “terrestrisch, mäßig frisch”) and intermediate nutrient availability. The stand was located in the climatic region in the lowlands (class “Vm”), with annual mean temperature of 8.5°C, annual precipitation sum of 602 mm, and a drought index, i.e. precipitation minus potential evapotranspiration from May to September, of 8 mm.

2.2 Data

Forest inventory in the study region is performed with the main objective to assess timber volume and growth increment. All the stands of the forest area of the forest district are sampled during one year and the sampling is repeated every 10 years. Diameter at breast height (cm) and basal area (m^3/ha) of each cohort (classified by species, age, and

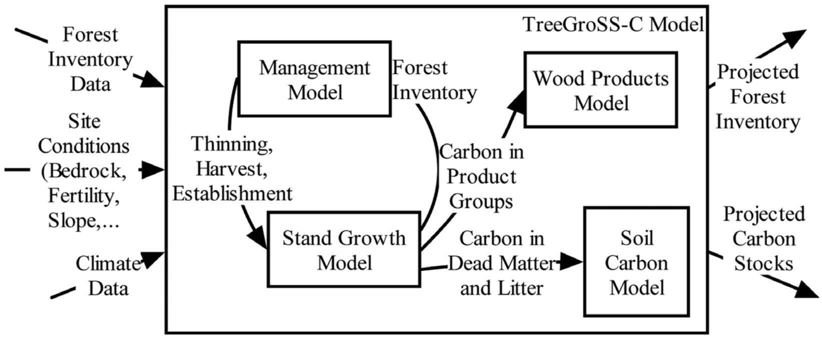

Fig. 4. Conceptual view of the TreeGrOSS-C model. Arrows denote inputs and outputs to the TreeGrOSS-C model and its submodels.

height distribution) are assessed with a relascope and on a small subset of trees also tree height is measured. Cohort data enters a database together with recorded age of the cohort, measured or interpolated height (m), calculated relative and absolute timber volume (m^3/ha; m^3), site index (expected tree height at age 100 years in m), the proportion of covered area within a layer of the stand (%), a species identifier and several other descriptive parameters such as social role, tree layer and damages.

Additionally, an inventory of site conditions has been performed, which is based on soil profiles and delineation of homogenous areas based mainly on local topography and ground vegetation (Kopp and Schwaneke 1991). The site inventory records information on bedrock, geology, moisture conditions and nutrient availability. The areas of this site evaluation are nested within areas of similar climatic conditions, which are based mainly on altitude and exposition in this inventory.

I used the climatic data from Vetter et al. (2005) and related it to the classes of the site inventory. Vetter et al. obtained the data from 11 stations of the German Meteorological Society (DWD Offenbach Germany) and aggregated it to 3 classes. The original data consisted of an hourly record of temperature, precipitation, water pressure deficit, solar radiation and day length from 1971–2001. Additionally I used the Simpel model (Hörmann 2006) to calculate potential evapotranspiration for spruce and for broadleaved species dominated stands.

2.3 Forest Ecosystem Carbon Model

In order to project the stand structure and the development of carbon stocks, I used the TreeGrOSS-C model which is described in more detail in appendix A and (Wutzler 2007). The model is an extension of the TreeGrOSS-model (Tree Growth Open Source Simulator), an empirical single tree based stand simulator which is based on data of long term monitoring plots in Central Germany (Nagel 1999, 2003, 2006). TreeGrOSS projects the development of diameter and height of individual trees by a species and site dependent potential growth that is diminished by the competition state of each tree. It contains modules to calculate the timber volume of trees, as well as modules to generate distributions of single trees, based on average diameter and height of tree cohorts.

I extended the TreeGrOSS model first, by modules to read and generate inventory information of the used inventory data, second, by modules to convert timber volume to carbon of several tree compartments and it's turnover by wood density (Weiss et al. 2000), biomass expansion factors (Lehtonen et al. 2004, Zianis et al. 2005, Wutzler and Wirth 2007), and average life times (Wutzler and Mund 2007), and third, by modules to allocate carbon in harvested timber to several product groups according to Mund et al. (2005). Next, I coupled the extended TreeGrOSS model to a model of forestry management, a simple wood product model, and the Yasso Soil Carbon model (Liski et al. 2005) (Fig. 4).

The management model compared the inventory of each cohort of the simulated stand to yield tables at each year that was listed in the corresponding yield tables. Then it generated thinning demands by specifying the accumulated basal area and the mean diameter of trees to be thinned determined by the difference to the corresponding yield table specification. The target value from the yield table was specified for monospecific stands only. Hence, the value was multiplied by the proportion of the basal area of the cohort to the sum of basal area of all cohorts. The amount of thinning was constrained to be at maximum 20% of the current basal area, in order to avoid stand instability. The stand was harvested at the last stand age that was recorded in the yield table of the dominating cohort and cohorts were re-established with the same shares of cohorts as in the initial forest inventory.

The wood product model tracked the carbon in several product groups that are defined by a common life time. It was assumed that an amount of wood corresponding to the reciprocal of the life time leaves the pool each year. This led to a first order decay approximation for the pool sizes.

The Yasso soil carbon model was split into a species-dependent and a species-independent part. The dependent parts were replicated in order to simulate multi-cohort stands. Yearly inputs of mean annual temperature, annual precipitation, and drought index were provided. The soil model was initialized by spinup-runs with modelled mean past litter production (Wutzler and Mund 2007) and adjusted with the transient correction to account for former disturbances (Wutzler and Reichstein 2007). The correction required an independent estimate of initial carbon stocks. Therefore, I extrapolated measured carbons stocks in mineral soil and organic layer based on the inventory of site conditions and the forest inventory. For the spatial extrapolation, I applied geo-matching in conjunction with the regression models developed by Wirth et. al. (2004), making use of the combined data of the forest inventory and the site evaluation.

The stand growth model had an internal time step of 5 years. The management model and the product model were implemented as discrete event models (Zeigler et al. 2000) and run according to the thinning events as specified by the yield tables. The Yasso soil carbon model was implemented as a quantized system that solved the differential equations with a time step adjusted to the accuracy of the pool changes (Kofman 1997) and received updated litter input rates at least each 5 years. In this study I analysed the simulated merchantable timber volume (m^3/ha), above ground wood with a diameter > 7 cm and carbon stocks (t/ha) in

– above and below ground biomass of living trees
– woody debris, i.e. the sum of dead wood, dead root and woody litter
– and the soil including the organic layer

2.4 Practical Scenario

In accordance with the goal of this study I did not introduce scenarios of climate change nor introduce changes in management practises. I projected the carbon stocks to the next century under practical assumption that management, i.e. timing and amount of thinning and harvesting and stand establishment, corresponded to yield tables. Climatic drivers were kept constant to the mean over the previous 40 years. The additional assumptions with the possible inclusion of climatic correction into empirical stand growth models (Matala et al. 2006) together with the uncertainty of regional and topographic climate scenarios (Running et al. 1987), would have increased model complexity and they would also have complicated the interpretation of the results.

