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Spatially Explicit Assessment of Carbon Stocks of a Managed Forest Area in Eastern Germany

Abstract The Kyoto-protocol permits the accounting of changes in forest carbon stocks due to forestry. Therefore, forest owners are interested in a reproducible quantification of carbon stocks at the level of forest management units and the impact of management to these stocks or their changes. We calculated the carbon stocks in tree biomass and the organic layer including their uncertainties for several forest management units (Tharandt forest, Eastern Germany, 5500 ha) spatially explicit at the scale of individual stands by using standard forest data sources. Additionally, soil carbon stocks along a catena were quantified. Finally, carbon stocks of spruce and beech dominated stands were compared and effects of thinning intensity and site conditions were assessed. We combined forest inventory and data of site conditions by using the spatial unions of the shapes (i.e., polygons) in the stand map and the site map. Area weighted means of carbon (C) stocks reached 10.0 kg/m² in tree biomass, 3.0 kg/m² in the organic layer and 7.3 kg/m² in mineral soil. Spatially explicit error propagation yielded a precision of the relative error of carbon stocks at the total studied area of 1% for tree biomass, 45% for the organic layer, and 20% for mineral soil. Mature beech dominated stands at the Tharandt forest had higher tree biomass carbon stocks (13.4 kg/m²) and lower organic layer carbon stocks (1.8 kg/m²) compared to stands dominated by spruce (11.6 kg/m²; 3.0 kg/m²). The difference of tree biomass stocks was mainly due to differences in thinning intensity. The additional effect of site conditions on tree carbon stocks was very small. We conclude that the spatially explicit combination of stand scale inventory data with data on site conditions is suited to quantify carbon stocks in tree biomass and organic layer at operational scale.

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Introduction

Several studies quantify carbon stocks in forests by using national inventories for forests and soils (e.g. Baritz and Strich 2000, Dieter and Elsasser 2002, Karjalainen et al. 2002, Laitat et al. 2000, e.g. Liski et al. 2002, Schlamadinger 2003). Lindner et al. (2002) and Nabuurs et al. (2002) estimated carbon stocks in forests by usage of frequency distributions of forest types. All of these studies calculate carbon stocks and their errors accurately using statistics at the scale of nations or federal states, which is sufficient for the national communications to the UNFCCC (United Nations Framework Convention on Climate Change) (UNFCCC 1997). However, forest owners are interested in carbon pools at stand level and the level of forest management units. The above studies cannot account for the spatial heterogeneity of carbon stocks caused by different site conditions and forest management at this spatial resolution. Further, the development of methodologies for spatially explicit estimations based on inventories can support validation of long-term eddy-covariance measurements of carbon dioxide exchange above forests. As found at the flux tower site in the Tharandt forest, the total source area (ca. 1 km^2) contributing to the atmospheric fluxes of carbon dioxide comprises a series of individually managed forest stands (Bernhofer 2003).

The present study aimed (1) to quantify spatially distributed carbon stocks and their uncertainties in tree biomass, the organic layer, and mineral soil at stand scale for an entire forest management unit, and (2) to explore relationships between carbon stocks and dominating tree species as well as influences of thinning intensity and site conditions. Using the Tharandt forest in eastern Germany as a case study, it is demonstrated in how far standard forest inventory data are suitable for the quantification of carbon stocks, and how the spatial distribution can be used to relate differences in these stocks to different species, thinning activities and site conditions.

Methods

Study Site

The Tharandt forest is located in Germany at 51° latitude and 13° longitude at elevations of 400 to 460m asl, about 20 km southwest of the city of Dresden. Mean annual air temperature is 7.2°C and mean annual precipitation is 800 mm (Bernhofer 2002). Most stands are dominated by Norway spruce (*Picea abies* [L.]. Karst.) interspersed with Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.), and European beech (*Fagus sylvatica* L.).

There are also several stands that are dominated by the latter species. While most of the younger stands include mixtures of different species, older stands are more homogenous.

The parent material is dominated by gneiss and porphyry. However it is very heterogeneous and partly covered by loess (Fiedler et al. 1989a). Dominant soil type is dystric cambisol. Podzols and stagnosols are also frequent. The forest area of 5500 ha comprised almost four forest management units. It was managed by the smallstrip-clearcutting system, which was commonly used in the former German Democratic Republic.

Data Sources

Forestry administration of the former German Democratic Republic performed an inventory of forest biomass for each stand every ten years. The inventory provides information of the area of the stands [m²] and tree parameters of homogeneous groups of trees within each stand: species, age [year], quadratic mean of diameter at breast height (DBH) [cm], height [m] (calculated from stand height curve for given DBH), timber volume [m³/ha], and basal area [m²/ha]. The inventory does not contain the variance of tree parameters, timber volume of trees with a DBH smaller than 7cm, nor the number of trees within a group of trees. We used an inventory of Tharandt forest that was conducted in 1988 and the last amendment by yield tables was done in 1993. The link between records of forest inventory and the location in space is provided by the stand map. Each shape (i.e., polygon) of the stand map refers to an administratively formed area that consisted of one or a few stands.

During 1960 – 1970, forestry administrations of the Eastern Germany started an inventory of site conditions (Kopp and Schwaneke 1991). The raw data of the soil profiles have been aggregated and classified to site classes. A site class consists of the categorical site parameters of climate/topography, parent material, water regime, nutrient availability, and moisture index. The parameter parent material, in this inventory, is a mixed description of topography, soil type, and bedrock. Moisture conditions are described by the two parameters water regime and moisture index. Water regime describes the seasonality of moisture (alternating: clear seasonality, constant: no change with time, variable: other wetness-specific classes e.g., moisture dynamics near well-springs). Moisture index defines ordinal subclasses of water availability within each class of water regime. Local experts delineated areas of homogeneous site parameters using mainly topography and vegetation. Results of this survey are provided in the site map. Each shape of the site map has a site class and a local classification of soil types assigned to it. Details on the site parameters and their categorical values can be found in the literature (Gemballa et al. 2001, Rehfuess 1990, Schwaneke 1989, 1965). In this paper we try to use terms of the world reference base soil classification (WRB) (FAO 2006) where possible, despite there is no unique mapping between WRB and the soil classification of this inventory.

Additionally, we used data of 10 soil profiles out of a transect (the Esberg Catena, Fiedler et al. 1989b) for quantifying mineral soil carbon stocks. Profiles were taken from soil pits, which extended down to bedrock and were analysed according to German soil classification (AG BODEN 1994). Locations of the soil profiles comprised different soil types. For each mineral horizon (Pietrusky 1975) and (Fiedler et al. 1989a) measured coarse stone content and carbon content. We further determined fine soil bulk density per mineral horizon by using a mixed sample of fife soil cores (100 cm^3).

Combining the Data Sources

Data on site conditions were related to shapes of the site map while records in the forest inventory were related to shapes of the stand map. However, stand map and site map did not match. In order to combine the maps and their related records we used an approach that was based on the spatial **union of maps** via a geographical information system (GIS) (Figure 1).

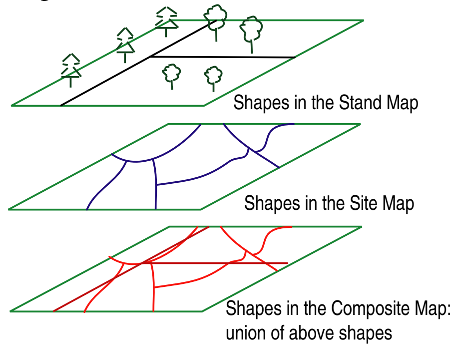

Figure 1: Union of the shapes of the stand and site map. Each shape of the composite map corresponds to exactly one shape of the stand map and one shape of the site map.

We used the information system `CQuant` (Wutzler 2002) to relate information from both, forest inventory and site parameters to the corresponding shapes of the united map. For each shape of the united map carbon stocks were quantified using the combined dataset. As far as not mentioned otherwise, units of calculated masses refer to pure carbon (e.g., kg/m^2). Finally, the results were aggregated to the corresponding shapes of the stand map or the site map by an area-weighted mean (equation 1). Several shapes of the composite map correspond to one stand of the stand map or one site class in the site map.

$$\bar{c}_K = \frac{\sum_{i \in K} A_i \cdot c_i}{\sum_{i \in K} A_i} \qquad (1)$$

where $\bar{c}_K$: mean result of area K (set of shapes) [kg/m²], i: index of the shapes within area K, A_i: area of shape i [m²], c_i: carbon stock per area for shape i [kg/m²]

Spatially Explicit Error Propagation

For estimating the relative error of the spatial mean, relative errors of the areas were assumed to be small compared to relative error of the carbon stock estimates. Hence, the size of areas can be considered to be exact. Further, we assumed carbon stocks to be uncorrelated between stands. With the rules of error propagation for uncorrelated sums and products, the relative error of the mean carbon stock from equation 1 is calculated by equation 2.

$$R(\bar{c}_K) = \frac{\sqrt{\sum_i \left(A_i \cdot c_i \cdot R(c_i)\right)^2}}{\sum_i (A_i \cdot c_i)} \qquad (2)$$

for area K [kg/kg], i: index of the shapes within area K, A_i: area of shape i [m²], c_i: carbon stock per area for the shape i [kg/m²], $R(c_i)$: relative error of carbon stock for shape i [kg/kg]

Similarly, stocks and errors can be aggregated to other coarser spatial levels e.g., the entire study site, or all area that is dominated by a specific species.

Tree Biomass Carbon Stock Quantification

We calculated the **biomass** of each tree homogenous tree group by using biomass expansion factors (BEF) according to equation 3.

$$m_{CTreeGroup} = V * D_R * BEF * C_{conc} \qquad (3)$$

where $m_{CTreeGroup}$: carbon stock of the tree group [kg]; V: timber volume [m³ dry wood including bark]; D_R: wood density [kg/m³], BEF biomass expansion factor [kg/kg]; C_{Conc}: carbon concentration [kg/kg]

For spruce the BEFs of Wirth et al. (Wirth et al. 2004) were used (Table 1). They are dependent on age and site index. For pine the age dependent combined factors (KBEF = D_R * BEF) of Lehtonen et al. (Lehtonen et al. 2004) were applied. For pine we used a higher uncertainty than reported, because the factors were developed in Finish forests. For other coniferous species, the BEF of spruce were applied, but densities as reported by Löwe et al. (2000) were used. For beech Wirth et al. (2004) report age-dependent combined factors. All other broadleaved species were treated like beech but corrected for wood density (density of species / density of beech). We used species-specific carbon contents that were reported by Weiss et al. (2000).

For estimating the relative error of a tree group carbon stock, we can assume the errors of timber volume, density, BEF, and carbon content to be independent. Hence, relative error equals the sum of squared relative errors of the single factors. Timber

Table 1: Factors for estimating tree carbon stocks. (a): (Wirth et al. 2004) (b): (Lehtonen et al. 2004), DR: dry wood density, C_{Conc}: carbon concentration, BEF: biomass expansion factor, KBEF: D_r*BEF

Species	D_R [kg/m³] (Löwe et al. 2000)	C_{Conc} [%] (Weiss et al. 2000)	BEF [kg/kg]
spruce	377 (a)	50.1	(a) Site index >34 = 1.544 + 0.999 * exp(-0.094 * age); Site index < 25 = 1.89 + 2.41 * exp(-0.085 * age) medium site index: = 1.655 + 2.366 * exp(-0.114 * age)
pine	430	51.1 (like fir)	(b) KBEF = 0.7018 + 0.0058 * exp(-0.01*age)
beech	550	48.6	(a) KBEF = 0.74 + 0.636 * exp(-0.018 *age)
other coniferous	larch 430; others 370	51	like spruce
other broadleaved	oak: 560, others: 550	oak 49.5, locust 49.2, ash 49.7, cherry 49.7, birch 48.5, others 49	like beech

Table 2: Relative errors (R) for estimating stand tree carbon stocks. (a) (Wirth et al. 2004) (b) (Weiss et al. 2000) (c) (Lehtonen et al. 2004), R(timber volume) = 12% (Kurth et al. 1994). DR, CConc,BEF, KBEF see table 1.

Species	$R(D_R)$	$R(C_{Conc})$	R(BEF)	Resulting $R(C_{Stock})$
spruce	9% (a)	1%	site index > 25: 5.6% (a)	16.0%
			site index <= 25: 10% (a)	18.1%
pine	11% (b)	1%	R(KBEF) = 6% ((c): reported 2.8%)	13.5%
beech	6% (a)	1%	R(KE) = 13.4%; R(KBEF) = 13.36%	18.0%
other coniferous	11% (b)	2%	site index > 25: 8%	18.2%
			site index <= 25: 12%	20.3%
other broadleaved	11% (b)	2%	15%	19.3%

volume has a relative error (standard deviation / mean ≈ ¼ range of 95% confidence interval) up to 12% (Kurth et al. 1994). By using species-specific carbon contents we can assume relative errors to be below 1% for main species and below 2% for other species (Table 2). Table 2 also reports species-specific stand to stand density errors and errors of the biomass expansion factors. For combining the errors of all tree groups within one stand, independent errors of the tree groups are assumed and absolute errors are added.