2.5 Four Approaches of Aggregating Forest Inventory Data

The aim of this study was to assess the effect of aggregating multi-cohort, multi-species stands to only one cohort on the projection of carbon stocks. Hence, I ran the TreeGrOSS-C model in several scenarios which differed in the way of how the input data has been aggregated before (Table 2). First I ran the model with the data of all the stands and all the cohorts to form a baseline (detailed approach, Fig 1c). Second, I ran the model for each stand but with only a single aggregated cohort, i.e. a monospecific stand (aggregated approach). The properties spe-

Table 2. Approaches of aggregating the forest inventory data.

	Cohort aggregation	
Stand aggregation	**Detailed** Each stand All cohorts	**Aggregated** Each stand Single aggregated cohort
	Subsampled Subset of 46 stands All cohorts	**Stratified** 110 strata of district inventory data Single aggregated cohort

cies, age, diameter, height, and site index of this aggregated cohort corresponded to the dominating cohort. The basal area, timber volume, and covered area of the aggregated cohort corresponded to the sum across all the cohorts within the stand. Third, I analyzed a subset of 46 randomly selected stands with all cohorts (subsampled approach, Fig. 1b). The number of 46 stands was chosen because there were 46 plots of the national forest inventory (BMVEL 2005) within the study area. And fourth, I aggregated all the inventory data into classes according to four species groups, age classes of 10 years, and three classes of site quality according to site index (Kramer and Akça 1995) (stratified approach, Fig. 1a). For each class I ran a simulation with one cohort using the data of site conditions and the climate record for the area that was most abundant within the forest area that was represented by the class.

2.6 Statistical Analysis

Mean carbon stocks at forest district scale and at the two sub regions of the Eastern and Western growing region were calculated with weighting the stands or classes by their corresponding stand area. In order to compare the significance of differences between the approaches I used a bootstrap analysis (Davison and Hinkley 1997) of 1000 times randomly sampling stands or classes with replacement. This mimics a 1000 times resampling of the forest district. From each bootstrap sample I recalculated the weighted mean of simulated carbon stocks (tC/ha) by one of the aggregated approaches and I recalculated its difference to the weighted mean of the stocks that were simulated by the detailed approach (Fig 1c) for each bootstrap sample. The mean, the standard deviation, and the 2.5% to 97.5% confidence interval of the difference were estimated from the empirical cumulative distribution function across the bootstrap samples. The bias, i.e. the mean difference to the detailed approach, was significant if the 95% confidence interval did not include the zero difference. In the same manner I calculated the differences between approaches and their statistics of the stock change (tC/ha/yr) from 2003 until 2013, 2023, 2053 and 2103. The bootstrap analysis is here more appropriate than t-tests or rank-tests because it accounts for both, the strong non-normality of the distribution and the different weights, i.e. areas, of each stand or observation.

3 Results

3.1 Stand Level

First, I compared the aggregated versus the detailed approach (Table 2) at single stands. In the aggregated approach the information on the interspersed species has been discarded. Hence, the simulation of the two approaches differ most by differences between species in thinning operations and by different carbon mass per timber wood volume, i.e. the parameters wood density and biomass expansion factor. For example, at the A stand less pre-commercial thinning or self-thinning was simulated with the aggregated approach (Fig. 5a). This was because of stronger thinning for the interspersed cohorts than for the dominating spruce cohort, which was prescribed by the yield tables. Further the species of the interspersed cohorts were also less shade-tolerant than the dominating cohort and the model calculated stronger self-thinning. This resulted in higher standing timber volume in tree biomass but in lower tree biomass because of differences in conversion factors. At the same time, less dead wood was produced with the aggregated approach. Hence, there were lower carbon stocks in woody debris and soil (Fig. 5b and 5d). Besides thinning, also differences in litter production and litter turnover between species were important for

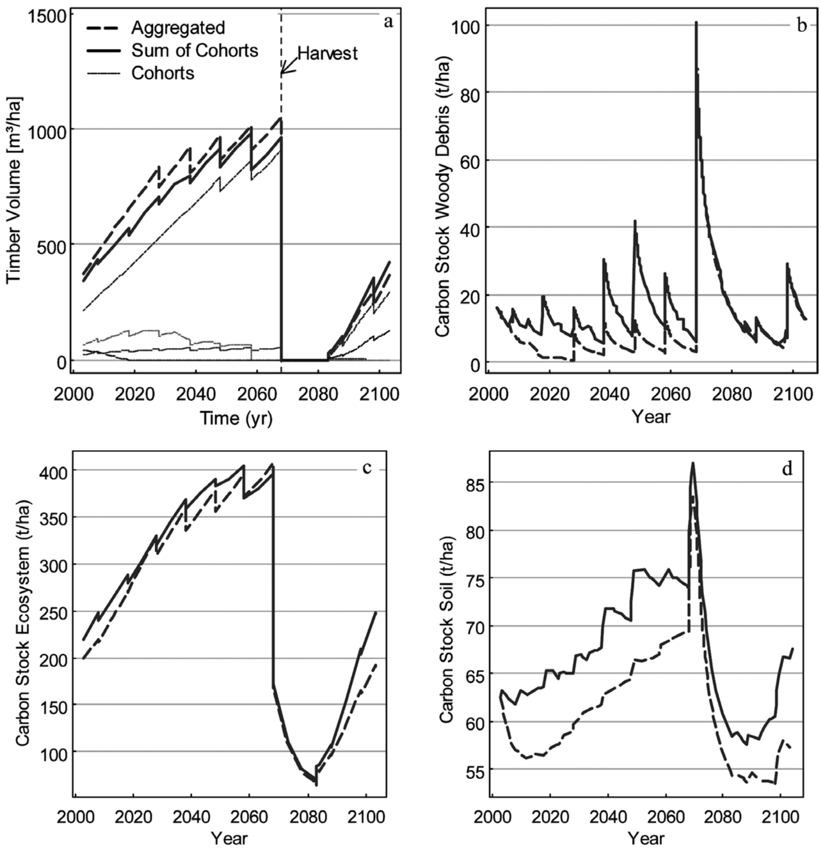

Fig. 5. Stand scale differences of projections of timber volume a), carbon stocks in woody debris b), ecosystem c), and mineral soil d) between the detailed approach (solid line) and the aggregated approach (dashed line) for the A stand. The several dash-dot lines in panel a correspond to the four simulated tree cohorts (Table 1) in the stand growth model.

woody debris and soil carbon stocks.

When ecosystem carbon stocks were compared, i.e. the sum of carbon stocks in above and below ground biomass, woody debris, and soil, the aggregated approach resulted in lower initial carbon stocks for the example stand (Fig. 5c). Because of the differing description of species in the aggregated approach, there were differences in volume equations, wood density, biomass expansion factors and initial carbon stocks. These differences caused the deviations in initial ecosystem carbon stocks at the beginning of the projection in 2003 in the aggregated approach compared to the detailed approach.