Organic Layer Carbon Stock Quantification

Carbon stocks in the organic layer were estimated by regression models that have been developed for Thuringian forests. The models have been fitted to carbon stocks of O_l, O_f, and O_h layers that were measured at 178 plots in Thuringian forests (Wirth et al. 2004). According to the combination of bedrock and the dominating tree species one out of four models was selected. We checked applicability for the Tharandt forest at four spruce dominated stands where stocks were measured. In all models the single predictor was nutrient availability. The parameters bedrock and nutrient availability were derived from the data of the site evaluation in the following way. The categorical indices of site parameter nutrient availability was transformed to an ordinal scale (k, r (rich) →1; m (medium) →2; z, a (poor) →3).

The broad range of site parameter parent material was grouped and related to the required classification of bedrock (Table 3).

Table 3: Grouping of site parameter parent material.

hydro (L)	dominated by water regime (mainly gleysols and stagnosols) (site map indices Lg,Sg,B,Lu,Gg,Gu)
acidic (G)	dominated by acidic bedrock (Sf, P)
sand (S)	dominated by sandy bedrock (Sn, Sb)
loess (LL)	dominated by loess bedrock (LL, Ls, Lb, Gn)
basic (C)	dominated by basic bedrock (Ba)

Symbols in brackets in the first column represent the category identifiers that are used to select the regression model of organic layer carbon stocks (Wirth et al. 2004). Symbols in brackets at the second column represent identifiers of parent material according to the site evaluation (Schwaneke 1989, 1965).

For each plot the relative prediction error of the regression model was assigned corresponding to the combination of species and bedrock (Wirth et al. 2004). Values range from 23% for conifers on soils dominated by loess to 73% for broadleaved forests on any parent material. In order to propagate the error of organic layer carbon stocks from the shapes in the united map to the stand, we divided the area weighted standard deviations (= stock · relative error) by the area weighted mean stock (equation 1).

Mineral Soil Carbon Stock Quantification

Calculation of **mineral soil** carbon stocks was based on a simple model of several homogenous layers (equation 4).

$$m_{CHorizon} = \Delta h \cdot (1 - r_{stones}) \cdot \sigma_{bulk} \cdot r_C \qquad (4)$$

$m_{CHorizon}$	mass of carbon within pedogenetic horizon [kg/m²]
Δh	height of the layer [m]
r_{stones}	content of stones (d > 2mm) within soil volume [m³/m³]
σ_{bulk}	fine soil (d < 2mm) bulk density [kg/m³]
r_C	carbon content of fine soil [kg/kg]

We used pedogenetic horizons instead of fixed depths, because there are rapid changes in soil properties at the edge of horizons in stagnosols and podzols. These soil types comprise large parts of the study area. In order to compare soil types and site classes, the soil carbon stocks of soil horizons were summed over horizons within surface soil (A), subsurface soil (B) and soil influenced mainly by bedrock (C) (AG BODEN 1994).

The relative error can be calculated by equation 5 if factors are considered independent of each other.

$$R(m_{Horizon}) = \sqrt{\begin{array}{l} R(\Delta h)^2 + R(r_{stones})^2 \\ + R(\sigma_{bulk})^2 + R(r_C)^2 \end{array}} \qquad (5)$$

where R(x): relative error of factor x; other symbols as in equation 4. Δh: height of the layer [m], r_{stones}: content of stones (d > 2mm) within soil volume

$[m^3/m^3]$, σ_{bulk}: fine soil (d < 2mm) bulk density $[kg/m^3]$, r_C: carbon content of fine soil [kg/kg]

Ståhl et al. (2004) assumed relative errors of 30% fine soil bulk density, 40% stone content, 80% carbon content for a large scale inventory in Sweden. However, horizontal changes of stone content, layer thickness and likely also fine soil bulk density and carbon content are well captured by the stand map, which delineates changes across a few 10' m. Therefore, we assumed lower relative errors of 10% layer thickness, 20% stone content, 50% carbon content, and 15% fine soil bulk density within one horizon at the extend of a shape in the site map of fixed size. Assuming uncorrelated errors, standard error propagation (equation 5) resulted in a relative error (precisions) of a single horizon of 57%. We did not have estimates of correlations among the factors and the soil horizons. Inclusion of these correlations would decrease the relative error. Assuming independent errors of the horizons, the relative error at plot scale was calculated by equation 6. Relative error decreased with the number of sampled horizons per site.

$$R(m_{Plot}) = \frac{\sqrt{\sum_i \left(m_i \cdot R(m_i)\right)^2}}{\sum_i m_i} \qquad (6)$$

where $R(m_{Plot})$: relative error of soil carbon stock at Plot (area of a site shape) [kg/kg]; i: index of soil horiozon; h_i: depth of horizon [m]; m_i: horzion carbon stock [kg]; $R(m_i)$: relative error of horizon carbon stock [kg/kg]

Raw data of mineral soil carbon stocks was sampled only for spruce dominated stands. We assumed no differences in mineral soil carbon stocks by dominating species, because these differences are small compared to differences with site conditions (Mund and Schulze 2005).

Statistical Analysis of the Species Effect on Tree Carbon Stocks

Information on tree groups in the inventory was available only for a part of the area of about 4080 ha. The other part consisted of non-stocked areas or very young stands, for which timber volume was not recorded in the inventory. The spatial distribution of carbon pools and the mean values refer to the stocked area only. Effects of species were studied using a constrained population. Stands dominated by age classes above 150 years (48.0 ha) were neglected, because extrapolating stocking density far from given yield table values is error-prone. Further, the **standtype constrained population** consisted of more or less monospecific stands related to the stand map (Figure 1, top). Mixed stands were excluded by requiring the dominant tree group to cover at least 65% of the stand's basal area and 65% of the stand area. This population covered 38% of the totally stocked forest area and 49% of the forest area that was dominated by spruce, pine, or beech. The same inventory record on different site conditions only counts as one entity in this population.

Significance of differences between carbon stocks of trees and the organic layer between spruce and beech was tested with an unpaired t-test. Area weighted means and their relative errors were calculated by equations 1 and 2, and variance of the mean values by equation 7. Next, the t statistics (Quinn and Keough 2002, p37) was calculated by equation 8. Finally, the probability of this statistics was obtained by the density distribution with $n_{Beech} + n_{Spruce} - 2$ degrees of freedom using the dt function of the R-statistics package version 2.1.1.

$$\mathrm{var}(\overline{m}) = \left(\overline{m} \cdot R(\overline{m})\right)^2 \qquad (7)$$

where var($\overline{m}$): variance of area weighted mean carbon stock; $\overline{m}$: area weighted mean of carbon stocks; $R(\overline{m})$ relative error of area weighted mean carbon stock

$$t = \frac{\overline{m}_{Beech} - \overline{m}_{Spruce}}{\sqrt{\mathrm{var}(\overline{m}_{Beech}) + \mathrm{var}(\overline{m}_{Spruce})}} \qquad (8)$$

where t : t-statistics applied for difference in stocks of beech and spruce. (Square of the standard error corresponds to the variance of the mean)

When studying effects on tree biomass carbon stocks, the number of observations was set to the number of observed stands. When studying effects on the organic layer, the number of observations was set to the number of plots that had been used to construct the regression models (beech 17, coniferous 160) (Wirth et al. 2004).

Statistical Analysis of Thinning Intensity Effect on Tree Carbon Stocks

In order to compare tree biomass carbon stocks by species across different thinning intensities we **corrected observed carbon stocks** of different thinning intensities to a comparable standard value. We used the proportion of actual basal area to the standard basal area (Kramer and Akça 1995) as a simple parameter of thinning intensity. In the following we refer to this proportion as **stocking density**. We interpolated standard basal area for each inventoried group of trees by using yield tables

tree group	yield table
beech	Dittmar et al. (1986)
spruce	Wenk et al. (1985)
pine	Lembcke et al. (1976)
larch	Schober R (1987)

Table 4: Yield tables used to interpolate stocking densities. Data from (Nicke 1997)

(Table 4) observed stand age, and interpolated site index. Site index was interpolated using yield tables, observed age, and height. Hence, standard basal area represents the expected (according to permanent study sites) basal area, and is dependent on site quality. If stocking density is smaller than one, stands have been thinned more intense than usual.

Correction was done in the following way. First, we fitted the equation "CBiomass = $b_0 + b_1 \cdot \ln(\text{Age}) + b_2 \cdot \text{stockingDensity}^2 + b_3 \cdot \ln(\text{Age})\text{:stockingDensity}$" for each species to the standtype-constrained population. Second, this models was used to predict carbon stocks with observed thinning intensity and stocks with thinning intensity 1 for each plot. Finally, each tree biomass carbon stock was corrected by the factor "predicted stock with standard thinning intensity / predicted stock with observed thinning intensity". Significance of the difference between mean corrected carbon stocks of beech and spruce was tested by an unpaired t-test (equation 7 and 8).

Statistical Analysis of Site Condition Effect on Tree Carbon Stocks

Not only thinning intensity, but also different site conditions potentially confound the effect of species on tree carbon stocks. In order to study the effect of site conditions the combined information of the site map and the stand map was used. The **site condition constrained population** that consisted of plots of the composite map (Figure 1, bottom) which had to comprise an area of at least 0.4 ha. In addition to the constraints for monospecific stands, we excluded plots on steep terrain (indicated by a flag in site map) and plots outside the main local climate class. Hence, precipitation, temperature and insulation were about the same in all studied plots. The site constrained population covered 33% of the totally stocked forest area and 41% of the forest area that was dominated by spruce, pine and beech. Plots with the same inventory record but different site conditions were treated as different entities.

Similar to correcting for different thinning intensities, we used regression models to correct additionally for the effects of nutrient availability, water regime, and moisture index. We experimented with many model forms (also including parent material) and investigated variance, residuals, and the Akaike Information Criterion (Akaike 1987). However, there was no clear favourite model. We present results, that were obtained with the following model: "CBiomass ~ ln(Age) + stockingDensity² + NutrientAvailability + WaterRegime + WaterRegime :MoistureIndex". The model equation contained coefficients and dummy variable for each level of the categorical factors (Quinn and Keough 2002, p136). The site parameter moisture was not treated as main effect because it describes subclasses of site parameter water regime.

First, this model was fitted to the site condition constrained population for each species. Second, this model was used to predict carbon stocks with observed conditions and stocks with the fixed conditions (stocking density 1, medium nutrient availability, and moderate moisture of constant water regime) for each plot. Finally, each tree biomass carbon stock was corrected by the factor "predicted stock with fixed conditions / predicted stock with observed conditions". Significance of the difference between mean corrected carbon stocks of beech and spruce was again tested by an unpaired t-test (equation 7 and 8).

Results

Mean Carbon Stocks

Area weighted mean carbon stocks in above ground **tree biomass** amounted to 10.0 ±0.6 kg/m² (Figure 2 left, Table 5).

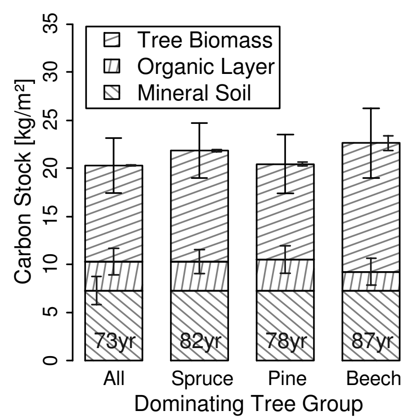

Figure 2: Area weighted mean main carbon stocks of stands in the Tharandt forest. Left bar represents all the entire stocked area including other species and mixed stands, the other three bars represent a constrained population of more or less monospecific stands. Arrows denote standard deviation of the area weighted mean stocks, numbers in the bars represent the area weighted mean age. For results of individual compartments see Table 5.

This mean stock refers to the area, for which timber volume was recorded in the inventory (88% of total area). Related to total area, which includes also non-stocked areas and very young stands, mean carbon pool reached 8.8 kg/m². Largest carbon stocks of 22.5 kg/m^2 were found in stands dominated by old beech. Mean carbon stocks of the **organic**

layer amounted to 3.0 ±1.35 kg/m². Maximum carbon stocks in the organic layer of 5.1 kg/m² were calculated for coniferous stands at sites with poor nutrient supply, while minimum organic layer carbon stocks of 0.8 kg/m² were calculated for deciduous stands at rich site conditions. In **mineral soil,** area-weighted carbon stock of the area around the transect was 7.3±1.4 kg/m². The relative carbon content in individual layers of the soil profiles is shown in Table 6. Each profile corresponds to a different site class. The maximum carbon stock 18.4 kg/m² was found at profile 18 (on loess dominated bedrock with a very deep A_{eh} horizon). The minimum carbon stock of 1.2 kg/m² was found at profile 24 (on acidic parent material with a thin A_{eh} horizon).