In addition, there were differences in initial woody debris carbon stocks (differences are between –7.3 and 2.9 t/ha in 95% of the stands) and soil carbon stocks (–19.0 to 11.9 t/ha) between the aggregated and the detailed approach (Fig. 6). These differences were larger than the difference in biomass stocks (–1.2 to 8.8 t/ha) and dominated the differences in ecosystem carbon stocks (–21.8 to 16.2 t/ha). However, these differences in initial carbon stocks between approaches were small compared to the differences between the stands (Fig. 7). The relative difference between the detailed and the aggregated approach of 2003 ecosystem carbon stocks did not exceed 2% for 71% of the stands. The mean of the absolute values of the differences was 2.3% and the standard deviation of the differences was 9.0%. However, eight stands differed by more than 20%. For a subset of

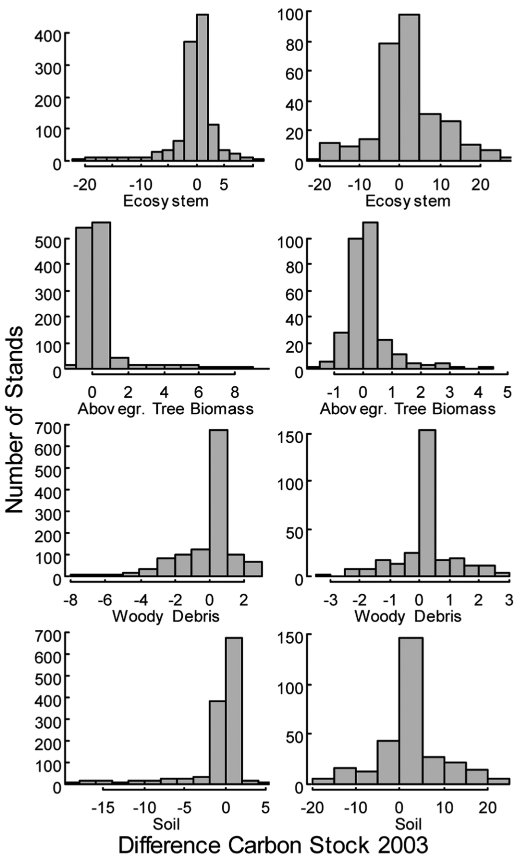

Fig. 6. Histogram of the differences in 2003 carbon stocks between aggregated and detailed approach (C_{aggr}-C_{detl})). The left column represents the Eastern growing region and the right column the Western growing region. Note the different scale of the x-axis which represents the empirical 95% confidence interval.

Fig. 7. Stand scale initial, i.e. year 2003, ecosystem carbon stocks (t/ha). The ellipse denotes one of the only few areas where the differences between approaches are larger than the resolution of the legend, i.e. the magnitude of differences between stands.

the stands the carbon stocks were overestimated by the aggregated approach, but for the other stands the stocks were underestimated. The histograms (Fig. 6) showed no apparent dominance of a direction of the difference between the aggregated approach and the detailed approach.

3.2 Forest District Scale

At forest district scale the bootstrap analysis detected a non-significant difference (–0.39 t/ha) in 2003 ecosystem carbon stocks between the aggregated and the detailed approach (Table 3). However, for the subsets of stands in the Eastern and the Western growing region there was a significant underestimation (–0.93 t/ha) and overestimation (+1.9 t/ha) respectively. The difference in the soil carbon stocks (95% of the bootstrap samples within –1.15 to –0.48 t/ha) was larger than the difference in biomass stocks (–0.78 to

Table 3. Bootstrap statistics about the differences of the aggregating approaches from the detailed approach in 2003 ecosystem carbon stocks (t/ha). $q_{2.5}$ and $q_{97.5}$: empirical 2.5% and 97.5% percentiles, p_0 zero difference in the empirical cumulative distribution function (outside 0.025 and 0.975 is significant).

Region	Mean	Std.Dev	$q_{2.5}$	$q_{97.5}$	p_0	bias
Aggregated–Detailed						
District	–0.39	0.21	–0.78	0.015	0.97	trend of underestimation
East	–0.93	0.19	–1.3	–0.54	1.0	significant underestimtion
West	1.9	0.62	0.65	3.1	0.0020	significant overestimation
Subsampled–Detailed						
District	–1.9	10	–24	14	0.50	no
East	0.37	11	–22	17	0.46	no
West	1.0	5.8	–11	8.0	0.50	no
Stratified–Detailed						
District	–3.9	0.92	–5.7	–2.1	1.0	significant underestimtion
East	–6.1	0.98	–8.1	–4.2	1.0	significant underestimtion
West	5.4	1.8	1.9	9.2	0.0010	significant overestimation

+0.015 t/ha) and in woody debris carbon stocks (–0.54 to –0.29 t/ha) (Fig. 8).

Further, when I compared the change in ecosystem carbon stocks between 2003 and 2023, there was a significant underestimation of these stock change by the aggregated approach of about –33 kg/ha/yr across the district and the sub regions. The difference regarding ecosystem stock change was dominated by biomass (95% of the bootstrap samples within –48 to –28 kg/ha/yr) compared to woody debris (+12 to +27 kg/ha/yr) and soil (–20 to –7 kg/ha/yr).

At district level, I could also compare the results of the subsampled and the stratified approach (Table 2) to the detailed approach. The studied population was the same, but the sample of individuals differed across the approaches. The box-plots of the distribution of carbon stocks in 2003 across the forest area showed that about 50% of the area had carbon stocks of 190 to 250 tC/ha and a median of about 220 tC/ha in all the four approaches (Fig. 9). The subsampled and the stratified approach did not represent areas of extreme (28 to 289 t/ha) carbon stocks. The bootstrap analysis showed comparatively wide confidence intervals (–24 to +14 tC/ha) for the difference in ecosystem carbon stocks 2003 between the subsampled and the detailed approach (Table 3). Hence, there was no significant bias detected. The bias with the stratified approach, i.e. the difference to the detailed approach, of 2003 ecosystem carbon stocks had the same directions for the regions as with the aggregated approach, and the bias was significant for all regions.

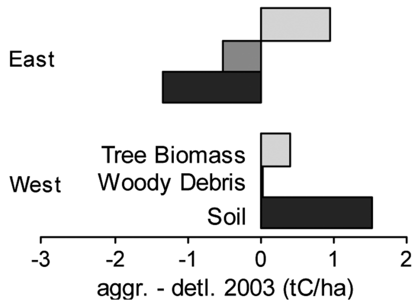

Fig. 8. Differences in district mean carbon stocks 2003 between aggregated and detailed approach.