Table 5: Mean carbon stocks in forest compartments of stands in the Tharandt forest.

	all	spruce	pine	beech
mean age [y]	73	82	78	87
tree biomass				
stock [kg/m²]	10.0	11.6	9.9	13.4
sd [kg/m²]	0.1	0.1	0.2	0.8
cv [%]	1%	1%	2%	6%
n	1228	375	80	20
organic layer				
stock [kg/m²]	3.0	3.0	3.5	1.8
sd [kg/m²]	1.4	1.2	1.6	1.3
cv [%]	45%	42%	45%	73%
n	177	160	160	17
mineral soil				
stock [kg/m²]	7.3			
sd [kg/m²]	1.4			
cv [%]	20%			
n	10			
total				
stock [kg/m²]	20.3	21.8	20.7	22.5
sd [kg/m²]	2.0	1.9	2.1	2.1
cv [%]	10%	9%	10%	9%

Mean values (stock), standard deviations (sd), coefficient of variation (cv) and number of samples (n) are indicated.

Spatial Distribution of Carbon Stocks

The spatial distribution of carbon stocks in **tree biomass and the organic layer** is shown for a selected area southwest of the hill “Esberg” in the Tharandt forest as an example (Figure 3). We depicted this area, because it overlaps with the soil transect and there is a beech-dominated stand in the centre, which is of equal age as the spruce dominated stand right next to it. Similar patterns of species composition and age class structure are found across the total Tharandt forest. The spatial pattern of the distribution of carbon stocks in tree biomass followed the stand map, because it represents species composition and age class structure. The carbon stock of the spruce stands at the upper right increased with stand age. However, the beech dominated stand at the centre had a higher stock than the neighbouring spruce stand of the same age. On the other hand, the beech dominated stand had a lower organic layer carbon stock. Spatial distribution of calculated organic layer carbon stocks, additionally, showed a pattern that followed the site map which has curvy edges, because different bedrocks are represented by this map. Spatial distribution of **mineral soil** carbon stocks showed a pattern that was related to the relative position to the slope (Figure 4). Plots with highest pools were all located at the slopes or near the bottom of the slopes. Low stocks were found at the plateau and lowest stocks are at the more level terrain of the surrounding area with shallow soils. There was a large range of values within a small distance.

Table 6: Soil characteristics of individual horizons of the profiles studied at the Tharandt forest.

profile number	horizon	depth (cm) from	to	density (g/cm³)	stone content (%)	carbon content (%)
1	arAh	0	5	0.6	0	5.2
1	aBv-Go	5	15	0.9	0	3.2
1	aGo-M	15	30	1.3	0	3.2
1	aGr	30	70	1.6	40	0.8
15	Aeh	0	5	0.9	5	5
15	Bsv	5	35	1.3	15	1.8
15	Bv	35	95	1.4	90	0
24	Ahe	0	8	0.5	0	2.75
24	AhBv	8	35	1.2	0	0
24	Bv-Sg	35	75	1.6	0	0
27	Ahe	0	6	0.8	50	6
27	Bv1	6	70	0.8	90	1.8
2	Aeh	0	4	1.1	5	2.1
2	Ae	4	20	1.5	8	0.3
2	Bsh	20	35	1.5	15	1.8
2	Bs2	35	110	1.5	5	0
5	Aeh	0	20	0.7	5	4.6
5	Bvs	20	50	1.3	15	3.5
18	Aeh	0	15	0.6	5	13.8
18	Ae	15	65	1.5	15	1
3	Ah	0	10	0.7	0	5.18
3	Ah-Sw	10	25	1.1	10	0
3	Sw	25	70	1.6	10	0
7	Aeh	0	10	1.1	15	12.4
7	Bv	10	25	1.3	20	0
23	Ahe	0	5	1.0	3	12
23	Bv-Sw1	5	65	1.4	20	0
23	Sw2	65	90	1.8	15	0

Profile numbers and Carbon content refer to Fiedler et al. (1989c) and Pietrusky (1975), horizon: description of soil horizons (AS Arbeitskreis Standortskartierung 1980).

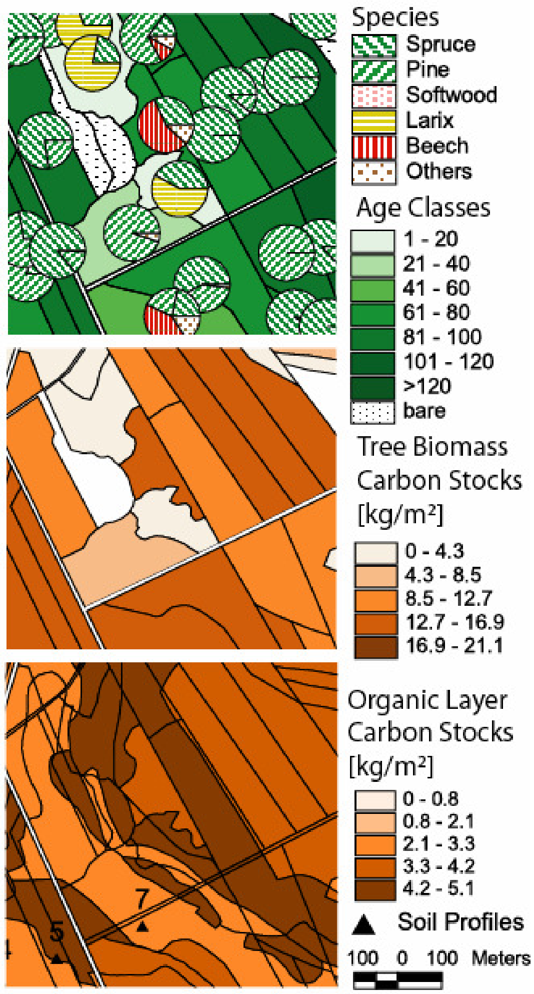

Figure 3: Spatial distribution of tree biomass and organic layer carbon stocks of several stands southwest of the hill "Esberg" in the Tharandt forest. Top) stand map showing species distribution and stand age (of the dominant tree group). Centre) tree biomass carbon stocks distributed according to the stand map. Bottom) organic layer carbon stocks distributed according to the composite map (union of the shapes of the stand map and the site map).