All four studied approaches agreed in the temporal development of carbon stocks. All four approaches projected a shift in the distribution of carbon with time (Fig. 10). This shift is explained by the unbalanced age class structure in the forest district (Fig. 3). Initially there was a dominance of stands of age class 40–50 years and this dominance persisted in time, as the respective stands grew older. Ecosystem carbon stocks were dominated by the tree biomass stocks, which are larger at higher age classes. When it comes to harvest of these cohorts after 2053, the carbon stocks decrease again until 2103 (Fig. 10).

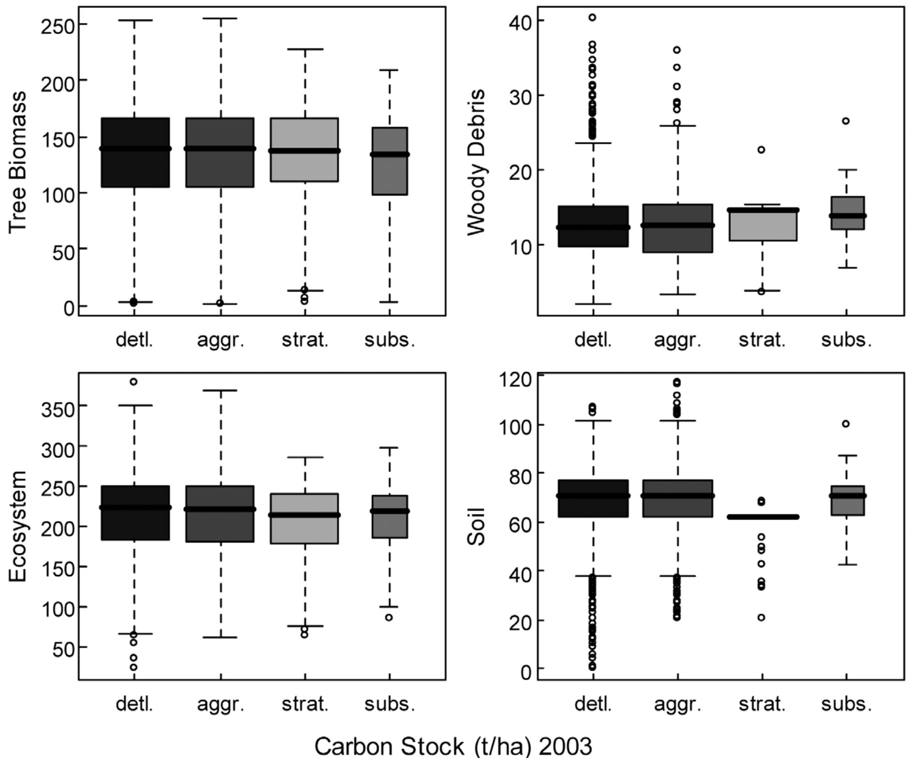

Fig. 9. Distribution of the carbon stocks 2003 (t/ha) across the forest area. The box plots for each approach denote the median (central line), the 25%, and, 75% (box edges), the range (arrows), and extreme values (circles) of the quantiles of forest area that have carbon stocks greater than the corresponding number indicated on the y-axis.

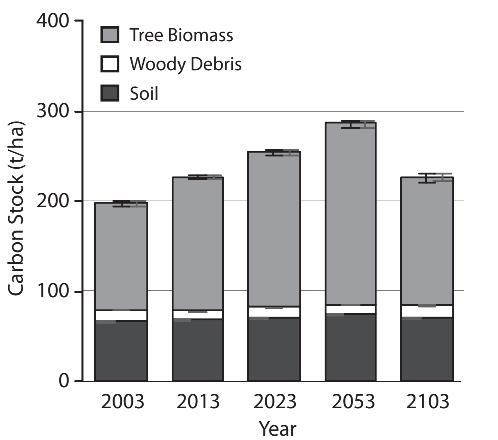

Fig. 10. Forest district scale projections of carbon stocks. Black arrows represent the 95% bootstrap confidence interval of the detailed approach and grey arrows the intervals of the aggregated approach.

When comparing the distribution of the carbon stock change between 2003 and the years 2013, 2023, 2053 and 2103, there were no obvious differences in the median and the quantiles of the distribution between approaches (Fig. 11). The subsampled and the stratified approach did not represent areas of the extreme carbon stocks changes. The bootstrap analysis of the carbons stock change from 2003 to 2023 found again large standard errors for the difference between the stratified and the detailed approach. Hence, this difference was not significant (Table 4). The stratified approach predicted a significantly larger stock change (0.48 t/ha/yr) than the detailed approach.

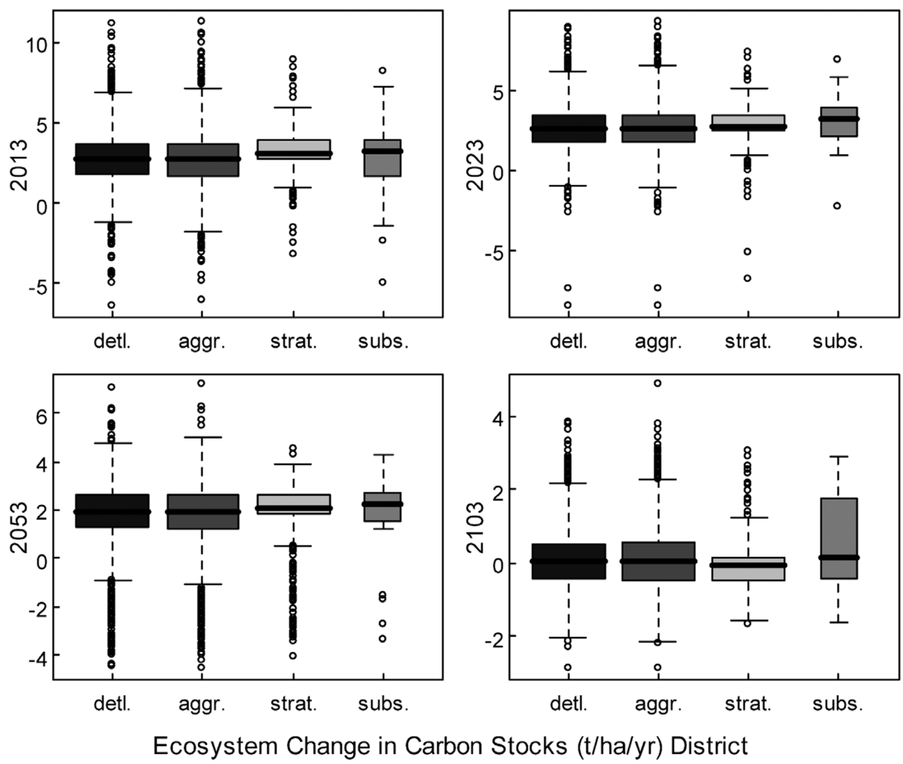

Fig. 11. Distribution of the carbon stocks change 2003–2023 (t/ha/yr) across the forest area. The box plots for each approach are interpreted like in Fig. 9.