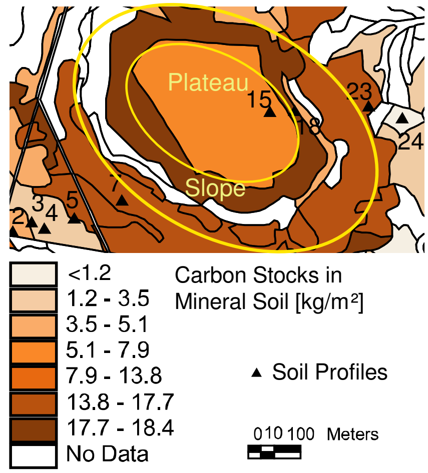

Figure 4: Spatial distribution of mineral soil carbon stocks across and around the hill "Esberg" distributed according to the site map. Triangles mark the location of the soil profiles for mineral soil carbon stock quantification. Labels represent soil profiles numbers.

Different Carbon Stocks of Spruce and Beech dominated Stands

Beech dominated stands had a significantly higher (1.83 kg/m², $p=0.026$) mean tree carbon stock than spruce dominated stands. This difference is not due to the slightly higher mean age of beech stands compared to spruce and pine, because beech stands have higher stocks in each age class (Figure 5 top). Contrary, there was also a non-significant trend of lower carbon pools in the organic layer (-1.05 kg/m², $p=0.34$) of beech dominated stands (Figure 6) with all parent materials except the ones, which were dominated by water (label hydro, mostly gleysols and stagnosols). With assuming neglectable differences in soil carbon stocks between species, total carbon stocks of beech dominated stands had a weak trend to slightly higher stocks (0.77 kg/m², $p=0.4$) than spruce or pine dominated stands (Figure 2, Table 5).

Effect of Thinning Intensity and Site Conditions on Carbon Stocks

Beech dominated stands are located at more favorable site conditions and are managed with higher stocking densities than the other stands (Figure 7). Correcting the stocks for the effect of stocking density yielded a decrease in beech carbon stocks at ages 50 to 110 years and an increase in coniferous carbon stocks (Figure 5 center). At these age classes, spruce dominated stands had slightly higher corrected carbon stocks than beech dominated stands. The difference between area weighted means (Equation 1) of corrected tree carbon stocks of beech and spruce decreased to 0.26 kg/m². This difference was not significant any more ($p=0.38$).

Correcting additionally for site conditions had only a marginal effect on tree carbon stocks (Figure 5 bottom). The drop of mean carbon stock of beech in the last correction is explained by the exclusion of many old beech stands at very steep sites when constructing the site constrained population. The differences in mean age in the site constricted population (beech 60yr, spruce 82yr) resulted in a lower area weighted mean tree carbon stocks of beech compared to spruce (-0.69 kg/m², $p=0.26$).

Organic layer carbon stocks were clearly influenced by site conditions, i.e., the parent material (Figure 6) and nutrient availability.

Within the sparse dataset of the mineral soil there was no specific single site parameter that had a clear influence with mineral soil carbon stocks (Figure 8). However, there were similar mineral soil carbon stocks with the same combination of site conditions (profile numbers 24 and 27, numbers 18 and 5).

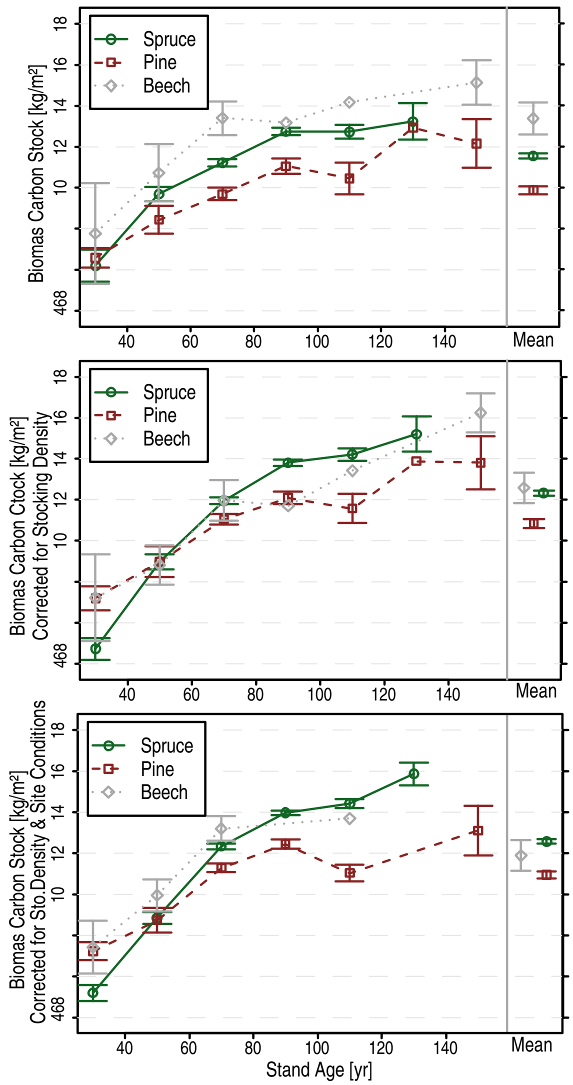

Figure 5: Area weighted mean tree biomass carbon stocks by species and age classes (21-40, 41-60, …). Arrows denote standard deviation of the area weighted means. Top) observed stocks. Centre) stocks corrected for stocking density by a regression model; Bottom) stocks corrected for stocking density, nutrient availability and moisture conditions.

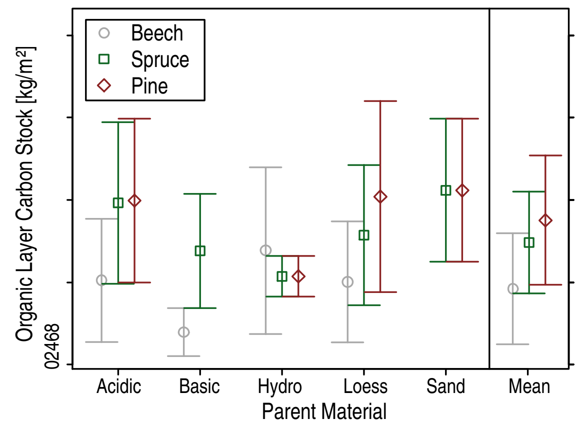

Figure 6: Organic layer carbon stocks by species and parent material. Mean values are area weighted. Error bars denote area averaged standard deviation.

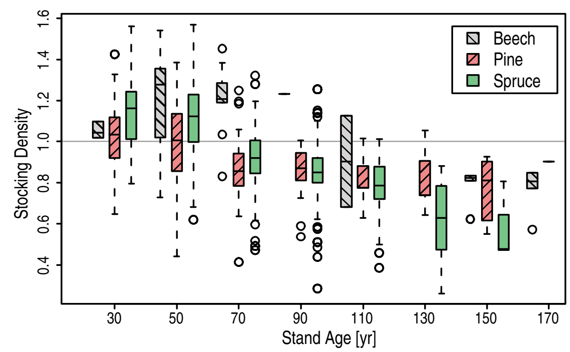

Figure 7: Distribution of stocking densities at the Tharandt forest by age classes of (21-40, 41-60, …). In this case, stocking density is the proportion of inventoried basal area to basal area suggested by yield tables (Table 4). It reflects thinning and harvesting strategies. Stands with values greater than 1 are thinned less than usual management, stand with values less than 1 are thinned stronger. The usual boxplots display the distribution of the values by the median (center of the box), 25% and 75% percentiles (hinges), minimum and maximum values (arrows), and outliers i.e. values greater than 1.5 times the spread outside the closest hinge (circles).

Discussion

The most important aspect of this study is the **spatially explicit quantification** of carbon stocks at the scale of a forest management unit in Central Europe at the resolution of individual forest stands based on standard forestry data. The spatially explicit results enable combined analysis with other spatial data sources. In this study we used the spatial combination of data of forest inventory and data of the site evaluation. This allowed the quantification of organic layer carbon stocks at stand scale (Figure 3, bottom) and it allowed the comparison of influences of stand characteristics and site conditions on tree carbon stocks (Figure 9). Other applications with e.g., digital elevation data or results of ground water modelling become possible but go beyond the scope of this paper. We spatially combined the stand and site datasets using the union of the shapes (Figure 1). In contrast, Wolff (2002) combined the stand and site datasets at grid points and regionalized results on the basis of regions with similar growth conditions. The approach of this study has the advantage of allowing the analysis of several carbon pools at the same high spatial detail. However, it is scalable only to the federal states of Germany that perform a stand based forest inventory. The focus on spatial distribution at this scale is new to carbon inventories in Central Europe. Hence we know only of one similar study from Thuringia (Wirth et al. 2004) and one study from France (Le Maire et al. 2005), which spatially quantifies carbon fluxes.

Results of the mean **tree biomass carbon stocks** in the Tharandt forest (8.8 kg/m² in relation to total forest area) agree with results from studies in

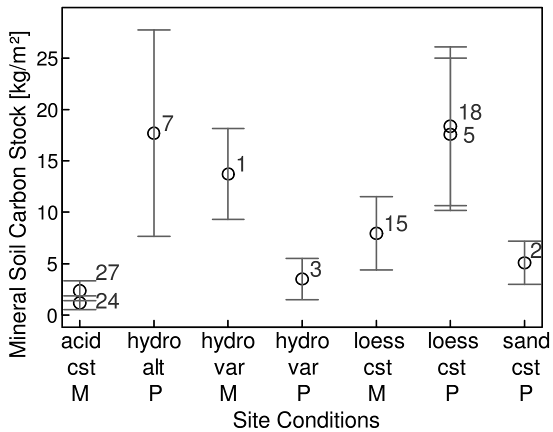

Figure 8: Mineral soil carbon stocks of the soil profiles by combination of site parameters. acidic, hydro, loess, sand: different parent materials (see Table 3); cst, var, alt: water regimes of different seasonality of moisture (constant, variable, alternating); M,P: moderate and poor nutrient availability. Error bars denote standard deviation of the calculated stock (equation 5 and 6).

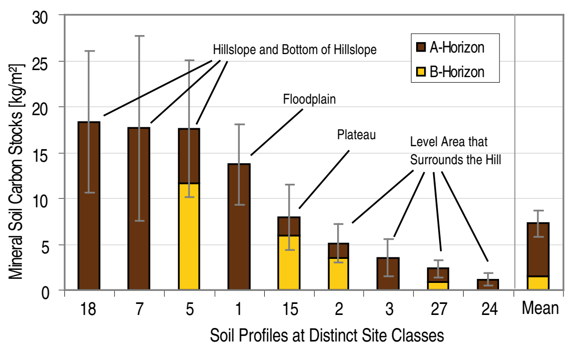

Figure 9: Mineral soil carbon stocks by profiles ordered descending. Mean values are area weighted. Error bars denote standard deviation of the calculated stock (equation 5 and 6). Labels indicate the position relative to the slope.

Thuringia of 8.2 kg/m² (Wirth et al. 2004) and a German management case study (8.7 kg/m²) (Karjalainen et al. 2002). They were lower than national inventory (9.8 kg/m²) (Baritz and Strich 2000). This is because there are higher stocks in the southern parts of Germany. Observed stocking density was low (Figure 7). This was likely due to extensive thinning during novel forest decline before the inventory in 1988. Hence, carbon stocks will increase with increasing stocking density. There are considerable differences in biomass expansion factors. The use of recent factors that were dependent on stand age and site index increased mean carbon stocks by the number of 1.7 compared to the factors used by Baritz and Strich (2000) (coniferous 1.14; broadleaved 1.24) for the first German national reporting. **Carbon stocks of the organic layer** (3.0 kg/m² Table 5) agree with the national inventory (2.1 kg/m²) (Baritz and Strich 2000), and agree with the Thuringian study (2.7 kg/,²) (Wirth et al. 2004), because we utilized the same quantification algorithm which is based on differences between stand types, parent materials and nutrient availability. At four spruce dominated stands mean organic layer carbon stocks of 4.8 kg/m² have been measured (Persson, personal communication). At these plots the used model estimated organic layer carbon stocks to 3.9 kg/m². This underestimation of 18% is within the error range of 42% for spruce stands. Area-weighted mean of **mineral soil carbon stocks** (7.3 kg/m² Table 5) agree with estimates of soil carbon in Thuringia (7.0 kg/m²) (Wirth et al. 2004) and with the national inventory (8.8 kg/m²) (Baritz and Strich 2000). All the stands, in which soil profiles were located, were dominated by spruce. There are indications that species composition affect incorporation of organic matter into the mineral soil (Fischer et al. 2002). However, these effect vary with site conditions (Berger et al. 2002) and they are small compared to differences caused by site conditions (Mund and Schulze 2005).