Table 4. Bootstrap statistics differences in ecosystem carbon stock changes from 2003 to 2023 (t/ha/yr). Symbols as in Table 3.

Region	Mean	Std.Dev	$q_{2.5}$	$q_{97.5}$	p_0	bias
Aggregated–Detailed						
District	–0.033	0.0060	–0.043	–0.021	1.0	significant underestimation
East	–0.033	0.0071	–0.047	–0.019	1.0	significant underestimation
West	–0.034	0.011	–0.056	–0.011	1.0	significant underestimation
Subsampled–Detailed						
District	–0.012	0.27	–0.53	0.48	0.56	no
East	0.0123	0.35	–0.51	0.61	0.46	no
West	0.017	0.15	–0.25	0.28	0.38	no
Stratified–Detailed						
District	0.48	0.031	0.42	0.54	0.0	significant overestimation
East	0.50	0.031	0.44	0.56	0.0	significant overestimation
West	0.41	0.091	0.23	0.58	0.0	significant overestimation

4 Discussion

This case study provides the first assessment of a potential bias in the quantification and projection of forest ecosystem carbon stocks with the aggregating forest inventory data of multi-cohort mixed stands. By driving a single-tree based empirical forest carbon balance model first with data on all cohorts and second with aggregated data (Table 2) it was possible to study the effect of abstracting from details of stand structure on the quantification of carbon stocks at the scale of stands and the scale of a forest district.

My hypothesis which stated that the aggregation of multi-cohort forest inventory data to a single cohort results in a bias in simulated forest ecosystem carbon stocks was first confirmed at stand scale. The difference in initial timber volume between the aggregated and the detailed approach was caused by differences in timber volume equations (Gregoire and Schabenberger 1996). With the example stand the aggregated approach, which subsumed the younger birch and spruce cohorts and the 10 years younger spruce cohort into the dominating spruce-cohort, resulted in a higher timber volume for the same basal area (Fig. 5). At the same time the approach resulted in lower carbon stock in tree biomass. This corresponds to the decrease of the biomass expansion factors with age (Lehtonen et al. 2004, Wirth et al. 2004, Lehtonen et al. 2007).

In addition, there were differences in initial woody debris and soil carbon stocks that were larger than the differences in biomass and differed between regions (Fig. 8). The difference in initial soil carbon stocks were caused mainly by differences in initial organic layer carbon stocks between coniferous and broadleaved species (Wirth et al. 2004) and to some extent also by differences in mean litter production (Wutzler and Mund 2007), and litter turnover (Liski et al. 2005).

The difference between the approaches in the predicted stock changes were mainly attributed to differences in thinning intensity in pre-commercial thinning and to differences in self-thinning between species in the example stand. The differences in diameter and height increment between species were less important (Fig. 5). This observation corresponds to the finding of the overruling effect of the thinning intensity of a similar forest in Central Germany (Wutzler et al. 2006). It also implies that a different representation of forestry management can significantly change the projection of the carbon sink during one rotation cycle.

At forest district scale the positive and negative deviations between the aggregated and the detailed approach balanced each other to a large extent (Fig. 6). Nevertheless, the size of the studied population was large enough so that the bootstrap analysis detected a trend of an overestimation at the district scale and an under and overestimation at the Eastern and Western growing region respectively (Table 3). However, this bias due to aggregation of stand data was small compared to the stocks and their changes (Fig. 10). The compensation of the bias at district scale might have been due to the fact that most of the interspersed species also occurred as dominant species. Therefore, I repeated the analysis independently for the Eastern and the Western part that differed in many aspects, most important in bedrock and species distribution. Although, there was a difference in the share of broadleaved species in the interspersed cohorts compared to the dominant cohorts within these regions (Fig 2), still negative and positive bias compensated so that the bias at district scale was small (Table 3). The disappearance of effects that are important at stand scale was also observed and discussed for environmental parameters in a monospecific process based forest growth model (Davi et al. 2006). From a theoretical perspective this is only expected, if the participating processes are linear (Harvey 2000). However, this was not strictly the case with this study as it was with Davi's study.

The opposing sign of the bias in the Eastern and the Western region allows us to discuss which reasons hindered a full balancing at the district scale. A possible reason for the bias ecosystem carbon stocks in 2003 is that spruce cohorts of age 50 years store about one third less carbon for the same timber volume compared to beech cohorts due to differences in wood density and biomass expansion factors (Löwe et al. 2000, Wirth et al. 2004). The interspersed cohorts have a larger contribution of broadleaved species compared to the dominating cohorts in the Eastern region and a smaller contribution in Western region respectively (Fig. 2). The aggregated approach subsumes a part of these cohorts within the dominating cohort. I, henceforth, expected an underestimation of biomass carbon stocks in the Eastern region and an overestimation in the Western region. Instead I observed a significant overestimation of biomass carbon stocks (+0.94 and +0.40 tC/ha) in both the Eastern and the Western region respectively with the larger overestimation in the Eastern growing region (Fig. 8). This is opposite of the expected differences and I, hence, conclude that this first reason has only a minor effect.

A second possible reason is that interspersed cohorts are of different age than the dominating cohorts. At the Eastern region the dominant cohorts were on average (basal area weighted mean) one year younger than the interspersed cohorts and at the western region 11 years older. Hence, I would expect an overestimation of carbon stocks by the aggregated approach in the Western region. This is in line with the observed carbon stocks (Fig. 8). This second reason is likely a major contributor to bias in carbon stocks.

A third possible reason is that the most broadleaved species have a higher mean litter carbon production than spruce and pine across the rotation cycle (Wutzler and Mund 2007). Therefore, I expect an underestimation of carbon stocks in woody debris and initial soil carbon in the Eastern region where broadleaved species are subsumed to pine and spruce cohorts. This is in line with a significant underestimation (–0.52 and –1.35 t/ha) in the Eastern region and an overestimation (0.02 and 1.52 t/ha) in the Western region for woody debris and soil carbon respectively. Because of the fact that differences in the approaches were mostly attributed to woody debris and soil (Fig. 8), this mechanism has a likely major effect on bias on carbon stock quantification.

The significance of the bias does not necessarily imply that the bias is important. When I compare the bias with the magnitude of the stocks and their changes (Fig. 10), the bias can hardly be presented in the graph and also the bias of the subsampled and stratified approach would hardly be seen. It is small compared to the range of the uncertainty of the ecosystem carbon stock prediction of the detailed approach (e.g. –0.39 tC/ha bias; 195.5 to 201.2 tC/ha 95% confidence interval of the detailed approach estimate of ecosystem carbon stocks in 2003, i.e. only about 7% of the uncertainty range). The bias is small enough compared to the uncertainty range, so that I conclude that it is not important for the quantification and projection of carbon stocks at this case study. This study considered only uncertainty introduced by sampling the population of forest stands and the aggregation of the inventory data. If, additionally, the uncertainty of the forest inventory and the model were considered, the uncertainty ranges would increase, and the relation of the bias to the uncertainty range would be even smaller. In order to verify that the smallness of the bias is a general phenomenon, it is necessary to repeat similar studies at various forests. However, I do not expect the bias to increase at other forests to the magnitude of the uncertainty range.

The observation of higher simulated carbon stocks in woody debris and soil for spruce stands that are interspersed with broadleaved species counteracts with the observation of lower timber volume (Fig. 5a). Such antagonistic effects of mixture on productivity are observed, when species compete for the same resources (Pretzsch 2003, Pretzsch 2005). However, the results confirm that a lower timber production of mixed stands does not imply lower carbon storage, which corresponds to findings by Jandl et al. (2007a).

We shoed a strong legacy effect of an unbalanced age class distribution (Fig. 10). This legacy effect of age classes has already been simulated before for the study region (Vetter et al. 2005, Böttcher 2007). Since, this age class effect is also observed in other regions of the world (Albani et al. 2006), it contributes to the projected exhaust of the terrestrial sink (Canadell et al. 2007).

The advantages of using an empirical distance independent tree based forest ecosystem carbon balance model are that I was able to run it at each individual stand including the full inventory data of all cohorts. I could take detailed account for site quality, as expressed by the site index, and for the effects of thinning operations on stand development. The drawback of this approach, however, was that I could not explicitly represent climate change in the stand growth submodel. On the contrary, mechanistic approaches allow more confidence in longer term projections that are effected by changing environmental conditions, but require more detailed input parameters and input data (Grote and Pretzsch 2002, Porté and Bartelink 2002, Matala et al. 2003). With explicitly accounting for climate change I expect the stand growth and the biomass carbon stocks later than 2003 to be higher than with the presented simulations (Mund et al. 2002, Jandl et al. 2007b). The soil carbon either may be higher because of enhanced litter input or be lower because of enhanced decomposition of soil organic matter. Climate change could, however, affect species differently and alter competition, growth, and self-thinning. On the other hand, the changes in biomass carbon stocks are mainly a result of a changing age structure and thinning intensities in these managed forests. Therefore, I expect the effects of climate change in the next 100 years to be overruled by forestry management to a large extent.

Despite these restrictions, this case study provides evidence, that the bias in carbon stock changes due to aggregation of stand data is only 7% of the uncertainty range, i.e. 95% confidence interval of the detailed approach, and hence this study provides evidence that the application of the aggregated and the stratified approaches is valid.

5 Conclusions

This case study on the potential bias, which is introduced by representing multi-cohort mixed forest stands by only one tree cohort, confirms a small but significant bias. It is based on several scenarios of aggregating forest inventory data of 1616 stands of a forestry district in Central Germany and the simulation of a single-tree based empirical forest carbon balance model. At stand scale the ecosystem stocks that were quantified for 2003 with the aggregated approach differed from the detailed approach by 2.3%, but at the district scale only by 0.05%. The sign or the magnitude of the bias in simulated biomass, dead organic matter, and soil carbon stocks differed between two sub regions. By comparing the differences between the regions to the bias in carbon stocks I identified likely major causes for the bias. For the quantification of the initial stocks the differences in age between interspersed and dominant cohorts were important as well as differences in litter production between species. For the projection of the carbon stocks over the next 100 years, the differences in forestry management were important, namely the amounts of wood extracted by thinning operations. Because of the smallness of bias, e.g. only 7% of the size of the 95% confidence interval of the detailed approach for the carbon stocks in 2003, this case study collects evidence that the approaches of carbon stock quantification, that represents stands or stratums by a single cohort, are valid at the scale of a forest district or larger.

Acknowledgements

I wish to thank two anonymous reviewers for their constructive critics of an earlier version of the article. And I want to thank my colleague Cornelius Middelhoff for fruitful discussions on the statistics and the clarity of the manuscript.

References

Albani, M., Medvigy, D., Hurtt, G.C. & Moorcroft, P.R. 2006. The contributions of land-use change, CO_2 fertilization, and climate variability to the Eastern US carbon sink. Global Change Biology 12(12): 2370–2390.

BMVEL 2005. Die zweite Bundeswaldinventur-BWI2 – Der Inventurbericht. Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft. 231 p.

Böttcher, H. 2007. Forest management for climate change mitigation – modeling of forestry options, their impact on the regional carbon balance and implications for a future climate protocol. Albert-Ludwigs-Universität, Freiburg. 157 p.

Canadell, J.G., Pataki, D.E., Giffort, R., Houghton, R.A., Luo, Y., Raupach, M.R., Smith, P. & Steffen, W. 2007. Saturation of the terrestrial carbon sink. In: Canadell, J.G., Pataki, D.E. & Pitelka, L.F. (eds.). Terrestrial ecosystemens in a changing world. Global Change – The IGBP Series 24. Springer, Heidelberg. p. 26.

Davi, H., Bouriaud, O., Dufrêne, E., Soudani, K., Pontailler, J.Y., Le Maire, G., Francois, C., Breda, N., Granier, A. & Le Dantec, V. 2006. Effect of aggregating spatial parameters on modelling forest carbon and water fluxes. Agricultural and Forest Meteorology 139(3–4): 269–287.

Davison, A.C. & Hinkley, D.V. 1997. Bootstrap methods and their application. Cambridge University Press, Cambridge. 582 p.

Freibauer, A., Böttcher, H., Scholz, Y., Gitz, V., Ciais, P., Mund, M., Wutzler, T. & Schulze, E.-D. 2008. Setting priorities for land management to mitigate climate change. Climatic Change (submitted).

Gamborg, C. & Larsen, J.B. 2003. Back to nature – a sustainable future for forestry? Forest Ecology and Management 179(1–3): 559–571.

Gregoire, T.G. & Schabenberger, O. 1996. Nonlinear mixed-effects modeling of cumulative bole volume with spatially correlated within-tree data. Journal of Agricultural, Biological, and Environmental Statistics 1(1): 107–119.

Grote, R. & Pretzsch, H. 2002. A model for individual tree development based on physiological processes. Plant Biology 4(2): 167–180.

Harvey, L.D.D. 2000. Upscaling in global change research. Climatic Change 44(3): 225–263.

Hasenauer, H. 2006. Sustainable forest management: growth models for Europe. Springer, Berlin. 398 p.

Hörmann, G. 2006. Simpel Speichermodelle zum Bodenwasserhaushalt. Ökologiezentrum der Universität Kiel.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K. & Byrne, K.A. 2007a. How strongly can forest management influence soil carbon sequestration? Geoderma 137(3–4): 253–268.

— , Neumann, M. & Eckmullner, O. 2007b. Productivity increase in Northern Austria Norway spruce forests due to changes in nitrogen cycling and climate. Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde 170(1): 157–165.

Kofman, E. 1997. Discrete event based simulation and control of continuous systems. Dissertation – Facultad de Ciencias Exactas, Ingenieria y Agrimensura Universidad Nacional de Rosario.