In comparison to carbon quantification studies that used national inventories (e.g, Baritz and Strich 2000, Dieter and Elsasser 2002, Ståhl et al. 2004) we used **stand scale inventories**. These stand scale inventories comprise a larger number of samples per area but trade in a lower precision of the single timber stock measurement (12% relative error, Kurth et al. 1994). The errors are of the two inventory types are comparable only at the same scale. When aggregating several single measurements to a comparable scale, the variance of the mean stock reduces with the square root of the sample number (Weiss et al. 2000). This is also true for the area explicit error propagation (equation 2). With the individual stand approach also the bias due to correlation between BEF and timber volume shown by Vilén et al. (2005) for sample inventories is bypassed. At the total stocked area of the Tharandt forest the relative error of the mean carbon stock in tree biomass was only 1% (Table 5). However, the different estimates for biomass expansion factors that were reported (Levy et al. 2004) suggest, that there might be a bias when applying the factors apart from the region, where the factors were assessed. Further, there might be also a bias in the stand scale timber volume measurement. The bias does not decrease with the number of measured plots.

A similar reasoning is true for mineral soil carbons stock errors based on **sampling stratified for site classes**. We could use only a low sample size of 10 plots, however, in comparison there are only 4 plots of the national soil inventory (BML 1996) at the total Tharandt forest. The approach of this study has the advantage of explicitly stratifying for more or less homogenous areas of mineral soil carbon stocks (Figure 4). The relative error of mineral soil carbons stocks at plot scale is dominated by the real heterogeneity of the stocks within the plot, and only to a part by measurement errors. Therefore we can justify choosing lower estimates of relative error of the measured factors compared to Ståhl et al. (2004), whose single plots represented a vastly greater area. Usage of the small scale inventory was the precondition of the spatial union and the comparison of influencing factors at the scale of forest management units.

When analyzing the **factors that influence carbon stocks**, we found a significant influence of site conditions only on organic layer carbon stocks (Figure 6). Effects of site condition on tree biomass carbon stocks were overshadowed by effects of stocking density (Figure 5). This implies that forest carbon models that currently focus on environmental conditions ,e.g., Biome-BGC (Thornton 1998), should include thinning activities in a more explicit way. Further, we did not find relationships between single factors of site conditions and mineral soil carbons stocks (Figure 8). The large differences in mineral soil carbon stocks within short distances imply that extrapolation studies should aggregate the results of single plot measurements using the areas of a proper stratification, e.g. the shapes of the site map. The only factor that effected mineral soil carbon stock that we noticed, was the position relative to the slope in the catena (Figure 4). This can be seen more clearly when arranging the profiles by carbon stock (Figure 9). The only exception of high mineral soil carbons stock afar from the slope was profile 1 near the source of a little brook. We can not draw conclusions from this sparse dataset because there are many confounding factors (bedrock, ground water table, etc.). However, this spatial pattern could be related to horizontal transport processes. This would imply that models of soil carbon dynamics to take such processes into account. Further it would imply that extrapolation studies that are based on large-scale inventories could stratify plots by small-scale topography. This topic needs further research.

The used approach of accounting for differences in stocking density and site conditions by using regression models (Figure 5) is only valid if there are not too many differing factors. We could ensure this by constraining the studied population to a not too large area of the same climate and similar topography. If the studied population encompasses larger area, there are too many confounding factors. However, it is necessary to account for different influencing factors as it was demonstrated in the comparison of tree biomass carbon stocks between species.

Beech dominated stands had higher tree biomass carbon stocks than stands dominated by spruce in the Tharandt forest (Figure 2, Table 5). This was a combined result of lower stand density of beech stands, a higher wood density of beech stem wood, and a slightly higher beech BEF (Table 1). This was not alone a species effect, but also an effect of different management. Stocking density was lower in spruce dominated stands (Figure 7) and accounting for this effect rendered the difference between theses species insignificant (Figure 5 center). At the time of the inventory forest management did not promote mixed species stands. However, there were many interspersed tree groups in younger stands that probably originated from natural regeneration. This observation enforces the need for research on mixed species stands. The results of comparing species are based on a much smaller population that excluded mixed stands in comparison to the results of the total forest that included all available stand data. We did not investigate shrubs and ground vegetation. However, these pools could contribute considerable carbon stocks, specifically at low stand densities (Solon and Roo-Zielinska 2003). With changes in forest management also dead wood can become important again in managed forests (BML 2004). An evaluation of species concerning carbon sequestration requires consideration of mean retention times of the wood products, changing growth conditions due to climate change and risks of disturbances. Considering only the main differences in current tree biomass stocks and organic layer stocks in the forest, we can recommend promoting beech in forests with similar site conditions as the Tharandt site.

This study focused on carbon stock quantification. The average stock is relevant for climate change mitigation, because the difference in carbon stocks is removed from the atmosphere carbon pool. For short term changes the **carbon dynamics** (i.e. fluxes and turnover) is more important. There are different effects of thinning intensity and site conditions on this factor, because with favourable site conditions carbon turnover is higher (both, increased uptake and increased respiration and export). In order to investigate dynamics, the inventory data has to be combined with modelling studies (Kurz et al. 2002). This will also give insight in underlying ecosystem processes. However, this is future work for Central European forests at this scale.

Conclusions

1. Standard forestry data was sufficient to quantify carbon stocks of tree biomass and the organic layer spatially explicit at stand scale. This was possible by combining data sets using the union of the stand map and the site map. Quantification of mineral soil carbon stocks required further soil sampling.

2. Usage of small scale inventories with a low precision at plot scale (18% of carbon stocks in stand tree biomass and 57% in mineral soil horizon) allowed a reasonable precision at the scale of forest management units (1% tree biomass carbon stocks and 20% mineral soil).
3. High small scale spatial heterogeneity implied the necessity to explicitly account for the areas represented by the single plots when aggregating to coarser scales.
4. The spatial combination of data sources allowed comparing different factors that influence carbons stocks. The accounting for confounding effects by regression models proofed to be a helpful tool at this scale. Thinning activities significantly affect tree biomass carbon pools. However, we did not find a significant affects of site conditions on tree biomass carbon pools within the same climate.
5. Mature beech dominated stands at the Tharandt forest had higher tree biomass carbon stocks and lower organic layer carbon stocks compared to spruce. This was to a big part an effect of differences in thinning intensity.

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