Kohm, K.A. & Franklin, J.F. 1997. Creating a forestry for the twenty-first century. The Science of Ecosystem Management. Island Press, Washington, DC.

Kopp, D. & Schwaneke, W. 1991. Standörtlich-naturräumliche Grundlagen der ökologiegerechten Forstwirtschaft: Grundzüge von Verfahren und Ergebnissen der forstlichen Standortserkundung in den fünf ostdeutschen Bundesländern. Dt Landwirtschaftsverlag, Berlin

Kramer, H. & Akça, A. 1995. Leitfaden zur Waldmeßlehre. SauerländerVerlag, Frankfurt am Main. 266 p.

Larsen, J.B. & Nielsen, A.B. 2007. Nature-based forest management – Where are we going? Elaborating forest development types in and with practice. Forest Ecology and Management 238(1–3): 107–117.

Lasch, P., Badeck, F.W., Suckow, F., Lindner, M. & Mohr, P. 2005. Model-based analysis of management alternatives at stand and regional level in Brandenburg (Germany). Forest Ecology and Management 207(1–2): 59–74.

Le Maire, G., Davi, H., Soudani, K., Francois, C., Le Dantec, V. & Dufrêne, E. 2005. Modeling annual production and carbon fluxes of a large managed temperate forest using forest inventories, satellite data and field measurements. Tree Physiology 25(7): 859–872.

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R. & Liski, J. 2004. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. Forest Ecology and Management 188(1–3): 211–224.

— , Cienciala, E., Tatarinov, F. & Mäkipää, R. 2007. Uncertainty estimation of biomass expansion factors for Norway spruce in the Czech Republic. Annals of Forest Science 64: 133–140.

Liski, J., Korotkov, A.V., Prins, C.F.L., Karjalainen, T., Victor, D.G. & Kauppi, P.E. 2003. Increased carbon sink in temperate and boreal forests. Climatic Change 61(1–2): 89–99.

— , Palosuo, T., Peltoniemi, M. & Sievänen, R. 2005. Carbon and decomposition model Yasso for forest soils. Ecological Modelling 189(1–2): 168–182.

Löwe, H., Seufert, G. & Raes, F. 2000. Comparison of methods used within member states for estimating CO_2 emissions and sinks according to UNFCCC and EU monitoring mechanism: forest and other wooded land. Biotechnology, Agronomy, Society and Environment 4: 315–319.

Matala, J., Hynynen, J., Miina, J., Ojansuu, R., Peltola, H., Sievänen, R., Väisänen, H. & Kellomäki, S. 2003. Comparison of a physiological model and a statistical model for prediction of growth and yield in boreal forests. Ecological Modelling 161(1–2): 95–116.

— , Ojansuu, R., Peltola, H., Raitio, H. & Kellomäki, S. 2006. Modelling the response of tree growth to temperature and CO_2 elevation as related to the fertility and current temperature sum of a site. Ecological Modelling 199(1): 39–52.

Mund, M., Kummetz, E., Hein, M., Bauer, G.A. & Schulze, E.-D. 2002. Growth and carbon stocks of a spruce forest chronosequence in central Europe. Forest Ecology and Management 171: 275–296.

— , Profft, I., Wutzler, T., Schulze, E.D., Weber, G. & Weller, E. 2005. Vorbereitung für eine laufende Fortschreibung der Kohlenstoffvorräte in den Wäldern Thüringens. Abschlussbericht zur 2. Phase dem BMBF-Projektes "Modelluntersuchungen zur Umsetzung des Kyoto-Protokolls". TLWJF Gotha. 128 pp.

Myneni, R., Dong, J., Tucker, C.J., Kaufmann, R.K., Kauppi, P.E., Liski, J., Zhou, L., Alexeyev, V. & Hughes, M.K. 2001. A large carbon sink in the woody biomass of northern forests. PNAS 98: 14784–14789.

Nabuurs, G.J. & Schelhaas, M.J. 2002. Carbon profiles of forests across Europe, an application of co2fix. Ecological Indicators 1: 213–223.

Nagel, J. 1999. Konzeptionelle Überlegungen zum schrittweisen Aufbau eines waldwachstumskundlichen Simulationssystems für Nordwestdeutschland. Schriften aus der Forstlichen Fakultät der Universität Göttingen und der Nieders. Forstl. Versuchsanstalt, 128. J.D. Sauerländer's Verlag, Frankfurt a.M. 122 p.

— 2003. TreeGrOSS: Tree Growth Open Source Software – a tree growth model component. Programmdokumentation Niedersächsischen Forstlichen Versuchsanstalt, Abteilung Waldwachstum, Göttingen. 25 p.

— 2006. The silvicultural decision support system BWINPro. In: Hasenauer, H. (ed.). Sustainable forest management: growth models for Europe. Springer, Berlin. p. 59–63.

— , Albert, M. & Schmidt, M. 2002. Das waldbauliche Prognose- und Entscheidungsmodell BWINPro 6.1. Forst und Holz 57(15/16): 486–493.

Perry, C.H., Jandl, R., Peltoniemi, M., Wutzler, T., Matteucci, G. & Woodall, C. 2008. Detecting direct human-induced effects on the carbon balance of forest ecosystems using models and national forest inventory data. Forest Ecology and Management (submitted).

Porté, A. & Bartelink, H.H. 2002. Modelling mixed forest growth: a review of models for forest management. Ecological Modelling 150: 141–188.

Pretzsch, H. 2003. Diversity and productivity of forests. Allgemeine Forst und Jagdzeitung 174(5–6): 88–98.

— 2005. Diversity and productivity in forests: evidence from long-term experimental plots. In: Forest Diversity and Function. p. 41–64.

Running, S.W., Nemani, R.R. & Hungerford, R.D. 1987. Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulating forest evapotranspiration and photosynthesis. Canadian Journal of Forest Research 17(6): 472–483.

Thurig, E. & Schelhaas, M.J. 2006. Evaluation of a large-scale forest scenario model in heterogeneous forests: a case study for Switzerland. Canadian Journal of Forest Research 36(3): 671–683.

UNFCCC 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change.

Weiss, P., Schieler, K., Schadauer, K., Radunsky, K. & Englisch, M. 2000. Die Kohlenstoffbilanz des österreichischen Waldes und Betrachtungen zum Kyoto-Protokoll (The carbon balance of the Austrian forest and considerations in view of the Kyoto-protocol). Monographien. Umweltbundesamt, Vienna, Austria.

Vetter, M., Wirth, C., Bottcher, H., Churkina, G., Schulze, E.D., Wutzler, T. & Weber, G. 2005. Partitioning direct and indirect human-induced effects on carbon sequestration of managed coniferous forests using model simulations and forest inventories. Global Change Biology 11(5): 810–827.

Wirth, C., Schulze, E.-D., Schwalbe, G., Tomczyk, S., Weber, G. & Weller, E. 2004. Dynamik der Kohlenstoffvorräte in den Wäldern Thüringens-Abschlussbericht zur 1. Phase des BMBF-Projektes "Modelluntersuchung zu Umsetzung des Kyoto-Protokolls". Thüringer Landesanstalt für Jagd, Wald und Fischerei, Jena Gotha. 300 p.

Wutzler, T. 2007. Projecting the carbon sink of managed forests based on standard forestry data. Dissertation – FSU Jena.

— & Mund, M. 2007. Modelling mean above and below ground litter production based on yield tables. Silva Fennica 41(3): 559–574.

— & Reichstein, M. 2007. Soils apart from equilibrium – consequences for soil carbon balance modelling. Biogeosciences 4: 125–136.

— & Wirth, C. 2008. Generic biomass functions for common beech (Fagus sylvatica L.) in Central Europe – predictions and components of uncertainty. Canadian Journal of Forest Research – June issue.

— , Köstner, B. & Bernhofer, C. 2006. Spatially explicit assessment of carbon stocks of a managed forest area in Eastern Germany. European Journal of Forest Research 126(3): 371–381.

Zeigler, B.P., Praehofer, H. & Kim, T.G. 2000. Theory of modeling and simulation. 2nd edition. Academic Press. 450 p.

Zianis, D., Muukkonen, D., Mäkipää, R. & Mencuccini, M. 2005. Biomass and stem volume equations for tree species in Europe. Silva Fennica Monographs 4. 64 p.

Total of 54 references

Appendix A: The TreeGrOSS stand growth model

The TreeGrOSS (Tree Growth Open Source Software) model (Nagel 2003) is a public domain variant of the BWinPro model (Nagel et al. 2002). According to the classification of Porté and Bartelink (2002) it belongs to the class of non-gap distance-independent tree models. The empirical model is based on data of a growth and yield experiments of about 3500 plots in northern Germany. It uses the potential growth concept (Hasenauer 2006), which reduces species and site dependent potential relative height growth of a top height tree $i_{hrelPot}$ by the single trees competition situation (A1).

$$i_{hrel} = i_{hrelPot} + p_1(h_{100} / \mathrm{h})^{P2} \qquad \text{(A1)}$$

Where p_1 are species specific constants, h_{100} is the topheight of the stand, i.e. the mean height of the highest 100 trees, and h the height of the considered specific tree. The basal area growth of a tree is estimated by Eq. A2.

$$\ln(\Delta a_{Basal}) = p_0 + p_1 \ln(c_S) + p_2 \ln(age) + p_3 c_{66} + p_4 c_{66c} + p_5 \ln(\Delta t) \qquad \text{(A2)}$$

Where p_1 are species specific constants, c_S is the crown surface area calculated from diameter, height of the tree, and the topheight of the stand,

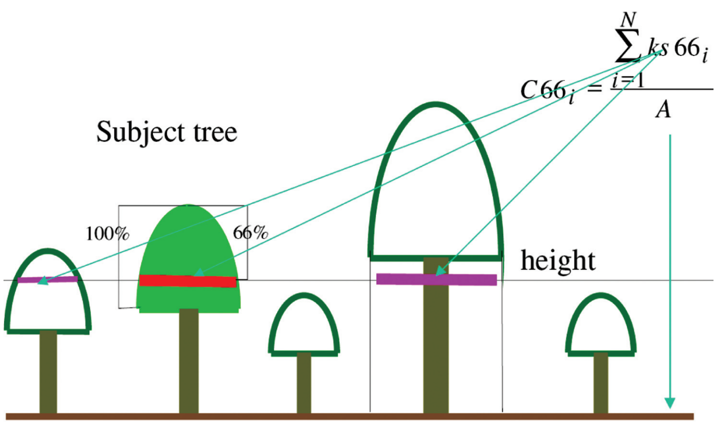

Fig. A1. Calculation of the competition index in TreeGrOSS (taken from Nagel 2003). At a height of 2/3 (or 66%) of the crown length all crowns are cut, if they reach that height. If the crown base is above the height then cross sectional area of that tree will be taken. The sum of the cross sectional area is divided by the stand area.

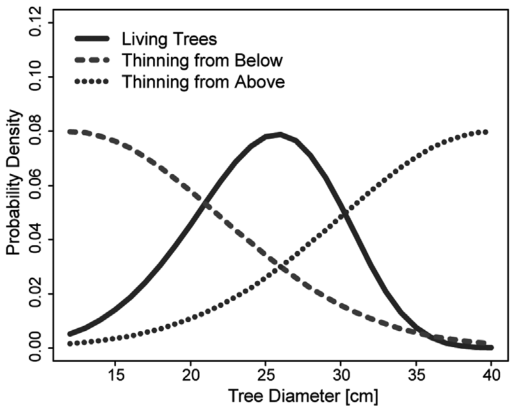

Fig. A2. Selecting trees for thinning in the model by a probability distribution of tree diameter.

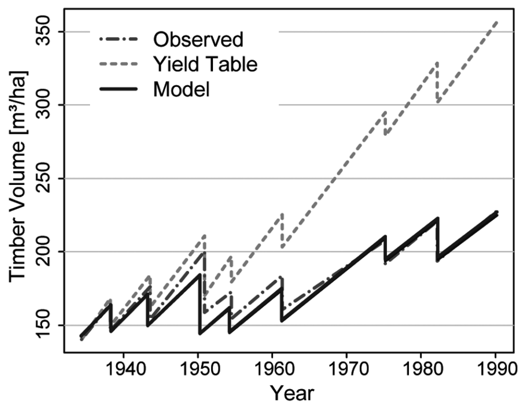

Fig. A3. Comparison of inventoried timber volume from a suppressed beech cohort of the permanent inventory plot Leinefelde 245 to model predictions by a yield table (Dittmar et al. 1986) and predictions of the TreeGrOSS model.

age is the tree age, Δt is the time period of usually 5 years, c_{66} is the competition index (Fig A1) and c_{66c} is an index that increases when the competition situation is relieved, i.e. neighbouring trees are thinned.

Further, I extended the model by thinning routines based only on information of the sum of basal area and mean quadratic diameter of thinned trees. These routines selected trees randomly from a probability distribution of tree diameters (Fig. A2). Eventually, I used one side of a Gaussian distribution with a mean of the cohorts minimum or maximum diameter, respectively to thinning from below or above, and a standard deviation chosen in a way, so that the expected quadratic mean diameter of thinned trees was equal to the specified one.

The model and the extensions were validated against plot data of permanent sampling inventories of three monospecific stands and two multi-cohort stands within the study region. An example is shown in Fig. A3. The TreeGrOSS model performed at least as good as local yield tables with significant improvements for co-dominant and suppressed cohorts. The complete time series, which at several stands covered more than 100 years, were kindly provided by the Eberswalde forestry research institute and the chair of Forest Growth and Timber Mensuration at TU-Dresden and preprocessed by Mund et al. (2005).